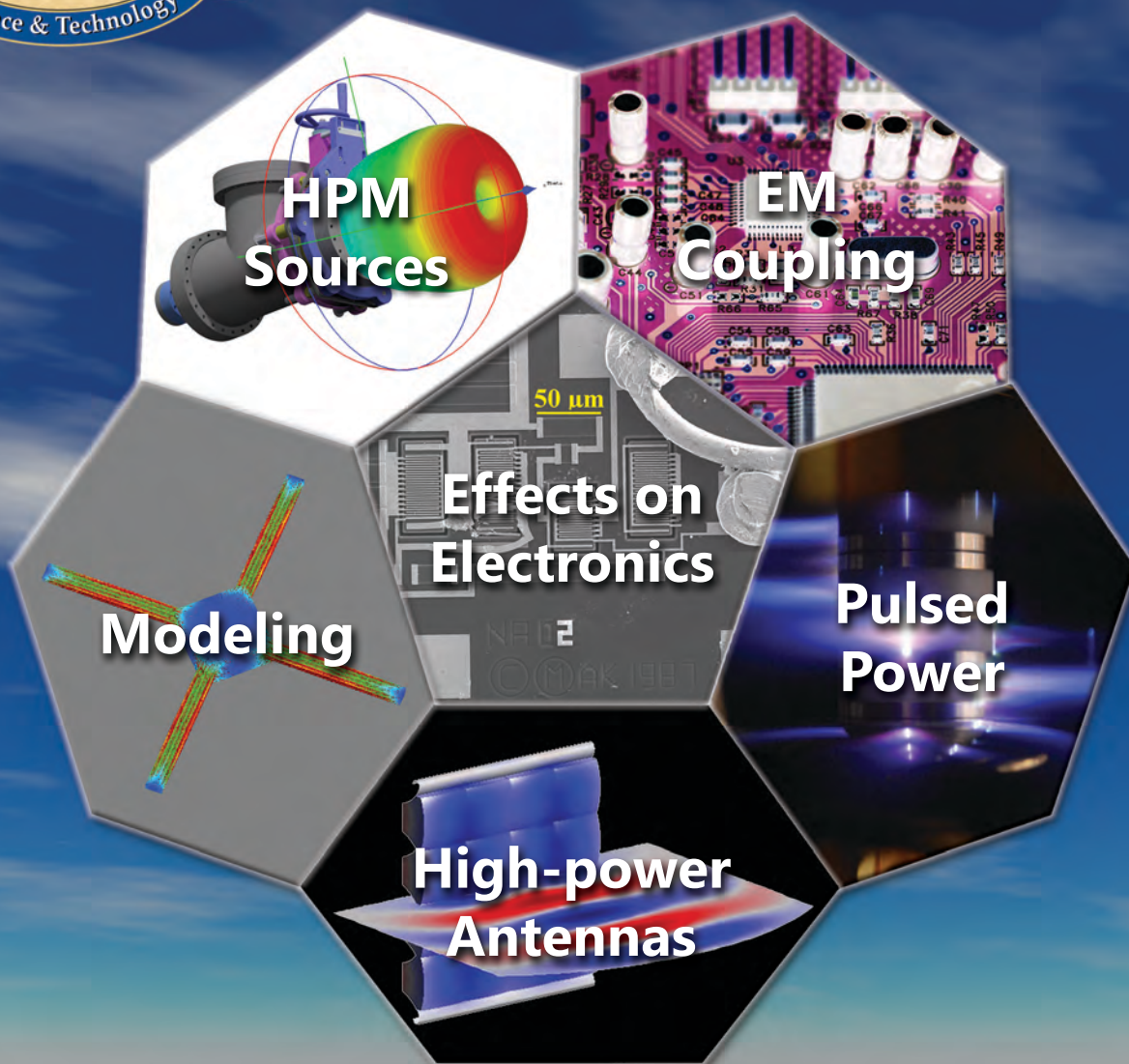




DIRECTED ENERGY WEAPONS (DEW) HIGH POWER MICROWAVE (HPM) 6.1 PROGRAMS FY21 ANNUAL REPORT

Mr. Ryan Hoffman, Program Manager

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**Directed Energy Weapons (DEW)
High Power Microwave (HPM) Program
Annual Report for FY21**

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**Directed Energy Weapons (DEW) High Power
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Introduction

**Program Officer
Ryan Hoffman, Office of Naval Research**

The Directed Energy Weapons (DEW) Program of ONR was initiated in response to the rapid development and growing threat of directed energy technologies by adversaries. Directed energy weapons are defined as electromagnetic systems capable of converting chemical or electrical energy to radiated energy and focusing it on a target, resulting in physical damage that degrades, neutralizes, defeats, or destroys an adversarial capability. The U.S. Navy uses HPM to gain and sustain tactical, operational, and strategic advantage in the arena of EM Maneuver Warfare and Integrated Defense for U.S. forces across the full range of military operations, including power projection and integrated defense missions. The ability to focus radiated energy reliably and repeatedly at range, with precision and controllable effects, while producing measured physical damage, is the measure of DEW system effectiveness. In anticipation of DEW advancements, the ONR HPM Program comprises a portfolio of initiatives and research projects which seek to provide the science and engineering basis for means and methodologies to provide the Navy advanced HPM technologies, systems, and techniques enabling a new class of weapons that will be highly effective in the battlespace. The goal is to be the most effective steward of DEW systems.

Asymmetric threats are proliferating worldwide and likely will continue to do so until such time as effective countermeasures are deployed. Often enough, Rules of Engagement will restrict kinetic engagement with asymmetric threats contingent on the particulars of the scenario. DEW systems – or more specifically for this report, HPM weapons – are expected to allow Naval commanders significantly more flexible responses to a number of asymmetric threats, including various small surface craft and unmanned aerial vehicle (UAV) threats. This flexibility is possible since the restrictions on engaging targets might be removed or reduced based on recognition of 1) the low collateral damage and 2) the non-lethal and reversible effects associated with HPM weapons.

HPM weapons create pulses of electromagnetic energy over a broad spectrum of known radio and microwave frequencies, causing either temporary or permanent results on electronics within targeted systems at scalable effects. HPM weapon systems can be used to disrupt, disable, or potentially destroy critical electronic circuitry in target systems, even in restricted scenarios, while also having the advantage of low cost per shot. HPM weapons deliver electromagnetic energy through coupling of the electromagnetic wave to target circuits through aperture or cable points of entry, thereby inducing currents in the circuitry capable of causing a variety of effects. Potential effects include erroneous signals, system lock-up, shutdown, loss of communications between systems, and physical damage.

As DEW falls within the Fundamental Research part of the broad ONR Science & Technology Investment Portfolio, projects funded are long-term initiatives, covering basic research or applied science. These investigations can have a five to twenty year horizon. Across the HPM technology thrust areas, research projects within the program include performers from academia, industry, government laboratories, and small businesses. Moreover, the program includes performers whose research is financed through Navy SBIR/STTR funding. In addition, science and technology solutions from an international technical community are afforded through ONR Global, which funds projects that foster cooperation in areas of mutual interest with global partners. The program encourages the cross-pollination of ideas and

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collaboration among performers worldwide, and offers an annual review where performers provide updates on the status of their research and present results to their DEW peers. Furthermore, data and facilities sharing are encouraged within the program. This approach contributes to increased success for the program and for the Navy.

Focus areas cover HPM sub-systems that optimize power and/or energy density at the electronic target for a variety of platform sizes and capabilities while minimizing size, weight, power and cost. Examples of related areas for S&T investment and research include supporting technologies such as power electronics, pulsed power drivers, power modulators, as well as frequency agile RF sources and antennas.

Additional research focus areas include research into electronic system coupling, interaction, and effects with the first goal of enabling development of predictive effects tools for current systems. A second goal of this work includes an exploration of in band and out of band coupling and interaction mechanisms. This exploration will exploit developing advances in frequency and bandwidth agility both to identify new potential weapon system possibilities as well as to achieve significant improvements in size, weight, power, and cost in new variants of existing systems.

Research Challenges and Opportunities

- RF coupling and modeling tools to capture complex EM wave interactions with electronics and associated enclosures, RF component disruption, along with novel techniques for experimental validation. Prediction of effects on electronics with improved techniques for HPM lethality testing and analysis. Analysis of HPM coupling mechanisms, electronic device interaction physics, and component level effects validated through experiment. Development of tools and techniques for more efficient identification and utilization of novel RF waveforms.
- Pulsed power/power electronics; including high energy density capacitors, power conditioning, high voltage switches, dielectric insulators, 3D printed/novel materials and power modulator pulse forming networks that enable higher duty cycle operation
- Solid state and vacuum electronic based HPM sources that provide frequency and waveform parameter tunability and are reconfigurable to adapt to changing requirements; computer codes for modelling HPM physics to enable the next generation of devices
- Wide bandwidth high power amplifiers that provide the ability of very rapid waveform adjustment.
- High power, low profile, or conformal antenna designs and capable radome materials, novel array concepts, high power beam steering techniques and distributed beam forming approaches.
- Novel HPM sensors, instrumentation and algorithms are of interest for measurement of waveforms and diagnosing system performance as well as applied to Electronic battle damage indication (eBDI).

Novel High-Power Microwave System Designs Using Nonlinear Transmission Lines

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Project Title: Novel High Power Microwave System Designs Using Nonlinear Transmission Lines

Annual Summary Report: FY2021

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Section I: Project Summary

1. Overview of Project

Abstract: Nonlinear transmission lines (NLTLs) are of great interest to the Navy for solid state high repetition rate directed energy systems. This project investigates the suitability of novel composite materials for NLTLs in a high-power microwave (HPM) source. Since understanding the current state of NLTL research will guide potential areas of improvement, we have performed an extensive review of current NLTL technology and topologies, constructed composites with various volume loadings of barium strontium titanate (BST) and/or nickel zinc ferrite (NZF), which exhibit nonlinear permittivity and permeability, respectively, and tested NLTLs constructed with these composites. We report the linear permittivity of BST, NZF, and BST/NZF composites as a function of volume loading and the linear permeability as a function of frequency and volume loading. We observe notable increases in permeability as we exceed 15% NZF for the NZF composites and 10% NZF for the NZF/BST composites. We observe reasonable agreement between effective medium theories (EMTs), finite element simulation using CST Microwave Studios, and experiment from 1 to 4 GHz for the various composites. The main outstanding challenge is measuring bulk BST permittivity for entering in the model. We have also tested a novel composite-based NLTL system where the NLTL is used simultaneously as the HPM source and pulse forming line. Future work will involve testing propagation from an NLTL-based system with an antenna.

Objective: The goal of this project is to evaluate the feasibility of constructing an NLTL based system based on composites containing nonlinear dielectric materials in a polymer base dielectric. The resulting composite dielectric properties will be measured using a vector network analyzer (VNA) to determine the complex permittivity and permeability of the composite. This will provide a baseline for determining the relationship between the volume loading of the nonlinear electric and nonlinear magnetic inclusions in a material to the dielectric properties of the composite. These measurements will be used to develop a model based on common effective medium theories, such as the Maxwell Garnett model, to guide material design. This model can be coupled with electromagnetic simulations to optimize an NLTL system as a radio frequency (RF) source.

Introduction: Increased global volatility motivates the development of devices for nonlethal deterrence. Directed energy devices can provide forceful persuasion at a distance for both civilian and military peacekeepers. Additionally, increasing occurrences of vehicular terrorism further drive the development of technology to stop vehicles from a distance before they can injure civilians or destroy property. Militarily, disabling motorized attacks before contact with troops is critical for reducing casualties while keeping the attackers alive for future interrogation. Directed energy technology can provide these capabilities, although system size often limits application in the field. Thus, developing compact HPM devices could facilitate fielding devices for nonlethal defense with increased standoff range or for radar or weapons systems for aircraft or ships. This effort

assesses the design of novel NLTLs by examining the impact of composites comprised of various combinations of dielectric and magnetic inclusions and leveraging various geometries, such as tapering, used in conventional transmission lines for matching. This may increase efficiency and energy in the RF output as it relates to pulse width while also providing design flexibility.

Background:

Materials are a challenge for NLTL design. Figure 1 shows a simple example of a NLTL. One may represent a conventional transmission line with lumped elements as an inductor in series with a resistor on the top line and a capacitor in parallel with a shunt conductor in the vertical lines with the resistor and conductor representing losses. An NLTL has a similar setup, as shown in Figure 1, except that either the inductor or capacitor (or both) vary with current or voltage, respectively. This modulates the delivered pulse to generate an RF signal with tunability of the NLTL important for controlling the frequency of the resulting RF.

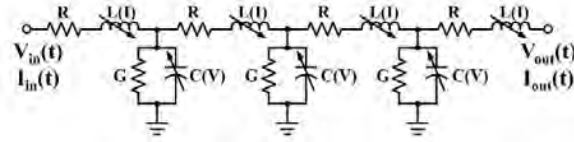


Fig. 1 Lumped element representation of a nonlinear transmission line (NLTL) comprised of both nonlinear capacitance $C(V)$ a function of voltage and inductance $L(I)$ a function of current that translates an input voltage $V_{in}(t)$ and current $I_{in}(t)$ into an output voltage $V_{out}(t)$ and output current $I_{out}(t)$. An NLTL may be constructed with nonlinear capacitance and/or inductance. In general, loss may be included through a resistance R in series with the inductor or a conductance G in parallel with the capacitance.

While NLTLs are growing in importance for generating RF, challenges remain in constructing them with high voltage and power capabilities, as required in many HPM applications, and in tunability for wideband applications or capability to be used at multiple frequencies. Based on the definitions above and the circuit diagram in Figure 1, one method to generate an NLTL involves using a varactor, whose capacitance varies with applied voltage, generally sigmoidally (rapidly increasing over a narrow voltage range). Understanding the importance of this dependence is critical for understanding the potential flexibility in design. Early NLTLs often used nonlinear capacitance to induce this phenomenon, resulting in soliton formation.

Varactors are generally low voltage devices, which presents a challenge for high power applications. Additionally, the frequency cannot be tuned for a given varactor. A recent alternative growing in popularity involves using ferrites to provide nonlinear inductance in meandering NLTLs. Texas Tech University (TTU), the Air Force Research Laboratory (AFRL), and others have also developed and applied such approaches for gyromagnetic NLTLs for HPM and high-power radiofrequency applications. The initial TTU NLTLs provided peak voltages of approximately 50 kV with 15% power efficiency and frequencies of a few GHz. TTU next considered the impact of material, such as nickel-zinc, yttrium iron garnet, magnesium-zinc, and lithium ferrites, on performance. They demonstrated that varying the material's bias magnetic field provided active delay control and that the material's ferromagnetic resonance line width played a significant role in microwave generation. TTU next showed that one could effectively tune the output by controlling the bias voltage, which subsequently impacted the electrical properties of the NLTL due to its nonlinear nature, enabling the construction of a single, frequency-agile device

capable of operating from 1.8 to 2.6 GHz with powers from 1 MW to 3 MW; however, higher voltages (on the order of 40 kV) resulted in corona discharge, limiting application at higher voltages. Thus, attaining higher powers required combining multiple NLTLs, which they demonstrated for arrays of either two or four NLTLs. The NLTL could then be incorporated into a solid-state HPM source to generate microwave pulses with a frequency of 2.1 GHz with a pulse repetition frequency of 65 MHz. AFRL designed a spatially dispersive ferrite NLTL with axial bias that was frequency tunable from 0.95 to 1.45 GHz with instantaneous power levels of tens of MW and durations from 4 to 17 ns.

A Russian group from the Institute of High Current Electronics has also studied gyromagnetic RF sources using NLTLs. Their early work used saturated NiZn ferrites as an active nonlinear medium and found an optimum length of approximately 1 m for producing a 1000 pulse burst at 200 Hz repetition rate for a peak RF power of 260 MW with a central frequency of 1.2 GHz and of 0.25 GHz at -3 dB level and 0.4 GHz at -10 dB level. They have also demonstrated electronically controlled beam steering by connecting two NLTLs to one high voltage driver with each NLTL capable of producing RF pulses from 50-700 MW at frequencies from 0.5 to 1.7 GHz with 100 Hz repetition rate. Gyromagnetic NLTLs have also generated high power ns RF pulses with field strengths up to 40 kV/cm, durations from 4 to 25 ns, and frequency from 0.6 to 1.0 GHz to provide flexible output at laboratory scale for biological experiments. They have also subsequently extended their frequency output to 4 GHz with a peak voltage of 175 kV for 100 Hz repetition rates during one second. Their ferrite line in the NLTLs implements a continuous unit of NiZn rings of M200VNP type of a total length of 700 mm. At lower frequencies (~300 MHz), they have also used a gyromagnetic NLTL as a peak power amplifier of an input pulse. They applied a 500 kV pulse with a full-width-half-max duration of 7 ns to the NLTL to increase the pulse amplitude to 740 kV while reducing the pulse duration to ~2 ns. This increased the power from ~6 GW on the input to ~13 GW on the output at a 1 kHz pulse repetition rate in burst mode.

Alternatively, the University of New Mexico developed a hybrid line consisting of both nonlinear capacitors and inductors. While this is a promising approach that could provide some ability for tunability, one must attain appropriate inductance and capacitance behavior to achieve a constant transmission line impedance.

2. Activities and Accomplishments

The first part of Fiscal Year (FY) 2021 focused on completing the manuscript concerning composite measurements and modeling for which we highlighted results in the FY20 report. Specifically, we published papers on the following topics:

- 1) Nonlinear permeability of composites containing nickel zinc ferrite (NZF) or NZF with barium strontium titanate (BST).
- 2) Permittivity, permeability, and breakdown strength of composites containing *either* NZF *or* BST.
- 3) Permittivity, permeability, and breakdown strength of composites containing *both* NZF *and* BST.
- 4) Modeling of permittivity and permeability of composites containing NZF and/or BST.

We presented the majority of these results in the FY20 report, so this report will instead focus on the following key accomplishments:

- 1) Testing a composite-based NLTL with a Blumlein generator (published as an invited paper in *IEEE Transactions on Plasma Science*).
- 2) Developing and testing an NLTL used as a combined pulse forming line (PFL) and HPM source (provisional patent filed; published in *Review of Scientific Instruments*).
- 3) Examining the effect of NLTL impedance of pulsed RF generation from the combined PFL/HPM architecture.
- 4) Measuring nonlinear permittivity of composites containing bariums strontium titanate.

TESTING A COMPOSITE-BASED NLTL WITH A BLUMLEIN GENERATOR

NLTLs are typically driven by pulse forming networks (PFNs) or Marx generators, and one would intuitively hypothesize the microwave generation would not depend significantly on the method used to generate the input pulse to the NLTL. Since our laboratory had a Blumlein pulse generator constructed to drive a $10\ \Omega$ load with a 10 ns pulse duration and 1.5 ns rise- and fall-times, we used that to drive composite-based coaxial NLTLs comprised of NZF and BST inclusions. Applying a 30 kV pulse to the composite NLTLs produced frequencies ranging from 1.1 to 1.3 GHz with output powers over 20 kW. Figure 2 shows a representative waveform for a 30 kV pulse applied to a 25% NZF composite NLTL. Figure 3 shows the generated frequency output for this NLTL with different driving voltages in Fig. 3(a) and for a fixed driving voltage and various magnetic biases in Fig. 3(b). Without magnetic field bias, there is no clear trend in output power with increasing voltage.

Many common NLTLs require a bias voltage to generate RF; however, we do not observe a clear trend in output

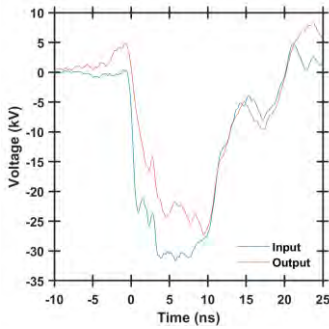


Fig. 2 Representative input and output voltage waveforms for a 25% NZF composite NLTL with a 30 kV input pulse.

power with increasing bias. This indicates the poor suitability of the Blumlein for driving an NLTL to generate RF.

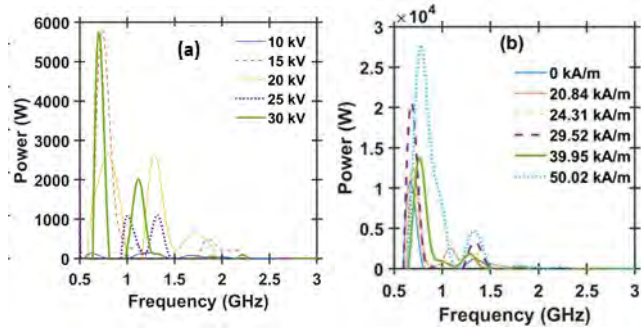


Fig. 3 Measured generated frequency output for a 25% NZF composite based NLTL (a) without and (b) with magnetic field bias. The absence of a trend in output power with increasing magnetic field bias indicates the poor suitability of the Blumlein for driving an NLTL.

Measured results and simulations using LT Spice showed that Blumlein modulators were insufficient to drive NLTLs to produce high power oscillations; however, LT Spice simulations showed that applying a standard PFN to the same NLTL produced the expected oscillations. Simulations for the Blumlein in Fig. 4(a) show that the NLTL does not introduce new oscillations into those already present from the Blumlein; Fig. 4(b) shows that the NLTL does introduce oscillations not present from the PFN alone. Thus, the Blumlein architecture is responsible for the

absence of oscillations. This difference arises because the mechanism for Blumlein pulse formation cancels the shockwaves responsible for inducing microwave production by the NLTL.

NLTL AS A COMBINED PFL/HPM SOURCE

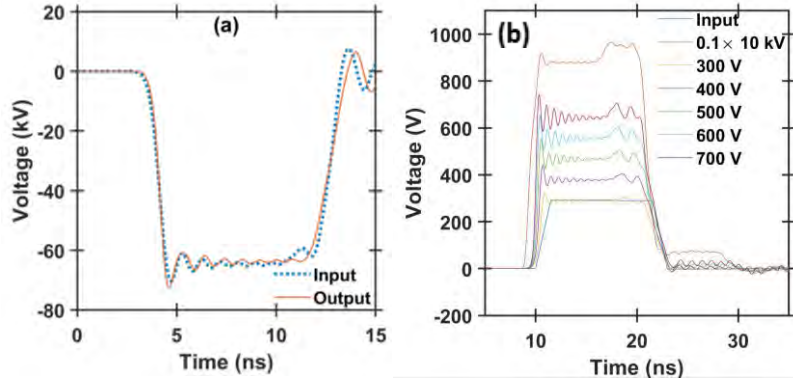


Fig. 4 Simulated (a) input and output waveforms to/from an NLTL based on a 10% BST/15% NZF composite in a silicone matrix driven by a Blumlein modulator and (b) output from a 10% BST/15% NZF composite NLTL driven by a pulse forming network (PFN). Driving the NLTL with the PFN introduces oscillations not present due to the PFN alone.

While NLTLs can generate high repetition rate, HPM with fewer auxiliary systems than conventional sources, we developed an even more compact HPM system that simultaneously utilized a composite based hybrid NLTL as the PFL and HPM generator in a single device. We designed the following three different combinations of nickel zinc ferrite (NZF) and barium strontium titanate (BST) inclusion volume loads in a polydimethylsiloxane (PDMS) host material to provide magnetic field dependent permeability and electric field dependent permittivity, respectively: 25% NZF, 10% BST/15% NZF, and 15% BST/10% NZF. For these experiments, the NTLs had an impedance of 10Ω . By constructing the NLTL in a coaxial geometry, this device uses the capacitance and length of the NLTL to generate a fast rise-time high voltage pulse with microwave oscillations that occurred both during and after the pulse after exceeding a threshold charging voltage. Figure 5 shows the output waveforms for these NLTLs under different applied voltages. The output frequency of the NLTLs ranged from 950 MHz to 2.2 GHz during the pulse for all volume loadings and was 1 GHz after the pulse for the 10% BST/15% NZF and 15% BST/10% NZF volume loadings, as shown in Fig. 6. The oscillations generated after the pulse were much higher in amplitude and achieved 160 kW at a 15 kV charging voltage for the 15% BST/10% NZF composite-based NLTL. Future work could involve designing a high voltage input connection to prevent breakdown and allow a higher charging voltage. Additionally, using a triggered spark gap switch would provide greater control over the repetition rate and charging voltage.

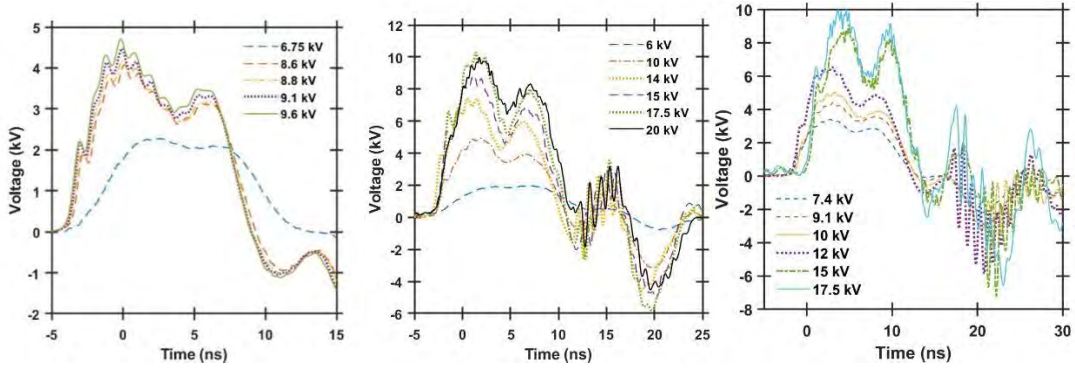


Fig. 5 Measured output waveforms combined PFL/HPM source architecture using NLTL composed of composites with (left) 25% NZF, (middle) 10% BST/15% NZF, (right) 15% NZF/10% BST.

One of the interesting observations that we have made in the course of our experiments concerns the importance of the impedance of the NLTL for generating RF. We have performed experiments using the inductive adder that we purchased as part of a separate DURIP to drive our composite NLTLs. The main mode of the inductive adder is to drive $50\ \Omega$ NLTLs, although it can drive loads with impedances down to $\sim 25\text{--}30\ \Omega$. Our initial experiments using the inductive adder to drive $50\ \Omega$ composite NLTLs did not generate sufficient RF. We conjecture that this arises because the rise-time was not sufficiently fast to generate the shockwave. Since we are limited in what we can do concerning voltage and magnetic field bias, we have sent some sample NLTLs to NSWC Dahlgren for testing.

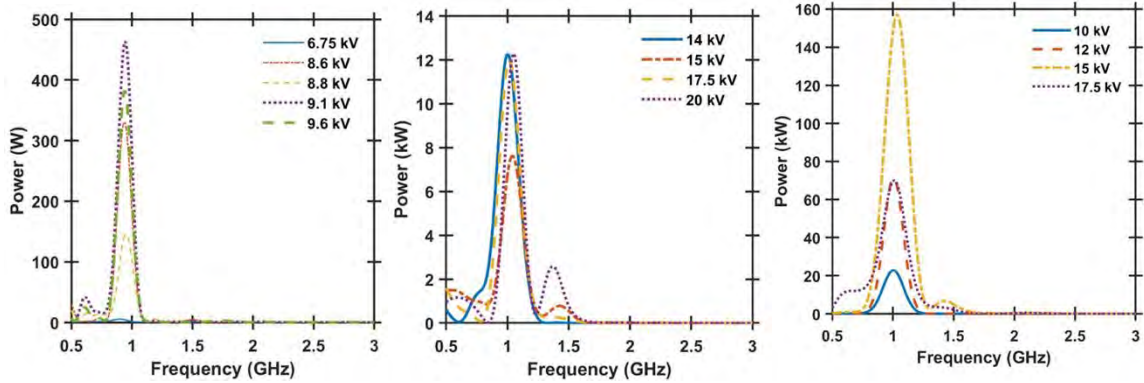


Fig. 6 Measured output spectrum of the oscillations following the applied pulse for NLTLs with composites made of (left) 25% NZF, (middle) 10% BST/15% NZF, and (right) 15% NST/10% NZF.

Generally, these limitations all stem from the inability to achieve a sufficient current across the NLTL. One interesting thought would be to decrease the impedance. Since we generated RF using the NLTL in the simultaneous PFL/HPM configuration, we varied the NLTL impedance and examined the resulting RF generated. We observed no RF with the $50\ \Omega$ NLTL in this configuration, while we generated some RF with the $25\ \Omega$ configuration. These results demonstrate the importance of impedance for generating RF, which has not previously been studied in detail for NLTLs, particularly given the difficulty in changing PFL impedances for standard devices.

NONLINEAR PERMITTIVITY MEASUREMENTS

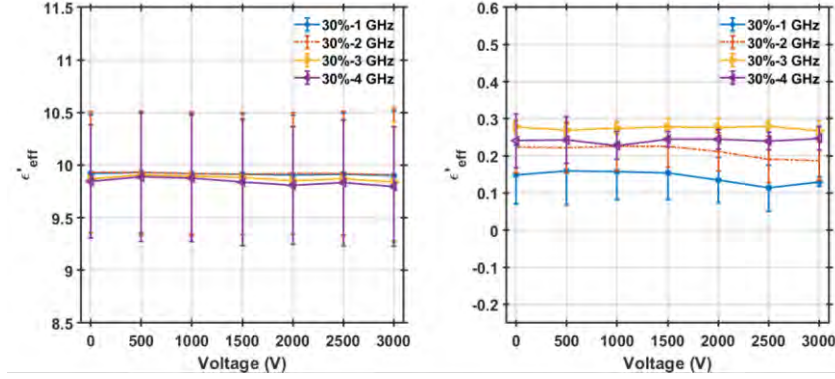


Fig. 7 (Left) Real and (right) imaginary permittivity of a 30% BST composite vary with bias voltage.

One of the important aspects of designing and constructing NLTLs as effective pulsed RF generators is appropriate tuning of the composite permittivity and permeability for different volume loadings of the inclusions. In FY20, we reported our measurements of linear permittivity and permeability and nonlinear permeability; completely characterizing electromagnetic behavior also requires measuring the nonlinear permittivity.

We measured the nonlinear real and imaginary permittivity of barium strontium titanate ($\text{Ba}_{2/3}\text{Sr}_{1/3}\text{TiO}_3$, BST) composites with volume fractions up to 30% for frequencies from 300 MHz to 4 GHz with a volume-averaged bias field from 0 to 1.43×10^6 V/m. We observed negligible nonlinearity for the highest volume loading as a function of electric field, as shown in Fig. 7.

A nonlinear effective medium theory was studied and used to predict the nonlinear effective permittivity with higher bias fields. The theoretical estimation suggests that exhibiting composite nonlinearity with various volume fractions from 20% to 50% requires the bias field to be at least above 10^7 V/m.

3. Findings and Conclusions

The major development as part of this grant was the application of the NLTL simultaneously as a PFL and HPM source, which has significant implications for device size. Future efforts optimizing magnetodielectric materials to adjust the composite behavior will enable tuning the output frequency while retaining dielectric breakdown strength. Furthermore, the source impedance may be varied from 10Ω to in excess of 50Ω with frequency tunability in the L and S bands. Eliminating the need for a separate PFL has enabled the development of a system with a volume of $\sim 15 \text{ in}^3$ (~ 0.25 liters) without including the prime power or antenna system. Future efforts with tuning the magneto-dielectric properties by adjusting the volume loadings of novel ferromagnetic and ferroelectric materials and multiferroic materials will provide increased frequency tunability with suitable dielectric breakdown strength. We have also demonstrated the importance of the NLTL impedance in generating RF with lower impedance NLTLs providing better performance. The

combined PFL/HPM architecture eliminates the need to match the output impedance of the PFL to the NLTL, providing extensive flexibility in selecting impedance.

We also demonstrated the importance of PFL design on NLTL performance. Specifically, for the same NLTL, we performed simulations showing that a standard PFL could generate a signal while a Blumlein generator would not. We are currently working with NSWC Dahlgren division to test some of our NLTLs with higher power and faster rise-time generators.

Finally, over the course of the full period of performance, we have developed techniques for constructing composites, measuring linear and nonlinear permittivity and permeability, and modeling composite behavior that will be valuable in future composite NLTL designs. While the present approach for measuring nonlinear permittivity encountered issues with raising voltage due to the sensitivity of the network analyzer, we have developed techniques that may be applicable to higher voltages in future studies. While not the major goal of future efforts, these approaches will enable the development of novel materials to improve the performance reported here.

4. Plans and Upcoming Events

Key plans for FY2022 follow:

- 1) Complete and submit manuscript on the effect of NLTL impedance on RF output in the NLTL as a simultaneously PFL/HPM architecture.
- 2) Complete testing of the NLTLs sent to NSWCDD, compare to previously performed Purdue simulations, and submit manuscript.
- 3) Complete manuscript on the nonlinear permittivity measurements.
- 4) Develop and test antenna system coupled to the NLTL in the combined PFL/HPM architecture, assess output, and write manuscript.
- 5) Recommendations for Future Work: Explore tunability of RF output using multiple NLTLs with various volume loadings.

Recommendations for Future Work:

- 1) Material optimization for enhancing and tuning RF generation.
- 2) System development, such as using power modulators with faster rise-time when the NLTL is mated with a separate PFL, multiple NLTLs with various properties, and connection to an antenna.
- 3) Continued development of the NLTL as a combined PFL/HPM source for compact systems to optimize power, efficiency, and NLTL impedance.
- 4) Assess relevant application space, including biomedical applications required pulsed RF radiation (e.g., sterilization and transfection at standoff).

5. Transitions and Impacts

We have provided sample composite-based NLTLs to NSWC Dahlgren to test with their modulators. Dr. Andrew Fairbanks, who was a Purdue Ph.D. student funded by this effort, started working for NSWC Dahlgren in 2021 after having worked there as a Pathways Fellow.

6. Collaborations

Andrew Fairbanks, Naval Surface Warfare Center Dahlgren Division; Jack Chen, Naval Surface Warfare Center Dahlgren Division; Eagle Harbor Technologies; Ryan McBride, University of Michigan; Walter Sessions, GTRI; Somnath Sengupta, Powerhouse Consulting; Peter Schubert, IUPUI; Peter Bell, Urban Air Mobility Coalition for Affordable Housing.

7. Personnel

Principal investigator: Allen L. Garner, 0.27 person-months

Business Contact: Tara Finley, 765-494-2583, tmfinley@purdue.edu

Team Members:

Xiaojun Zhu, graduate student, 12 person-months

Travis Crawford, graduate student, 6.1 person-months

Andrew J. Fairbanks, graduate student, 6.4 person-months

Subs: Georgia Tech Research Institute (GTRI) and the University of Michigan.

8. Students

3 graduate students / 5 undergraduate students

9. Technology Transfer

Provisional patent filed: A. J. Fairbanks and A. L. Garner, “Electromagnetic Wave Generator Based on Nonlinear Composite Materials,” 63/163,895. Working to convert to U.S. Patent application.

Working with NSWC Dahlgren to test NLTL at high voltage and also working to determine ways to test propagation using antenna. We have sent some NLTLs to NSWC Dahlgren for testing. We have also had some communications with AFRL (Don Shiffler) and ARL (Thad Thomas) about this technology in general. We have also worked with Peter Bell and Peter Schubert on some potential commercial ideas for NLT technology. In particular, we are working with Peter Schubert, who is an antenna expert, on developing a system that couples our NLTL in the simultaneous HPM/PFL architecture with an antenna for propagation. Our patent was selected for a senior design project for Business majors at Purdue for developing a business plan that may provide insight into potential commercialization opportunities.

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Archival Publications

1. **[INVITED]** A. J. Fairbanks, T. D. Crawford, M. E. Vaughan, and A. L. Garner, “Simulated and Measured Output from a Composite Nonlinear Transmission Line Driven by a Blumlein Pulse Generator,” *IEEE Transactions on Plasma Science* **49**, 3383-3391 (2021).

2. A. J. Fairbanks, T. D. Crawford, and A. L. Garner, “Nonlinear transmission line implemented as a combined pulse forming line and high-power microwave source,” *Review of Scientific Instruments* **92**, 104702 (2021).

3. X. Zhu, A. J. Fairbanks, T. D. Crawford, and A. L. Garner, “Modelling Effective Electromagnetic Properties of Composites Containing Barium Strontium Titanate and/or Nickel Zinc Ferrite Inclusions from 1-4 GHz,” *Composites Science and Technology* **214**, 108978 (2021).

4. A. J. Fairbanks, T. D. Crawford, J. A. Hernandez, J. D. Mateja, X. Zhu, T. N. Tallman, and A. L. Garner, "Electromagnetic Properties of Multiphase Composites Containing Barium Strontium Titanate and Nickel Zinc Ferrite Inclusions from 1-4 GHz," *Composites Science and Technology* **211**, 108826 (2021).
5. A. J. Fairbanks, T. D. Crawford, J. A. Hernandez, J. D. Mateja, X. Zhu, T. N. Tallman, and A. L. Garner, "Electromagnetic measurements of composites containing barium strontium titanate or nickel zinc ferrite inclusions from 1-4 GHz," *Composites Science and Technology* **210**, 108798 (2021).
6. T. D. Crawford, A. J. Fairbanks, J. A. Hernandez, T. N. Tallman, and A. L. Garner, "Nonlinear Permeability Measurements for Nickel Zinc Ferrite and Nickel Zinc Ferrite/Barium Strontium Titanate Composites from 1-4 GHz," *IEEE Transactions on Magnetics* **57**, 6100810 (2021).

Refereed Journal Articles in Preparation

1. T. D. Crawford, X. Zhu, and A. L. Garner, "Dependence of RF Generation on Nonlinear Transmission Line Impedance"
2. X. Zhu, A. J. Fairbanks, T. D. Crawford, and A. L. Garner, "Nonlinear Effective Dielectric Properties of Barium Strontium Titanate Composites at the Ultra-High Frequency"

Conference Papers

1. X. Zhu, A. J. Fairbanks, T. D. Crawford, and A. L. Garner, "Predicting Effective Dielectric Properties of Composites for Nonlinear Transmission Lines Using Effective Medium Theories and CST Microwave Studios," IEEE International Vacuum Electronics Conference, P5.2, 22 October 2020, pp. 305-306.
2. T. D. Crawford, A. J. Fairbanks, X. Zhu, J. A. Hernandez, T. N. Tallman, and A. L. Garner, "Development of Composites for Nonlinear Transmission Lines," IEEE International Vacuum Electronics Conference, P5.1, 22 October 2020, PP. 303-304.

Conference Oral Presentations

1. T. Crawford, A. Fairbanks, and A. Garner, "Testing composite based nonlinear transmission lines with various pulsed power drivers," 2021 IEEE International Conference on Plasma Science, 5O-E-02, Virtual 14 September 2021.
2. A. Fairbanks, T. Crawford, and A. Garner, "Composite-based nonlinear transmission line as a complete high power microwave system," 2021 IEEE International Conference on Plasma Science, 5O-E-01, Virtual 14 September 2021.
3. X. Zhu, A. Fairbanks, T. Crawford, W. Sessions, and A. Garner, "Microwave generation in coaxial, composite nonlinear transmission lines," 2021 IEEE International Conference on Plasma Science, 4O-C-05, Virtual 13 September 2021.
4. A. J. Fairbanks, T. D. Crawford, A. L. Garner, "Novel composite based NLTL as complete high power microwave system," 2021 Annual DE S&T Symposium, Student Workshop – HPM & Thermal, Virtual 24 March 2021.
5. A. J. Fairbanks, T. D. Crawford, J. A. Hernandez, T. N. Tallman, and A. L. Garner, "Nonlinear transmission line design using novel nonlinear composites," IEEE International Conference on Plasma Science, TA2-S6-009, Session D5M3-TA2.6, 09 December 2020. **[Chosen as selected paper]**
6. T. D. Crawford, A. J. Fairbanks, J. A. Hernandez, T. N. Tallman, and A. L. Garner, "Nonlinear Permeability Measurements of Single and Dual Inclusion Composites for NLTL Systems from 1-4 GHz," IEEE International Conference on Plasma Science, TA2-S6-007, Session D5M3-TA2.6, 09 December 2020.

Conference Poster Presentations

1. X. Zhu, A. J. Fairbanks, T. D. Crawford, and **A. L. Garner**, “Predicting Effective Dielectric Properties of Composites for Nonlinear Transmission Lines Using Effective Medium Theories and CST Microwave Studios,” IEEE International Vacuum Electronics Conference, P5.2, 22 October 2020.
2. T. D. Crawford, A. J. Fairbanks, X. Zhu, J. A. Hernandez, T. N. Tallman, and **A. L. Garner**, “Development of Composites for Nonlinear Transmission Lines,” IEEE International Vacuum Electronics Conference, P5.1, 22 October 2020.

Ph.D. Dissertation

A. J. Fairbanks, “Novel Composites for Nonlinear Transmission Line Applications,” Ph.D. Dissertation, May 2021.

MS Thesis

T. D. Crawford, “Nonlinear Permeability of Composites For Nonlinear Transmission Lines at Microwave Frequencies,” MS Thesis, December 2020.

11. Point of Contact in Navy

Andrew Fairbanks, NSWCDD, 29SEP2021; Jack Chen, NSWCDD, yeongjier@navy.mil, 17DEC2020

12. Acknowledgement/Disclaimer

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Nanoscale Effects on Gas Breakdown and Electron Emission

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Period of Performance: October 1, 2020 to September 30, 2021

Prepared by:

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Grant or Contract Number: N000014-17-1-2702

Date Prepared: 25 January 2022

Project Title: Nanoscale Effects on Gas Breakdown and Electron Emission

Annual Summary Report: FY2021

Principal Investigator: Allen L. Garner, 765-494-0618, algarner@purdue.edu
Purdue University

Section I: Project Summary

1. Overview of Project

Abstract: Accurately predicting gas breakdown voltage is becoming increasingly important as the trend toward electronics miniaturization increases. Microelectromechanical systems (MEMS), such as microactuators, pressure sensors, and high-frequency circuits, require microscale gaps and high operating voltages. Accurate breakdown voltage predictions for these systems will prevent discharges that could damage or destroy the device. Conversely, microplasmas use microdischarges for various applications, such as electric micropropulsion and environmental mitigation. Present research trends focus on developing micro- and nano-vacuum electronics for providing increased power densities and frequency for directed energy applications, including radar platforms for shipboard and aircraft systems. In particular, the Air Force and Navy have ongoing efforts exploring the field emission (FE) characteristics of arrays of carbon nanotubes, particularly exploring the implications of distance between emitters and variation of work function on electric field characteristics.

Objective: This effort will elucidate the impact of nanoscale effects on gas breakdown for microscale and smaller gaps by combining experiment, numerical analysis, and theoretical analysis. Specifically, it will assess the impact of surface irregularities, which alter the work function and field enhancement factors that drive field emission. This research fills a gap in understanding the influence on surface structure for electron emission and breakdown, which has significant implications for efficiency and equipment durability.

Introduction: Accurately predicting gas breakdown voltage is becoming increasingly important as the trend toward electronics miniaturization increases. From a directed energy perspective, which is critical for Navy and Air Force applications, present research trends focus on developing micro- and nano-vacuum electronics for providing increased power densities and frequency for shipboard and aircraft radar platforms. In particular, the Air Force and Navy have ongoing efforts exploring the field emission characteristics of arrays of carbon nanotubes, particularly exploring the implications of distance between emitters and variation of work function on electric field characteristics. Directed energy systems using laser or intense electromagnetic systems, including pulsed power and high-power microwave technologies, are constantly striving to achieve very high power densities using high frequency and more compact systems. As one goes to these smaller systems, higher electric fields arise and issues concerning breakdown, field emission, and space-charge limited flows increase significantly.

Background: Elucidating the impact of nanoscale effects on gas breakdown for microscale and smaller gaps requires combining experiment, numerical analysis, and theoretical analysis. Initial efforts involve the following:

- Assessing and applying analytic models relating field emission and space-charge limited flow, both at vacuum and general pressure, will elucidate the potential impact of space-charge on field enhancement to determine the point at which pressure no longer contributes.
- Performing experiments and developing analytic models will determine the impact of surface roughness and various flaws on surface on the work function and field enhancement, which measures the energy necessary to remove an electron from the cathode and plays a crucial role in the determining the field emission current.
- Performing molecular dynamics simulations to determine the implications of electrode geometry on electron emission and space charge effects to provide data for continuum breakdown theories.

These results were then applied to understanding experimental and theoretical analyses of gas breakdown for microscale gaps and smaller. Specifically, these steps included:

- Further coupling the existing electron emission and breakdown models to the one-dimensional Schrödinger equation to develop a universal breakdown model from the classical Paschen law to quantum scale for multiple gases.
- Analytic and numerical models developed by the Principal Investigator's group will be modified to incorporate the effects of surface roughness and space charge on field enhancement and work function and compared to the parametric experiments.
- Experimental measurements will be performed for gaps from microscale to approximately 100 nm at vacuum and atmospheric pressure to provide a basic parametric study of the mechanisms responsible for breakdown across a wide range of parameters.

This effort will ultimately pave the way for future work unifying all relevant modes of breakdown and electron emission across gap pressure and distance for numerous applications relevant to the Department of Defense, including directed energy, field emission, and micropropulsion.

2. Activities and Accomplishments

Fiscal Year 2021 (FY21) focused on completing the theoretical work on nexus theory and gas breakdown for non-planar diodes that we reported in previous years, performing particle-in-cell (PIC) simulations to better characterize the ionization coefficient for the strong electric fields present in micro- and nanoscale gaps, and completing nanoscale gas breakdown experiments at atmospheric pressure and in vacuum. Significant accomplishments during this period included the following:

- Submission and publication of a manuscript in *Physics of Plasmas* linking electron emission and breakdown mechanisms from the quantum space-charge limited current to Paschen's law (PL) for breakdown.
- Submission and publication of a manuscript in *Journal of Applied Physics* for a theory for microscale gas breakdown in a pin-to-plate geometry.
- Submission and publication of a manuscript in *IEEE Transactions on Electron Devices* deriving space-charge limited current for pin-to-pin and pin-to-plate geometries.
- Characterization of ionization coefficient for micro- and nanoscale gaps and a general semi-empirical estimate up to $\sim 15 \mu\text{m}$, corresponding to the transition to the traditional Paschen's law.
- Completion of nanoscale gas breakdown experiments and observation of gas breakdown from an operating condition where space-charge contributed to field emission.

- Dr. Garner was a coauthor on an invited Perspective in *Journal of Applied Physics* on space-charge limited current partially funded by this project. This paper was selected as a featured paper.
- Dr. Garner presented a plenary talk at the 2021 IEEE International Conference on Plasma Science based partially on work funded by this grant.

The details of the unified emission and breakdown theory were presented in the FY20 report and will not be repeated here. This report will focus on some additional insight from the pin-to-plate breakdown theory, the characterization of the ionization coefficient, and the nanoscale breakdown and electron emission experiments.

PIN-TO-PLATE GAS BREAKDOWN THEORY

In the FY20 report, we reported our modification of our previous theory coupling PL and field emission to account for pin-to-plate geometries by modeling the field enhancement. The approach changes the paradigm of these breakdown theories by fixing field enhancement and using work function as a fitting parameter rather than the inverse. In this approach, we accounted for the spatial dependence of ionization and non-uniform space charge in Poisson's equation to derive a breakdown equation analogous to the parallel-plate breakdown equation from our earlier work (e.g. FY19). We then fit the resulting equation to our pin-to-plate experimental results (Brayfield *et al.* 2019) and showed how the fitted work function varied with each breakdown event.

The FY20 report focused on this fit. In this report, we show some of the new insight that this theory provides. Figure 1 shows how changing the electrode work function and the gap distance alter the breakdown voltage. As expected from our prior asymptotic analysis for parallel plates that showed breakdown voltage decreasing linearly with gap distance for fixed pressure, work function, and field enhancement, the breakdown voltage decreases with decreasing gap distance rather than encountering the minimum voltage encountered by PL. Increasing the work function causes the breakdown voltage to increase. Interestingly, this behavior also seems linear. Thus, one could easily

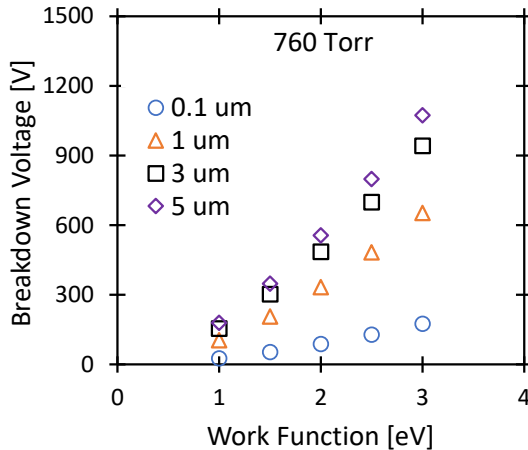


Fig. 1. Theoretically calculated breakdown voltage for a pin-to-plate geometry showing the effects of gap distance and work function (Loveless *et al.* Phys. Plasmas **129**, 103301 (2021))

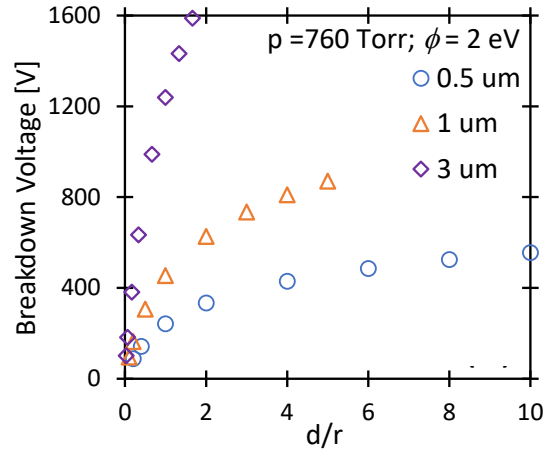


Fig. 2. Theoretically calculated breakdown voltage as a function of the ratio of gap distance d to electrode radius r for various gap distances (Loveless *et al.* Phys. Plasmas **129**, 103301 (2021))

envision future studies in tuning material behavior to attempt to reduce the work function to mitigate microscale breakdown.

In addition to assessing work function, we can also examine the influence of electrode radius. Figure 2 shows that decreasing the electrode radius r for a fixed gap distance d will ultimately cause the breakdown voltage to increase at a slower rate with increasing d/r . At lower d/r , the breakdown voltage becomes insensitive to changes in d and r because the geometry looks more like parallel plate. Since the breakdown voltage increases with d , the rate of increase with d/r increases more rapidly for the larger gaps. The smaller gaps suggest that the breakdown voltage eventually reaches a limit with further decreases in r (in essence, an infinitely thin electrode).

SPACE-CHARGE LIMITED CURRENT OF A PIN-TO-PIN GEOMETRY

In FY20, we reported the effect of surface waviness on work function. We could also consider the pin-to-plate geometry mentioned above as PL for a parallel plate to a second plate with a surface “bump.” In FY21, we considered the effect of such a perturbation on space-charge limited current (SCLC). To do this, we solved for SCLC for the more general pin-to-pin geometry by using variational calculus (VC) and recovered SCLC for a pin-to-plate geometry as a special case. We obtained the exact solution for the pin-to-plate (or tip-to-plate) geometry as

$$\frac{J_{\text{SCL}}^{\text{t-p}}}{J_{\text{CL}}} = \frac{\beta(1 + \beta)}{[\ln(\sqrt{1 + \beta} + \sqrt{\beta})]^2},$$

where β is the field enhancement factor and J_{CL} is the SCLC for a one-dimensional, planar diode in vacuum. Figure 3 shows this equation and the appropriate limits for small and large β . We also applied conformal transformations to derive the SCLC for a misaligned tip-to-tip geometry, where the axes of rotation of the hyperboloids are displaced by a small distance, and to study the effect of a small angle tilt in a tilted tip-to-tip geometry, which may occur in practice due to non-uniformity in electrode surface features.

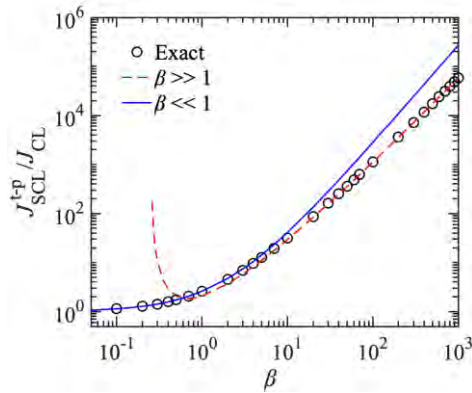


Fig. 3. Normalized SCLC $J_{\text{SCL}}^{\text{t-p}}/J_{\text{CL}}$ as a function of $\beta = \cot^2 v_c$ with approximations for $\beta \ll 1$ and $\beta \gg 1$ (N. R. Harsha and A. L. Garner, IEEE Trans. Electron Devices **68**, 6525 (2021)).

DETERMINATION OF IONIZATION COEFFICIENT

The ionization coefficient describes the volume processes contributing to the electron avalanche and eventual breakdown. Just like conventional gaps, field emission driven breakdown for microscale gaps depends on the ionization, especially as avalanche begins to contribute heavily to breakdown. The theory developed by Venkatraman and Alexeenko, on which our analytic theories are based, used the standard semi-empirical relationship for the ionization coefficient that was based on macroscale measurements performed in centimeter-scale gaps filled with gas at low pressure. Venkatraman and Alexeenko proposed a correction that was used with some success for microscale gaps (including our theoretical works); however, it still uses information from the empirical correlations based on macroscale measurements as the baseline and is only valid for a limited range of gap distances, pressures, and gasses. Specifically, while the correction accounts for the effective decrease in ionization coefficient at applied voltages that are on the same order as the ionization potential, it does not account for the macroscale ionization coefficient correlations failing at high reduced electric fields. While Venkatraman's work looked at extending these simulations, much remains incompletely characterized.

We have worked to expand the range of validity of these small gap, high electric field ionization coefficient. Using the PIC software XPDP1, we have determined ionization coefficient for pressures from 190 to 760 torr and gap distances from $0.75 \mu\text{m}$ to $10 \mu\text{m}$ and assessed various potential semi-empirical representations to replace the standard approach. We observed that we could fit the simulated α/p , where α is ionization coefficient and p is pressure, as a function of voltage V piecewise to $\alpha/p = a \exp(bp/E)$ for the left-hand part of the curve and $\alpha/p = k_1 V + b_1$ for the right-hand part of the curve, where a , b , k_1 , and b_1 are constants and E is the electric field in the gap. Figure 4 shows an example of the application of this approach for 760 torr.

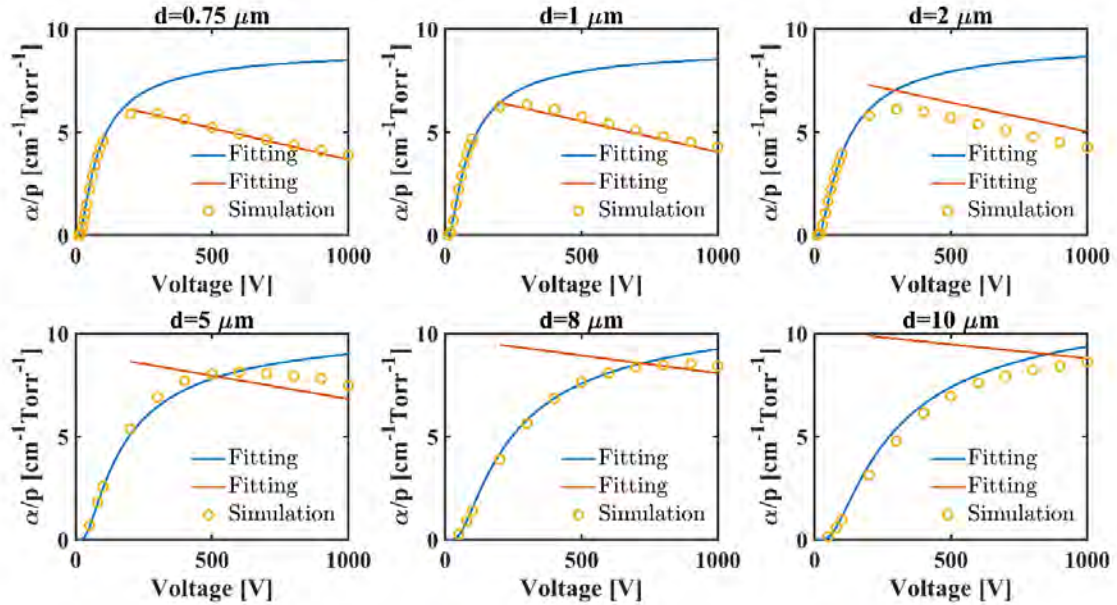


Fig. 4: Comparison of the simulation results and fitted lines for α/p as a function of voltage at $p=760$ Torr, where α is ionization coefficient and p is pressure.

NANOSCALE BREAKDOWN AND EMISSION EXPERIMENTS

We completed measurements of current as a function of voltage for electrodes with different emitter widths for 20-800 nm gaps at atmospheric pressure to measure breakdown voltage and assess electron emission behavior, for which we described preliminary results in FY-2021. The breakdown voltage V_b depends more strongly on effective gap distance d_{eff} than the ratio of the emitter radius to the gap distance. For 20 nm and 800 nm gaps, we measured $V_b \approx 5$ V and $V_b \approx 275$ V, respectively. Independent of emitter width, V_b decreased linearly with decreasing d_{eff} for $d_{eff} \gtrsim 200$ nm; for $d_{eff} < 200$ nm, V_b decreased less rapidly with decreasing d_{eff} , as shown in Figure 5, which may correspond to a change in the field enhancement factor for smaller gaps.

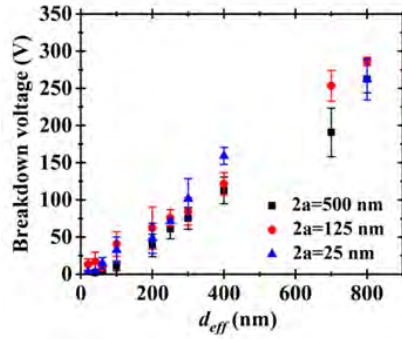


Fig. 5. Mean value and standard deviation of 3-5 individual experiments of breakdown voltage as a function of effective distance between the electrodes with emitters of diameter $2a$.

While gas breakdown usually proceeds directly from field emission, as for microscale gaps, some cases exhibit space-charge contribution prior to the transition to breakdown, as demonstrated by orthodoxy tests and current-voltage curves, as demonstrated in Figure 6.

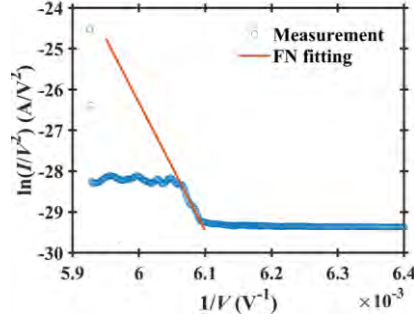


Fig. 6. Fowler-Nordheim (FN) plots for $d_{eff} = 400$ nm, $2a = 25$ nm, demonstrating the contribution of space-charge by the trend toward a horizontal line for small $1/V$.

Applying nexus theory, we determine that the range of d_{eff} studied is close to the transitions between field emission and SCLC in both vacuum and with collisions, as shown in Figure 7, indicating that a coupled theoretical solution would be required to precisely model the electron emission behavior.

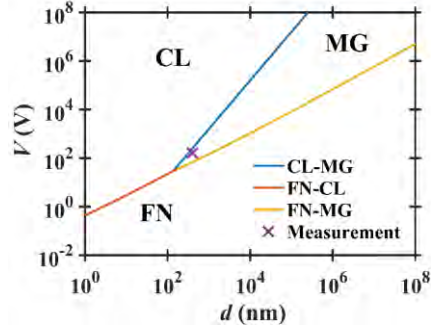


Fig. 7. Nexus plot comparing the experimental conditions to the theoretical transition between the Fowler-Nordheim (FN), Mott-Gurney (MG), and Child-Langmuir (CL) laws assuming fixed mobility $\mu = 0.059 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ at atmospheric pressure using the semi-empirical relationship between mobility, pressure, and electric field.

We have also performed experiments at $2 \mu\text{Torr}$ with Figure 8 showing the results for a $250 \mu\text{m}$ wide emitter. At smaller gap distances, we observe a linear increase in breakdown voltage with increasing gap distance, as we observed above at atmospheric pressure; however, unlike that case, the breakdown voltage plateaus with further gap distance increases rather than continuing to increase.

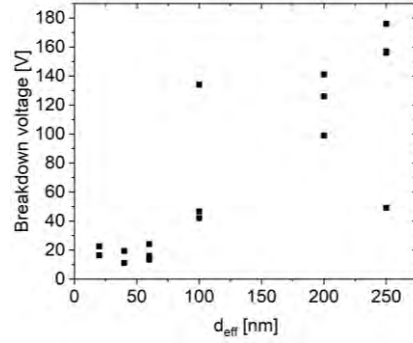


Fig. 8. Breakdown voltage as a function of gap distance at 2 μ Torr for a 250 μ m wide emitter.

Similar behavior has been observed in the vacuum breakdown literature. We conjecture that the behavior is most likely due to the difference in mechanism. At atmospheric pressure, breakdown is driven by field emission at lower gap distances and eventually by avalanche for gaps greater than approximately 10 μ m. In vacuum breakdown, heating and damage to the electrodes play a pivotal role and may lead to the change in behavior once this damage becomes sufficiently dominant. We will continue assessing this as we complete the final manuscript.

3. Findings and Conclusions

These efforts have further elucidated gas breakdown and electron emission across gap distance and pressure regimes. Our theoretical work yielded the first analytic solutions for field emission driven microscale gas breakdown from nonplanar diodes, while also providing a different perspective on fitting the equations by using work function rather than field enhancement. Moreover, it provided insight on the importance of work function for microscale gas breakdown, which may motivate future studies for tuning working function to either mitigate or enhance field emission depending on the desirability of microscale gas breakdown for a given application. Similarly, our work with pin-to-pin space-charge limited current using variational calculus and conformal mapping provided the first analytic solutions from first principles for such geometries. While there is immediate and obvious application of this approach for studying emission from pin-to-pin or pin-to-plate geometries, which are often used in field emitter applications, the application under this grant involves space-charge limited current in the presence of a surface imperfection represented as a bump. We have extended this work to analytically examine the effect of tilts of the pin (or bump), which can elucidate the implications of random orientations of surface roughness. Additionally, our assessment of ionization coefficient for strong electric fields at small gaps provides a further path toward improving these analytic theories for microscale gas breakdown. Coupled with the work we reported in FY20 on the application of nexus theory linking electron emission from quantum space-charge limited current to PL and the theory we derived for describing work function as a function of electrode surface waviness, we have developed a set of tools to examine emission and breakdown for numerous environmental, design, and electrode conditions.

Experimentally, we have demonstrated that it is possible for breakdown to transition from a non-purely field emission regime. This suggests potential modifications necessary in field emission driven breakdown theories going into the nanoscale regime. Furthermore, our efforts in nexus theory have examined the impact of mobility (i.e., pressure). One interesting scientific area of investigation would be to apply these same experimental and theoretical techniques to solid

materials and demonstrate the appropriate mechanistic transitions and potential implications on device reliability.

4. Plans and Upcoming Events

Upcoming significant events:

- 1) Submit manuscript on nanoscale gas breakdown and electron emission at atmospheric pressure to *Applied Physics Letters*.
- 2) Submit manuscript on nanoscale gas breakdown at vacuum to *Vacuum*.
- 3) Submit manuscript on ionization coefficient determination to *Journal of Physics D: Applied Physics*.
- 4) Dr. Garner will give a short course entitled “Unification of electron emission and breakdown mechanisms: Experiments and theory” at the 2022 IEEE International Power Modulator and High Voltage Conference based partially on work funded by this grant.

Future transitions:

- 1) Continue discussions with AFRL – particularly concerning sub-microscale breakdown experiments as this expands to sub-atmospheric pressure.
- 2) Work with NRL to transition breakdown theory (Kevin Jensen) and surface roughness effects (Ray Allen) for larger devices.
- 3) Discussions with Sandia National Laboratories about electron emission and breakdown.

Recommendations for Future Work:

- 1) Apply the theoretical technique for nexus theory to assess the transitions between electron emission mechanisms and the experimental techniques for nanoscale breakdown and electron emission developed as part of this grant to solids to understand how external electric fields may affect semiconductor materials.
- 2) Assess tuning of electrode materials (e.g., composites) to adjust work function to either enhance electron emission (e.g., field emitters or microplasma systems) or depress electron emission (e.g. increase breakdown voltage to avoid microscale gas breakdown).
- 3) Assess molecular level simulations for collisions in nanoscale gaps and relate to the nexus theories developed over the course of this grant. A future effort would require more computational resources to perform this linkage.
- 4) Apply this concept to higher pressures. In particular, examine and apply breakdown and electron emission physics for switches for generating fast rise-time, high power pulses.

5. Transitions and Impacts

We have worked with Dr. Russell Brayfield from Naval Research Laboratory (NRL) on finalizing the experimental portion of this effort and he has taken the general concept of these experiments to work on a proposal to perform detailed analyses of solid breakdown for 6.2 research with Purdue submitting a separate proposal to examine 6.1 research. Dr. Brayfield’s group at NRL has also reached out to Travis Crawford, a graduate student funded under a separate ONR group, about possibly performing a summer internship at NRL on related technologies.

6. Collaborations

Guodong Meng, international collaborator, N/A, National Academy Member (N), China
Ágúst Valfells, international collaborator N/A, National Academy Member (N), Iceland
Yangyang Fu, N/A, Academy Member (N), Michigan State University

Peng Zhang, N/A, Academy Member (N), Michigan State University
L. K. Ang, N/A, Academy Member (N), Singapore
John Luginsland, N/A, Academy Member (N), Confluent Sciences
Yee-Sin Ang, N/A, Academy Member (N), Singapore
Ayyaswamy Venkattraman, N/A, Academy Member (N), UC Merced

7. Personnel

Principal Investigator: Allen L. Garner, 0.98 person-months, National Academy Member (N).

Teams Members:

Haoxuan Wang, graduate student, 5.6 person-months, National Academy Member (N).

Business Contact: Tara Finley

Subs: None

8. Students

3 graduate students (1 funded by this effort, 2 funded by other projects whose deliverables had overlap with this)/1 undergraduate student

9. Technology Transfer

None.

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Archival Publications

1. **[INVITED PERSPECTIVE]** A. L. Garner, G. Meng, Y. Fu, A. M. Loveless, R. S. Brayfield II, and A. M. Darr, “Transitions between electron emission and gas breakdown mechanisms across length and pressure scales,” *Journal of Applied Physics* **128**, 210903 (2020).
2. A. M. Loveless, L. I. Breen, and A. L. Garner, “Analytic theory for field emission driven microscale gas breakdown for a pin-to-plate geometry,” *Journal of Applied Physics* **129**, 103301 (2021).
3. **[INVITED PERSPECTIVE, FEATURED]** P. Zhang, Y. S. Ang, A. L. Garner, Á. Valfells, J. W. Luginsland, and L. K. Ang, “Space-charge limited current in nanodiodes: Ballistic, collisional and dynamical effects,” *Journal of Applied Physics* **129**, 100902 (2021).
4. A. M. Loveless, A. M. Darr, and A. L. Garner, “Linkage of Electron Emission and Breakdown Mechanism Theories from Quantum Scales to Paschen’s Law,” *Physics of Plasmas* **28**, 042110 (2021).
5. N. R. Sree Harsha and A. L. Garner, “Analytic Solutions for Space-Charge-Limited Current Density from a Sharp Tip,” *IEEE Transactions on Electron Devices* **68**, 6525-6531 (2021).
6. H. Wang, R. S. Brayfield II, A. M. Loveless, A. M. Darr, and A. L. Garner, “Experimental study of gas breakdown and electron emission in nanoscale gaps at atmospheric pressure,” Submitted.

Manuscripts in Progress

1. H. Wang, R. S. Brayfield II, A. M. Loveless, A. M. Darr, and A. L. Garner, “Experimental characterization of breakdown and electron emission for nanoscale gaps at vacuum.”
2. H. Wang, R. S. Brayfield II, A. Venkatraman, A. M. Loveless, and A. L. Garner, “Ionization Coefficient for Nano- and Microscale gaps.”

Conference Papers

1. *A. M. Loveless*, A. M. Darr, and **A. L. Garner**, “Transitions in Electron Emission and Gas Breakdown from Nanoscale to Microscale,” IEEE Vacuum Electronics Conference, 20 October 2020, pp. 63-64. [Came out in IEEE Xplore in 2021]

Conference Oral Presentations

1. *H. Wang*, A. Loveless, A. Darr, and **A. Garner**, “Experimental Studies of Gas Breakdown and Electron Emission for Nanoscale Gaps,” 74th Annual Gaseous Electronics Conference, UF23.00004, Virtual 08 October 2021.
2. *A. Loveless*, A. Darr, *H. Wang*, J. Welch III, and **A. Garner**, “Theoretical Linkage of Electron Emission and Gas Breakdown Mechanisms,” 74th Annual Gaseous Electronics Conference, UF23.00003, Virtual 08 October 2021.
3. **[INVITED PLENARY] A. Garner**, “Diode physics: From Child-Langmuir to Paschen’s law,” 2021 IEEE International Conference on Plasma Science, Plenary 8, Virtual 15 September 2021.
4. *H. Wang*, R. Brayfield, A. Venkatraman, A. Loveless, C. Buerke, and **A. Garner**, “Calculation of ionization coefficient in microscale and nanoscale gaps using PIC/MCC simulations,” 2021 IEEE International Conference on Plasma Science, 5O-A-05, Virtual 14 September 2021.
5. *H. Wang*, R. Brayfield, A. Loveless, and **A. Garner**, “Experimental studies of gas breakdown and electron emission for nanoscale gaps at atmospheric pressure,” 2021 IEEE International Conference on Plasma Science, 5O-A-04, Virtual 14 September 2021.
6. *H. Wang*, R. S. Brayfield, A. M. Darr, A. M. Loveless, and A. L. Garner, “Experimental studies of electron emission and gas breakdown for nanoscale diodes at atmospheric pressure,” IEEE International Conference on Plasma Science, TA1-S1-070, Session D4N1-TA1.4+TA1.1, 09 December 2020.
7. *A. Loveless*, L. Breen, R. Brayfield, and A. Garner, “A Universal Theory for Microscale Gas Breakdown for a Pin to Plate Geometry,” 62nd Annual Meeting of the American Physical Society Division of Plasma Physics, NO03.00010, 11 November 2020.
8. *A. M. Loveless*, A. M. Darr, and A. L. Garner, “Transitions in Electron Emission and Gas Breakdown from Nanoscale to Microscale,” IEEE Vacuum Electronics Conference, 20 October 2020.

Conference Poster Presentations

1. *N. R. Sree Harsha* and A. L. Garner, “Analytical Solution for Space Charge Limited Current Emission from a Sharp Tip Using Variational Methods,” IEEE International Vacuum Electronics Conference, P8.22, 22 October 2020.

Invited Colloquia and Seminars

1. *A. L. Garner*, “Gas Breakdown and Electron Emission at Nanoscale,” Joint Webinar Series by Purdue University, USA and VIT, Vellore India, 23 September 2021 (Delivered virtually due to COVID-19).
2. *A. L. Garner*, “Directed Energy: From Source to Molecular Interactions,” School of Nuclear Engineering, Purdue University, West Lafayette, IN 10 March 2021 (Delivered virtually due to COVID-19).
3. *A. L. Garner*, “Modified Paschen's law for Microscale and Nanoscale Gaps,” Michigan Institute of Plasma Science and Engineering, Ann Arbor, MI, 13 October 2020. (Delivered virtually due to COVID-19).

11. Point of Contact in Navy

Russell Brayfield, NRL, 30SEP2021; Kevin Jensen, NRL, 21JUN2021; Joe Schumer, NRL, 10MAY2021; Jack Chen, NSWCD, 28JUN2019; Zachary Drikas, NRL, 23APR2021

12. Acknowledgement/Disclaimer

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Improving Performance of Crossed-Field Amplifiers Through Modulation Injection

Grant No. N00014-21-1-2024

Annual Report for Fiscal Year 2021

Period of Performance: December 11, 2020 to September 30, 2021

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Date Prepared: 31JAN2022

Project Title: Improving Performance of Crossed-Field Amplifiers Through Modulation Injection

Annual Summary Report: FY21

Principal Investigator: Allen L. Garner, 765-494-0618, algarner@purdue.edu, Purdue University

Section I: Project Summary

1. Overview of Project

Abstract: Crossed-field devices, such as crossed-field amplifiers (CFAs), offer high efficiency, high power density, and robust performance. Improved CFA gain-bandwidth product and reduced noise would contribute to greater use and operational capabilities. This report highlights our initial efforts at setting up simulations in ICEPIC and VSim and developing nexus theory to determine the device conditions for transition between various electron emission mechanisms. We are currently benchmarking ICEPIC to VSim using a commercial CFA and are preparing a manuscript for submission highlighting electron emission physics.

Objective: This effort will study the effects of electron modulation on a high power (1 MW) L-Band CFA using theory (Purdue University) and simulation using the particle-in-cell codes ICEPIC (Confluent Sciences) and V-Sim (Boise State University and Tech-X). The first task entails developing and validating a CFA model using thermionic emission models. This result will next be combined with secondary emission models and theories and validated. This will subsequently permit the examination of the causes of drive saturation and gain-bandwidth limitations. This combined theory and simulation will then be used to characterize the effects of electron modulation with and without secondary emission on gain, bandwidth, saturation, and noise on CFA efficiency, pulse width, output power, bandwidth, and frequency timing. Finally, an assessment on the impact of noise in the CFA will be performed by examining how particle orbits are impacted based on the thermionic and secondary emission models and the impact of space-charge on the electromagnetic properties of the device. This will involve including sensitivity analysis into the theoretical studies of single electron orbits, including second emitter into the theory and studying the interaction between electrons emitted from each source, and using simulation to examine electromagnetic mechanism in more detail.

The electromagnetic spectrum is becoming both congested and contested, requiring greater flexibility in electromagnetic sources. As platforms become much more loaded with electronics and technology, the compactness, efficiency, capability, and controllability of individual electromagnetic sources must increase. Therefore, this proposal strives to both maintain the high amplitude operation associated with DE technology and determine ways in which DE devices can provide information rich signals with choices in center band frequency, high bandwidth frequency modulation, and exquisite phase control. Traditional crossed-field DE devices, such as magnetrons, operate at high amplitude, but with only modest bandwidth or shot-to-shot frequency control. In contrast, the CFA provides bandwidth and phase control, but with orders-of-magnitude lower

power. Thus, the CFA characterization proposed here will determine the limitations in gain-bandwidth product and enhance CFA tunability, which is critical for electromagnetic warfare.

Introduction: Microwave vacuum electron devices (MVEDs) are critical for military infrastructure from radar and communications to electronic warfare, including emerging directed energy applications. While MVEDs are dominant in high frequency and high power regimes, improved device performance is essential to maintain the advantage over solid state devices. In particular, crossed-field devices, such as crossed-field amplifiers (CFAs), offer high efficiency, high power density, and robust performance. Improved CFA gain-bandwidth product and reduced noise would contribute to greater use and operational capabilities. Currently, there are no high-power CFA models available for public research studies at universities. This gap is especially important as we try to realize the promise of higher power devices represented by directed energy high-power radiofrequency (HPRF) devices. Almost every type of HPRF device is an oscillator. While these sources produce very high-power pulses, the waveform control, typically measured in the bandwidth, is insufficient for radar or communications. This restricts these directed energy (DE) sources to jamming and counter-electronics missions, rather than the more information-intense full-fledged electronic warfare. This proposal goes to the heart of the question “what are the limits to high-power amplifiers?”

Background: Crossed-field devices, such as crossed-field amplifiers (CFAs), offer high efficiency, high power density, and robust performance. Improved CFA gain-bandwidth product and reduced noise would contribute to greater use and operational capabilities. Currently, there are no high-power CFA models available for public research studies at universities. This gap is especially important as we try to realize the promise of higher power devices represented by Directed Energy High-Power RF (HPRF) devices. Almost every type of high-power radiofrequency (HPRF) device is an oscillator. While these sources produce very high-power pulses, the waveform control, typically measured in the bandwidth, is insufficient for radar or communications. This restricts these directed energy (DE) sources to jamming and counter-electronics missions, rather than the more information-intense full-fledged electronic warfare. This proposal goes to the heart of the question “what are the limits to high power amplifiers?” The university community currently lacks the well characterized, high power sources with intense space-charge that can mimic a HPRF device to address these questions. This problem becomes more acute for CFAs. CFAs are the highest power amplifiers widely used; however, they suffer from the limits of the gain-bandwidth product. The lack of a publicly available CFA model using first-principles, particle-in-cell simulations to serve as a benchmark for research hinders the examination of potential methods to improve design.

We will use a model of the L3 Technologies L4953 CFA (discontinued) that was operated by the Federal Aviation Administration (FAA). Because this model is discontinued and unclassified, L3 Technologies is willing to allow our team to use the design to develop a high-power CFA model. This CFA model would become a benchmark for CFA research in universities, industry, and national laboratories to allow comparing future simulations and modifications to CFAs and other amplifiers. After developing the model, we would then study the effects of electron modulation on gain, bandwidth, and noise. We can study, via simulation, the saturation effects that occur in CFAs and determine whether techniques such as current modulation can improve the gain-bandwidth performance including performance at higher input powers. This would include studying the cause of saturation and techniques to maintain/increase gain-bandwidth product for HPRF production. Table 1 summarizes our team’s overall research concept. We propose using two different simulations (VSim and ICEPIC) and theoretical analysis to (1) develop and validate CFA models

Figure 1: The CFA model (a) clipped along the z-axis showing the relevant dimensions and (b) a side view showing the intentionally excluded assemblies along with the relevant dimensions.

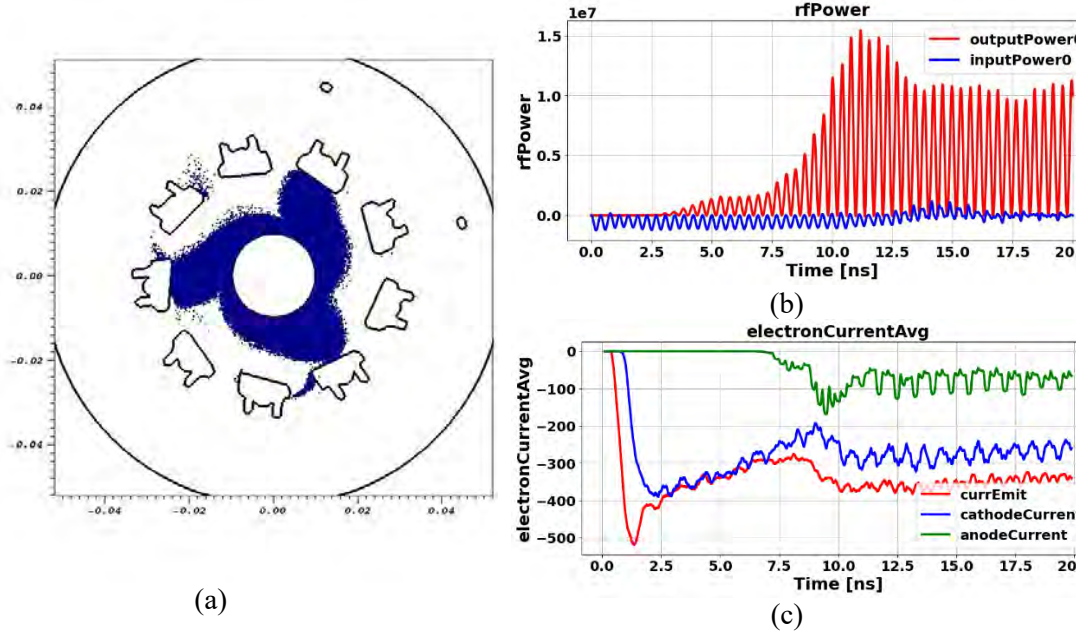


Figure 2: Results of implementing the space-charge limiting cathode model, showing (a) the electron spokes, (b) the RF input and output powers, and (c) the electron currents.

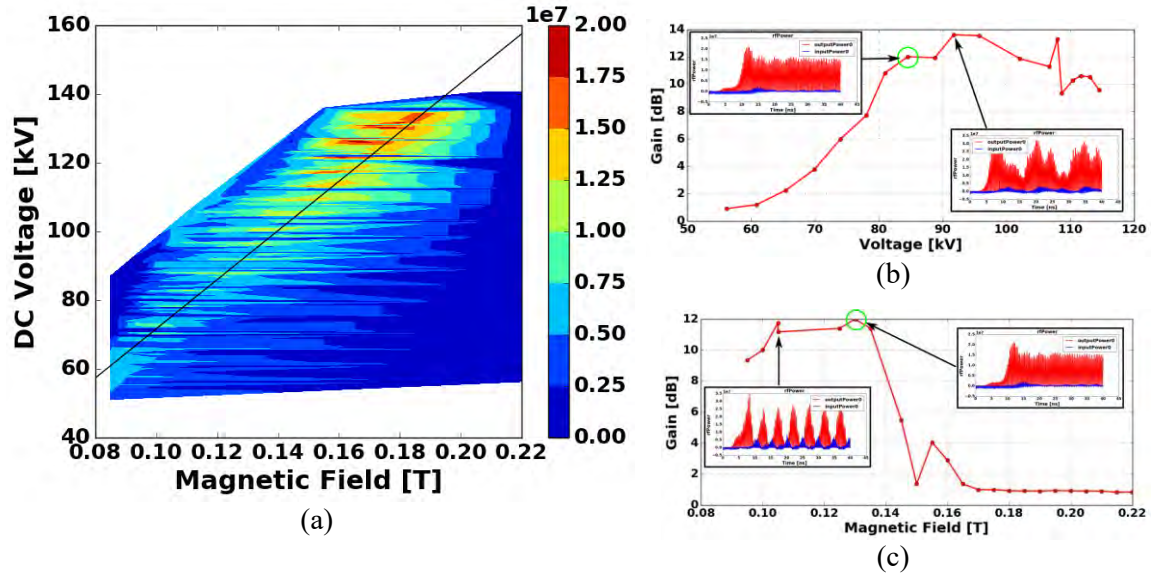


Figure 3: (a) A 2D color/contour plot of the output power vs the DC voltage and magnetic field. Centered about the operation point with $B = 0.13$ T, $V_{DC} = 85$ kV, and $P_{RF}^{in} \approx 450$ kW, the gain is shown for a (b) voltage sweep and a (c) magnetic field sweep. Insets in the plots show the output power vs time at those data points. The stable operation point is circled in green.

Fig. 2 shows the electron spoke pattern, input and output power, and electron currents of a simulation at typical operating parameters, $P_{in} = 500$ kW, $V_{DC} = 87$ kV, $B = 0.13$ T. The observed output power is about 5 MW, which is close to specification (4.7 MW), and the model predicts the correct anode current of 80 A.

Encouraged by these good preliminary results, characterization of the device began with a DC voltage and magnetic field sweep, shown in Fig. 3. The peak power follows the constant V/B line shown in black in Fig. 3(a). A lineout at $B=0.13$ T and $V=85$ kV is shown in Fig. 3(b) and (c), respectively. The lineouts show a peak in the output power at the optimum V/B ratio, but also show higher output power at non-optimum. The higher power at these non-optimum points are associated with a very large modulation of the output power. The cause of the modulation is of great interest, but research into this mechanism was postponed to improve the robustness of the DC voltage model.

The DC voltage implementation is very sensitive to the operation parameters of the device because of the large electron current from the cathode to the anode. To maintain the desired DC voltage under any conditions, the original implementation was replaced with a current source from anode to cathode with feedback. The current source is adjusted to maintain the proper DC voltage as read from a pseudopotential diagnostic from cathode to anode. The method, however, relies on a correct reading from the pseudopotential, which is known to be off due to calculating the potential using standard cells rather than cut-cells. This error caused the DC voltage to vary by up to 5-10 kV, which affects the CFA operation greatly. To keep the DC voltage consistent and accurate, the dimensions at the cathode and anode at the DC voltage port were altered to align perfectly with the grid. This ensured consistent and accurate DC voltages for any grid, and affected the CFA operation minimally because the DC port is quite separated from the CFA interaction region.

ICEPIC SIMULATIONS

Initial hot calculations produced very little power and ran in a mode characterized by four spokes. This prompted the execution of a series of calculations in which the anode-cathode voltage was progressively increased from one calculation to another. This succeeded in capturing high output power operation in a mode characterized by electron hub evolution into a three-spoked flow configuration. Over two dozen hot calculations were performed for an initial investigation into the device's operating conditions. For the most part, these calculations consisted of power injected at 450 kW (average input power) at frequency 1.28 GHz with varying anode/cathode voltage (AK voltage) and applied magnetic field. The applied magnetic field was varied from 800 G to 1800 G while the AK voltage was varied from ~65 kV to ~220 kV. The region of the cathode allowed to emit was also varied. Gains as high as 17 dB were observed in this series. While it was not a universal hard line, three-spoke flow usually occurred when the average AK voltage exceeded roughly half the Hull voltage. Highest gains were obtained for the greatest applied magnetic field used (1800 G) and voltages of about 60% of the Hull voltage. Figure shows the electron three-spoke flow configuration from one of these calculations.

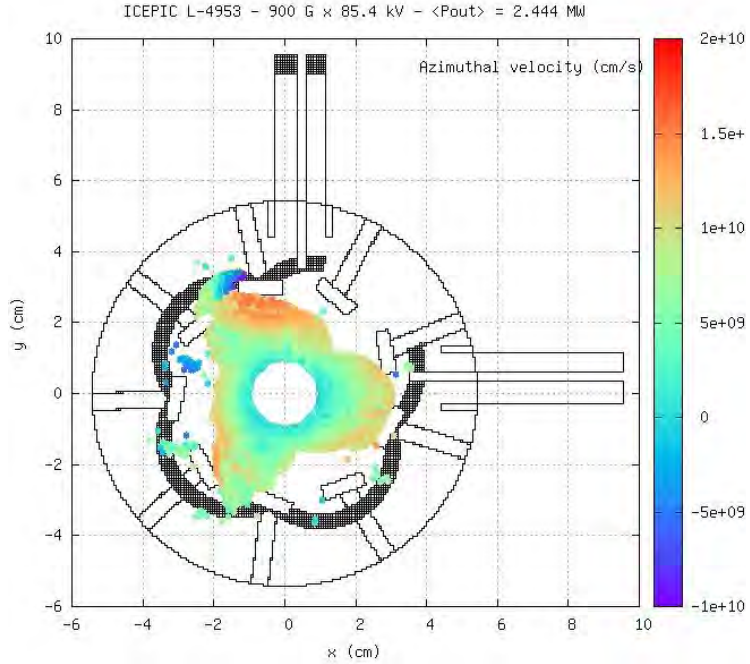


Figure 4: Three-spoke flow configuration from a calculation using a 900 G applied magnetic field at 85.4 kV voltage. Particles are color-coded to their value of azimuthal component of velocity.

For the hot calculations run to date, the ICEPIC primary cell space-charge-limited emission algorithm was employed (colloquially referred to as the PCE algorithm). This algorithm, operating with default settings, will emit one particle per cell per timestep when the electric field at the emitting face exceeds a user-defined threshold. A very low emission threshold was used for all of the calculations reported here. This algorithm is well-suited to emission from relatively broad, flat surfaces not dominated by small-scale geometric features such as sharp edges. Average currents for the three-spoke flow configuration ranged from 3.15 A to 329.1 A with average current densities ranging from 0.93 A/cm² to 39.3 A/cm².

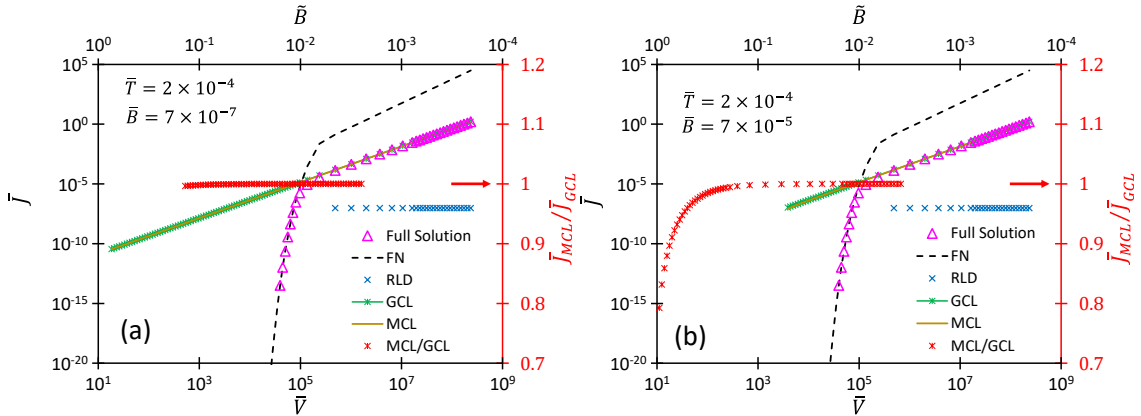
One feature observed in many instances of this initial slate of calculations is a high degree of modulation of the output power. When the modulation was strong enough, the dominant frequency of the output signal was observed to differ from the injected signal. The same dominant frequency was observed in most of the strongly modulated results. Our interpretation of this behavior is that

it indicates the presence of an oscillation. Identification and suppression of the oscillatory mode will form a major thrust of our efforts moving forward.

NEXUS THEORY

Previous studies of nonmagnetic diodes have theoretically identified the transitions, or nexuses, between multiple electron emission mechanisms by examining the relevant equations defining each individual mechanism and then deriving exact theoretical solutions that combined these mechanisms and approached the standard emission equations under appropriate limits. We have extended these studies by incorporating an orthogonal magnetic field and assessing the transitions between the Richardson-Laue-Dushman (RLD) formulation for thermionic emission, the Fowler-Nordheim (FN) equation for field emission, the space-charge limited current (SCLC) for the general (nonzero electron injection velocity, GCL) and (zero electron injection velocity, CL) Child-Langmuir laws for space-charge limited current, and the SCLC for a non-insulated (magnetic field below the Hull cutoff) and insulated (magnetic field above the Hull cutoff) diode.

Figure 5 shows the full solution for the current density as a function of applied voltage for a non-magnetically insulated crossed-field diode. Analogous to the non-crossed-field diode, the exact solution follows FN at low voltages and temperature (cf. Figs. 5(a) and 5(b)) before following the magnetic space-charge limited current (MCL) at higher voltages. For the higher temperature, electron emission initially follows RLD before transitioning into FN and, ultimately, MCL with increasing voltage. Figure 6 shows the nexus plots obtained by equating the asymptotic solutions representative of the individual emission mechanisms. In principle, we may choose the independent variable to be any of the parameters of interest; here, we select gap distance and magnetic field as examples. Areas far away from the nexuses may be readily estimated by the individual emission laws; conditions close to the nexus require more complete analysis combining the respective mechanisms. We have performed a similar analysis for magnetically insulated case with the major differences being the MCL limit and an additional factor of 2 in Poisson's equation to account for the emitted electron returning to the cathode.



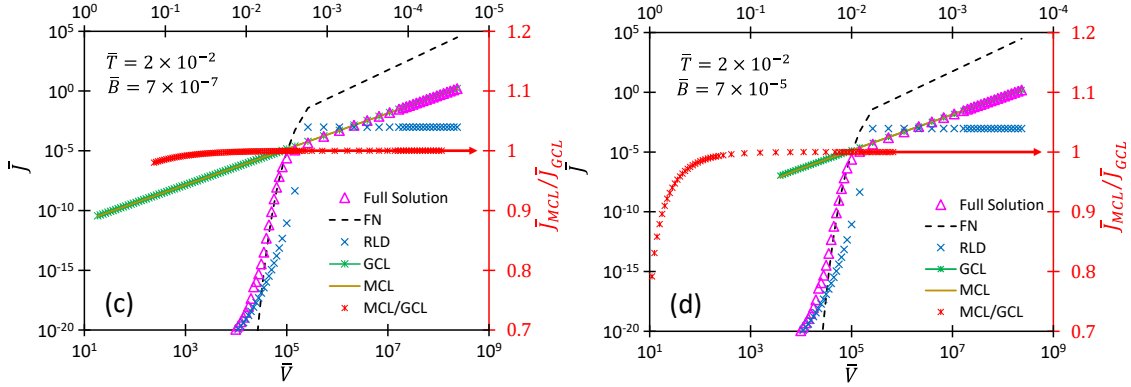


Fig. 5. Dimensionless current density $\bar{J}$ as a function of dimensionless voltage $\bar{V}$ at a dimensionless gap distance of $\bar{D} = 1.2 \times 10^6$ for dimensionless temperatures and magnetic fields of (a) $\bar{T} = 2 \times 10^{-4}$, $\bar{B} = 7 \times 10^{-7}$, (b) $\bar{T} = 2 \times 10^{-4}$, $\bar{B} = 7 \times 10^{-5}$, (c) $\bar{T} = 2 \times 10^{-2}$, $\bar{B} = 7 \times 10^{-7}$, and (d) $\bar{T} = 2 \times 10^{-2}$, $\bar{B} = 7 \times 10^{-5}$. The full solution follows either the RLD limit (c) or the FN limit (a, b, d) at low voltage, then converges to the MCL limit at high voltage. The ratios of the magnetic field to the Hull cutoff ($\tilde{B} = \bar{B}/\bar{B}_H$) and the MCL to the GCL ($\bar{J}_{MCL}/\bar{J}_{GCL}$) remain below unity, as demonstrated by the secondary axes.

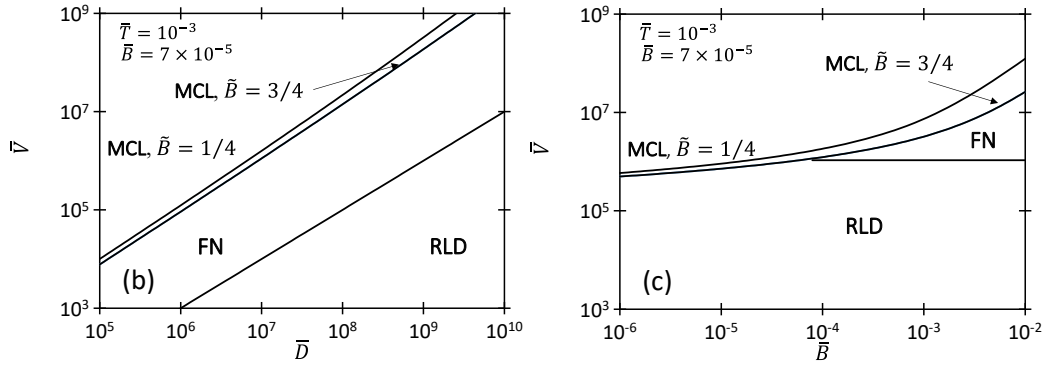


Fig. 6. Nexus plots of dimensionless voltage $\bar{V}$ as a function of dimensionless (b) gap distance $\bar{D}$ and (c) magnetic field $\bar{B}$ at magnetic field ratios of $\tilde{B} = B/B_H = 1/4$ and $\tilde{B} = B/B_H = 3/4$ demonstrating the regimes where RLD, FN, and MCL each govern emission.

3. Findings and Conclusions

The major efforts to date have focused on assessing the L-3 Technologies L-4953 crossed-field amplifier within ICEPIC and VSim to predict performance consistent with known operation conditions. For the VSim simulations, the geometry, DC voltage port, and current emission model were all developed and initial results agreed well with the device specifications. Proper modeling requires proper convergence by increasing the resolution and is ongoing. Additional simulations to understand output power modulation, port length, and stability are also ongoing. Further assessments comparing to the ICEPIC simulations also yielded results for output power and gain that are consistent with L-4953 operations. The calculations have also revealed aspects of performance that are not desirable for amplifier operation. These aspects have received a large proportion of our attention as the reporting period drew to a close and will be a primary driver for our continuing efforts. The nexus theory results have provided the first step characterizing the transition in emission mechanisms analytically that may provide insight to simulated behavior.

4. Plans and Upcoming Events

We are currently assessing the interaction between multiple cycloids using two-dimensional particle-in-cell simulations. These simulations will determine the dependence of device stability on the relative location and time of emission of the two cycloids. This will guide future theoretical development to elucidate the feasibility of using multiple emitters for electron modulation. Ongoing work will continue to assess the differences between ICEPIC and VSim simulations and their accurate representation of L-4953 operation. Upon completion, we will shift focus to examining gain-bandwidth limitations and effects of electron modulation on gain, bandwidth, saturation, and noise, while assessing the applicability of the simple theory on tuning electron modulation.

Recommendations for Future Work: Upon benchmarking, additional physics could be incorporated into the simulations to represent actual operation.

5. Transitions and Impacts

None.

6. Collaborations

John Luginsland, AFOSR, Ongoing discussions with Stellant Systems (formerly L3 Harris now).

7. Personnel

Principal investigator: Allen L. Garner, 0.99 person-months, National Academy Member (N)
Co-investigator or Co-PI: Jim Browning, 1 person-month, National Academy Member (N)
Co-investigator or Co-PI: Jack Watrous, 0.65 person-months, National Academy Member (N)
Co-investigator or Co-PI: John Luginsland, 1.45 person-months, National Academy Member (N)
Peter Stoltz, 0.28 person-months, National Academy Member (N)
Business Contact: Tara Finley
Team Members: Amanda Loveless, 5.76 person-months, National Academy Member (N)
Xiaojun Zhu, 2.88 person-months, National Academy Member (N)
Marucs Pearlman (Post Doc) -- 3 person-months, National Academy Member (N)
Nilesh Manker (Grad student) -- 5 person-months, National Academy Member (N)

8. Students

2/0

9. Technology Transfer

Discussions with John Luginsland from AFOSR on ICEPIC simulations and on setting up the cycloid particle-in-cell simulations. We have had preliminary discussion with Kevin Jensen and John Petillo from NRL on incorporation of the general thermal-field emission theory, particularly given the theoretical nexus theory work.

10. Products, Publications, Patents, License Agreements, etc.

Refereed Journal Article in Preparation

1. **[INVITED]** A. M. Loveless^P, A. M. Darr^G, and **A. L. Garner**, “Theoretical Linkage of Thermionic, Field, and Space-Charge Limited Emission for a Vacuum Crossed-Field Gap,” Submitted.

Conference Oral Presentations

1. **[INVITED PLENARY]** **A. Garner**, “Diode physics: From Child-Langmuir to Paschen’s law,” 2021 IEEE International Conference on Plasma Science, Plenary 8, Virtual 15 September 2021.
2. **[INVITED TALK]** *A. Loveless*^P, A. Darr^G, and **A. Garner**, “Electron emission nexus theory for a crossed-field diode,” 2021 IEEE International Conference on Plasma Science, 3I-B-02, Virtual 13 September 2021.

Conference Poster Presentations

1. *M. Pearlman*^P, J. Browning, J. Luginsland, P. Stoltz, A. Garner, and M. Worthington, “Simulation of L3-Harris L-4953 crossed-field amplifier,” IEEE International Conference on Plasma Science, 5P-C-02, Poster Session 5P-C, 14 September 2021.

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Theory and Experiments on Magnetically Insulated Line Oscillator (MILO)

Grant No. N00014-19-1-2262

Annual Report for Fiscal Year 2021

Period of Performance: October, 1, 2020 to September 30, 2021

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Grant or Contract Number: N00014-19-1-2262

Date Prepared: 1/31/2022

Project Title: Theory and Experiments on Magnetically Insulated Line Oscillator (MILO)

Annual Summary Report: FY2021

Principal Investigator: Ronald M. Gilgenbach, (734) 763-1261, rongilg@umich.edu
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Section I: Project Summary

1. Overview of Project

Abstract: The University of Michigan has developed and tested a higher impedance MILO, capable of operating with less than 10 kA of drive current. We performed simulations using Microwave Studio CST to investigate the feasibility of MILO operation with reduced pulsed power driver requirements. These simulations indicated a viable 5-cavity MILO design at 300 kV and 10 kA. This initial, single frequency design was successfully designed, tested, and published. We have constructed the complete solution of the Brillouin flow in planar MILO or planar Relativistic Magnetron, or some combination of the two, in cylindrical geometry with axial electron flow (as in cylindrical MILO), in cylindrical geometry with azimuthal electron flow (as in cylindrical magnetron and cylindrical RM), and in the radially converging flow in MITL (as in a linear transformer driver (LTD)). This comprehensive treatise on MILO operation has been published.

Objective: This project aims to improve understanding of the fundamentals of Magnetically Insulated Line Oscillators (MILO) through improvements in computational modeling and analytic theory backed by experimental results. This improved understanding will be applied to the development of efficient, multi-tone MILOs, and (with the aid of the University of New Mexico) transitioned to Naval Surface Warfare Center Dahlgren Division (NSWCDD) for testing on high value targets of interest.

Introduction: The MILO is a crossed-field device, basically, a linear magnetron, in which the magnetic field is self-generated by the electron current, thereby eliminating the need for external magnets or magnetic field coils. This means that the MILO is more compact, and lighter, than other high-power microwave (HPM) sources, including the relativistic magnetron.

Background: The goal of this research program is to generate multi-spectral, high-power microwaves from the Magnetically-Insulated-Line Oscillator (MILO). The topic of MILO was investigated extensively throughout the 1990's with excellent results, particularly at the Air Force Research Laboratories; however, since that time there have been major developments in: 1) low impedance, high current, pulsed power (Linear Transformer Driver, LTD), 2) 3-D EM particle in cell codes, and 3) innovative manufacturing techniques, (e.g., additive manufacturing/ 3D printing) that justify a new examination of MILO in the USA. It should be mentioned that Chinese laboratories have extensively investigated MILO and LTD in recent years, so it is crucial that the US refresh and rejuvenate MILO research to avoid technological surprises.

Previous ONR research at the University of Michigan, demonstrated that the Multi-frequency Recirculating Planar Magnetron (MFRPM) concept could generate 10's MW, high power microwaves in two different frequency bands, simultaneously. It is expected that the MILO could

generate even higher power levels at single or multiple frequencies. This research consists of analytic theory, 3-D EM PIC simulations and experiments.

The primary thrusts of this research included: a theoretical analysis of the Buneman-Hartree condition for analysis of MILO efficiency, gain, and startup; the viability of multi-frequency MILO; the effects of a modest external magnetic field; the compatibility of new low impedance drivers (such as LTD) for MILO; opportunities for additive manufacturing of MILO; and technology transfer for NSWC Dahlgren.

The first year of this research program concentrated on fundamental research to develop the scaling laws (e.g., Buneman-Hartree condition), computational modeling and single frequency experiments on the MILO. The second and third year became more applied MILO research. Prior to the COVID-19 pandemic, plans were in place to provide site visits to collaborators at Naval Surface Warfare Center at Dahlgren. We are presently working to re-establish these visits and improve technology transfer. As part of this effort, UM has joined the Naval Surface Technology Innovation Consortium (NSTIC). UM has also been collaborating closely with University of New Mexico (UNM) on our respective MILO developments.

MILOs were largely developed in the USA (1980's-2000), but recently have seen intensive research and development by potential competitor countries. Our goal is to address, via focused and transitional HPM research, some of the critical problems facing Navy operations due to asymmetric electronic threats, such as those faced by Marine warfighters in forward operating bases to those in littoral waters, and protection of high value targets, such as U.S. embassies in potential hot spots around the globe. These asymmetric electronic threats can come in the form of small airborne electronic drones, perhaps even COTS-type devices employed in boat or automobile-size machines.

2. Activities and Accomplishments

In the second full year of this research project, we continued to make great strides in analytic theory and simulation, while also conducting several experimental campaigns.

Analytic Theory of MILO

The Treatise on the theory of Brillouin flow [1], which is applicable to MILOs, magnetrons, and MITLs, was published in the Special Issue for Plenary and Invited Papers presented at the 2020 IEEE International Conference on Plasma Science. This theory was used to interpret several novel features observed in the MILO experiments, as documented in Drew Packard's recently completed Ph.D. thesis [2]. Chief among them are the discoveries that MILOs can operate below 10 kA, and that MILOs operate very close to Hull cutoff, in particular in the "double-valued" region (**Figure 2**). Both features, while consistent with the theory, were unexpected.

¹ Y. Y. Lau, D. A. Packard, C. J. Swenson, J. W. Luginsland, D. Li, A. Jassem, N. M. Jordan, R. D. McBride, and R. M. Gilgenbach, "Explicit Brillouin flow solutions in magnetron, magnetically insulated line oscillator, and radial magnetically insulated transmission line," IEEE Trans. Plasma Sci. (Oct 2021), 10.1109/TPS.2021.3092606

² D.A. Packard, "*Innovative Crossed-Field Devices for the Generation of High Power Microwaves*", doctoral dissertation, University of Michigan, Ann Arbor, MI, 2021.

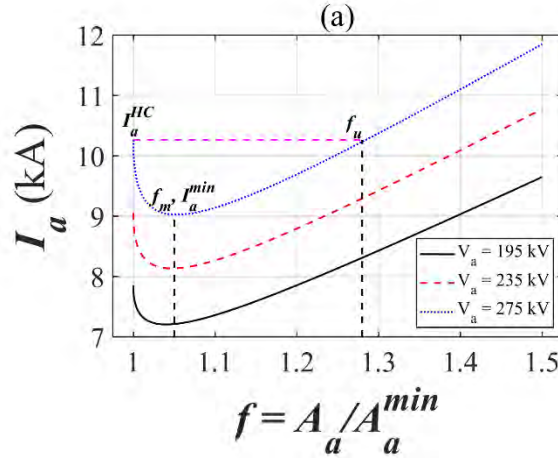


Figure 2: Input current I_a (a), electron hub current I_e as a function of flux ratio $f = A_a/A_a^{min}$ and parameterized over voltage V_a . The Hull cutoff condition is satisfied for $f > 1$. As f decreases towards unity, a v-shaped region appears in I_a due to the large increase in I_e in this parameter space. The maximum current of the v-shaped regime is the Hull cutoff current, I_a^{HC} , which is observed at $f = 1$ and at $f = f_u$ (the right vertical line). The minimum current of the v-shaped curve is I_a^{min} , at $f = f_m$ (the left vertical line).

We also published a paper on our single frequency MILO experiments [3]. In [3], we provided the details of the theory and simulations that were used to design and to interpret the experiments. Also included in [3] is a comparison of the theory and prior MILO experiments that were performed elsewhere (UK, France, China, and AFRL). It is anticipated that [1] and [3] will be landmark papers in the MILO literature.

High Impedance L-Band MILO

Following successful tests of the initial MILO prototype (detailed in the previous annual report), we designed and fabricated a second MILO with extraction, shown in **Figure 3**. A pair of choke cavities prevent oscillations from traveling back toward the pulsed power driver, a 5-cavity slow wave structure is designed to oscillate at 1 GHz, and an output cavity launches the wave into the coaxial section. Three, quarter-wave stubs shunt the DC current to ground while allowing RF current to pass through to the coax-to-waveguide converter (not shown).

³ D. A. Packard, Y. Y. Lau, E. N. Guerin, C. J. Swenson, S. V. Langellotti, A. Jassem, D. Li, N. M. Jordan, J. W. Luginsland, R. D. McBride, and R. M. Gilgenbach, "Theory, simulation, and experiments on a magnetically insulated line oscillator (MILO) at 10 kA, 240 kV near Hull cutoff condition," *Physics of Plasmas*, vol. 28, no. 12, p. 123102, Dec. 2021, doi: 10.1063/5.0071455.

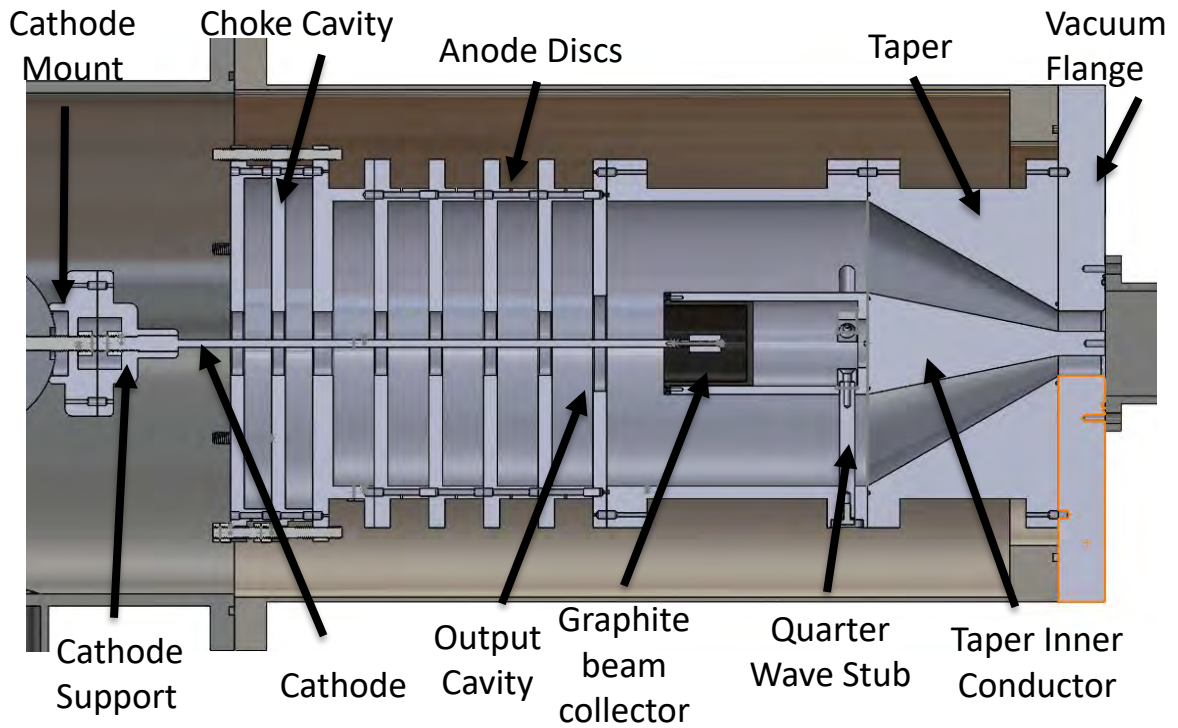


Figure 3: CAD drawing of the MILO prototype with axial extractor.

In previous simulations, we found a total current of 7.5 kA is required to achieve oscillation. Based on experimental tests with the initial MILO prototype, this electron current is achievable with the MELBA pulsed power driver. The average output power for this design is predicted at ~165 MW during the flat top of a -300 kV voltage input. This corresponds to a total efficiency of 6.9% and electronic efficiency of 41.3%.

The first component completed was the oscillator section (**Figure 4**). Using the B-dot loops, shown in the right side of **Figure 4**, we were able to conduct a cold test of the cavity, which showed a single mode at 1.044 GHz. This is in excellent agreement with the cold-tube HFSS simulations, which predicted a π -mode frequency of 1.0465 GHz.



Figure 4: Assembled slow-wave structure, comprised of a series of discs and annuli. The choke cavities are made of aluminum, but all other cavities are stainless steel to reduce plasma closure.

In the initial 14-shot series using the MELBA pulsed power driver, the 5-cavity MILO demonstrated 1.0105 ± 0.0121 GHz operation at 223 ± 27 kV, 6.7 ± 1 kA, and 1.9 ± 1.9 MW, for a resulting impedance of $33.5 \Omega \pm 1.3 \Omega$. All shots were conducted with zero applied axial magnetic field. A sample shot is provided in **Figure 5**.

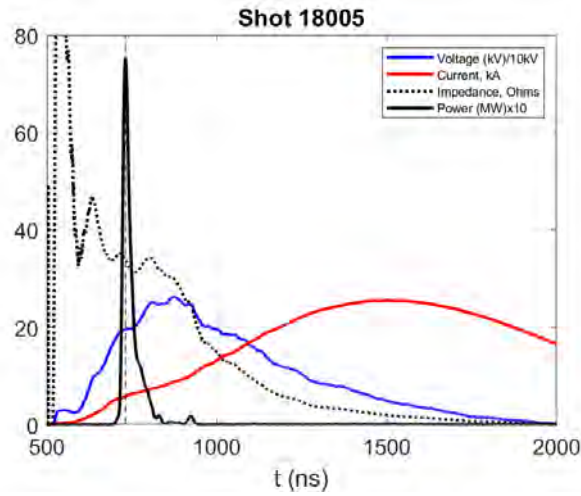


Figure 5: Voltage, current, impedance, and output power overlaid for shot 18005. At the instant of peak microwave generation, these quantities are 195 kV, 5.75 kA, 33.75 Ω , and 7.5 MW, respectively.

Operation at 1.5 MW extracted microwave output power was typical, with a single shot (**Figure 5**) reaching 7.5 MW. Frequency analysis indicates two different modes were dominant on a shot-to-shot basis, with the majority of shots operating in the π -mode at ~ 1.016 GHz and a few shots

operating at 0.99 GHz in what is likely the $4\pi/5$ -mode. The MILO typically began oscillating early in the voltage and current pulse, far before peak voltage and current. Consequently, while the pulsed power driver would eventually reach ~ 250 kV and ~ 10 kA, the MILO had ceased operation > 100 ns before this.

Optimizing Cathode Length

In these experiments, we varied the cathode length, L , and observed minimal variation in MILO performance. We conclude that in the present configuration the MILO is relatively insensitive to changes in cathode length.

In the previously reported configuration, the cathode length, L , is 38.1 cm. The cathode radius in the slow-wave structure (SWS) is 0.5 cm, and the downstream cathode radius (within the beam dump) is 1 cm. This results in a uniform, 2-cm radial anode-cathode (AK) gap in the SWS and in the beam dump, but a 2.3-cm gap axially in the beam dump. This geometry is shown in greater detail in **Figure 6**. With a larger axial gap, and field enhancement from the cylindrical geometry, we can expect the highest electric field (and the primary emission source) to be in the radial, rather than axial, AK gap.

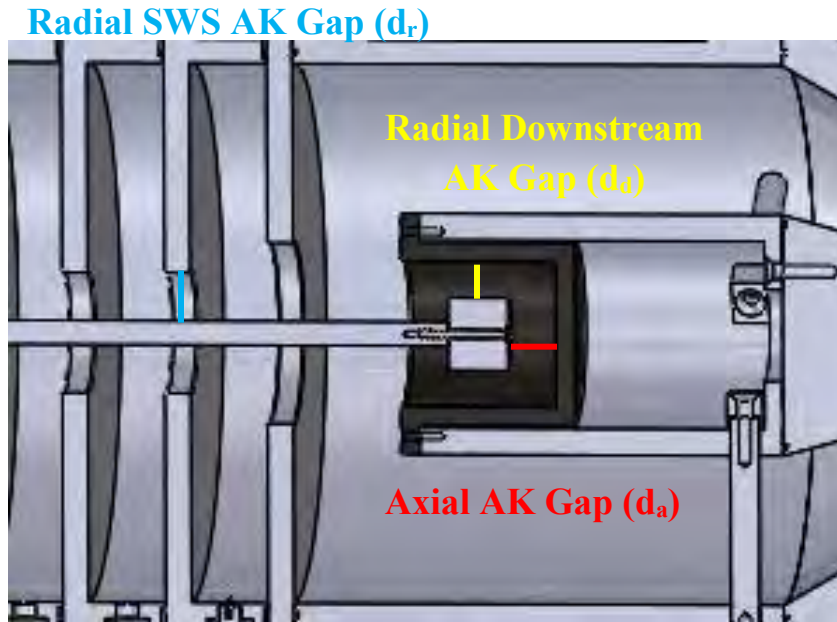


Figure 6: Detail of anode-cathode (AK) gaps in the MILO prototype. Variation in these parameters is expected to control the emission characteristics and operation of the MILO. The axial AK gap, d_a , has been varied from 1.7 to 2.3 cm.

In these experiments, the cathode length was increased by 0.3 cm and 0.6 cm, changing the axial AK gap to 2 cm and 1.7 cm, respectively. Previous work by AFRL has used cathode length to tune

MILO performance⁴. It should be noted, however, that the AFRL MILO did not have an increased cathode radius within the beam dump, so changes in length provided a nearly linear increase in effective emitter area; axial emission was not a consideration.

For our MILO geometry, a changing axial AK gap, d_a , could be expected to drive a more pronounced change in the current, as the space-limited-current in a planar gap is proportional to $1/d_a^2$. We found, however, there is not a notable change in output power as we increase L (and decrease d_a). The current at peak power decreases as d_a decreases, measuring at 6.7 ± 1 kA, 6.4 ± 0.8 kA, and 6.2 ± 1 kA, respectively. This trend is in opposition to the simple geometric relation given above. A possible explanation is that, as the axial gap decreases, the MILO is operating earlier in the current rise, resulting in lower current at the time of peak microwave power.

While the two longer cathodes both started oscillation earlier than the ~ 165 ns of the original, there was significant spread in all cases. This is further reinforced by the operating impedance data. Despite a narrower gap, the operating impedance (V/I) was effectively unchanged, remaining at nominally 32-36 Ohms.

The operating frequency (Figure 7a) shows the 1.7 cm gap was less likely to operate at ~ 1.017 GHz, which is in good agreement with CST-PS estimates of 1.012-1.016 GHz, depending on the downstream diode configuration. As Figure 7b shows, however, operating frequency was not correlated with output power.

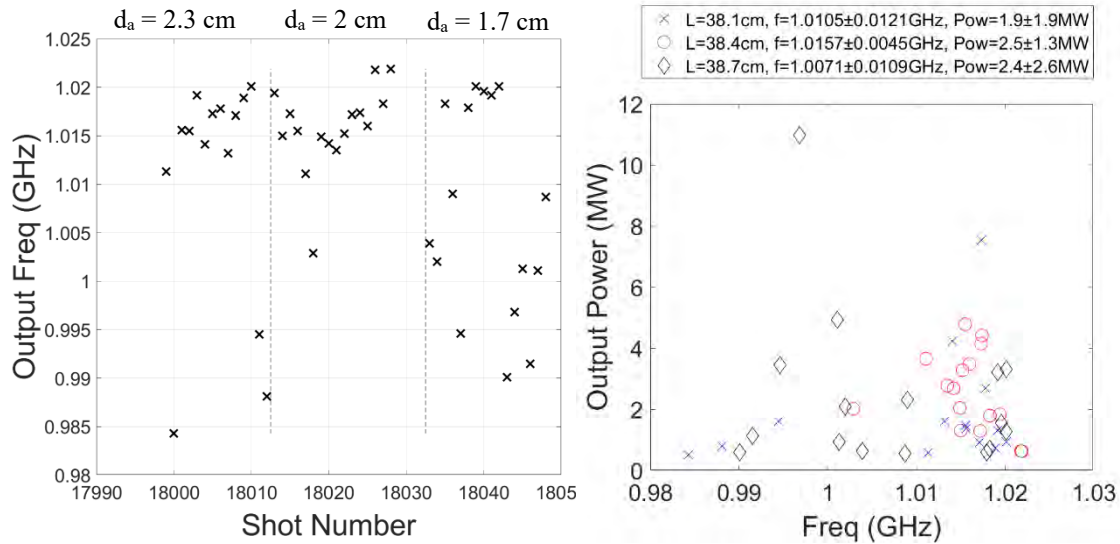


Figure 7: (a) Oscillation frequency for the three length variations. The 1.7 cm gap operated less reliably in the ~ 1.017 GHz mode. (b) Low frequency operation was not correlated with lower output power.

⁴ R. W. Lemke, S. E. Calico, and M. C. Clark, "Investigation of a load-limited, magnetically insulated transmission line oscillator (MILO)," *IEEE Transactions on Plasma Science*, vol. 25, no. 2, pp. 364–374, Apr. 1997, doi: [10.1109/27.602513](https://doi.org/10.1109/27.602513).

As reported previously, in the experiment without extraction the voltage and current at the time of peak microwave generation were $232 \text{ kV} \pm 15 \text{ kV}$ and $9.4 \text{ kA} \pm 0.9 \text{ kA}$, respectively, while the resultant impedance was $24.9 \Omega \pm 1.4 \Omega$. This is substantially higher current and lower impedance than what has been observed with the present MILO prototype with extraction. As shown in **Figure 8**, the experiment without extraction operated at $A_a/A_a^{\min} > 1.5$ on every shot, while the experiments with extraction have primarily operated with $A_a/A_a^{\min}$ between 1.1 and 1.3. However, our analysis discovered that MILO operation with a barely insulated electron beam ($A_a/A_a^{\min} = 1.1$) is not uncommon in previous experiments reported in the literature.

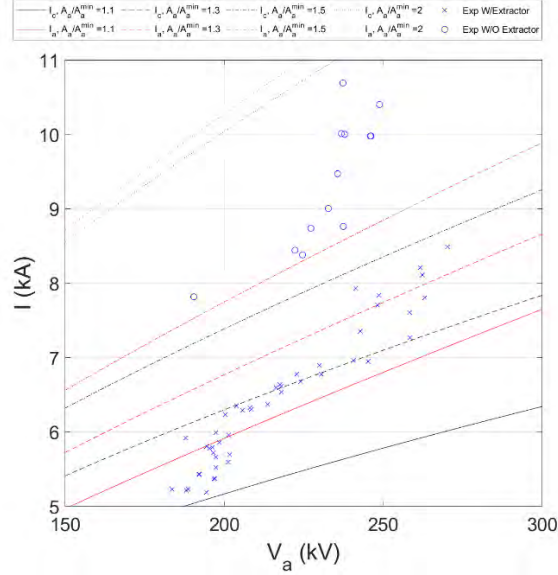


Figure 8: $A_a/A_a^{\min} \cong$ the magnetic field divided by the Hull cutoff magnetic field and measures the degree of magnetic insulation for experiments with and without extraction.

In summary, these experiments successfully demonstrated MILO operation at comparatively high impedance, and with moderate current requirements, close to Hull cutoff.

Optimizing Downstream Cathode Radius

Experiments were then performed with a new, larger radius cathode ($r_c = 7 \text{ mm}$), and significant improvements in output power and efficiency were observed. All our previous MILO experiments have utilized a cathode with radius $r_c = 5 \text{ mm}$. As shown in Figure 9, the configuration is nearly identical to what was previously reported; the anode is completely unchanged. With $r_c = 7 \text{ mm}$, the downstream cathode radius r_d became the independent variable, and was varied in two experiments from 8 mm to 10 mm.

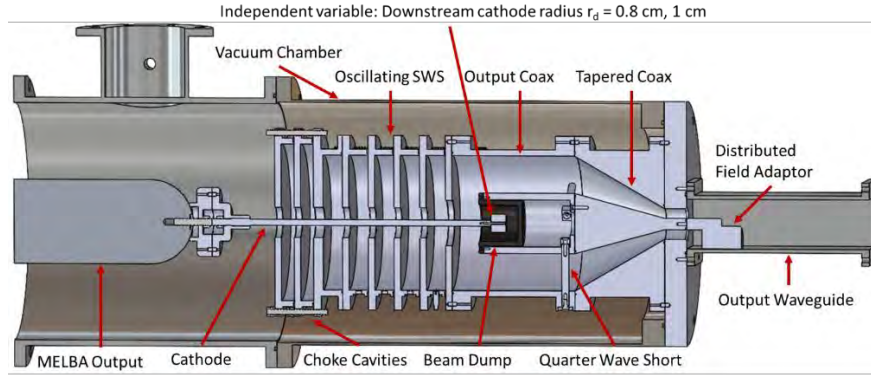


Figure 9: CAD rendering of the MILO assembly within the experimental chamber. The cathode radius r_c for this experiment was 0.7 cm, and two different downstream radii were tested: $r_d = 0.8$ cm, 1 cm.

Figure 10 illustrates a sample shot, where peak microwave generation of 24 MW is observed at 260 kV and 9 kA, an impedance of 28.5Ω . There were numerous other shots which eclipsed 20 MW generation, but none exceeded 30 MW, as illustrated in Figure 11. Single-digit efficiency ($>1\%$) was observed in a significant fraction of shots. Operation in the π -mode was observed very consistently between 0.98 GHz and 1 GHz, which is in acceptable agreement with PIC simulation estimates of 1.005 GHz in this cathode configuration.

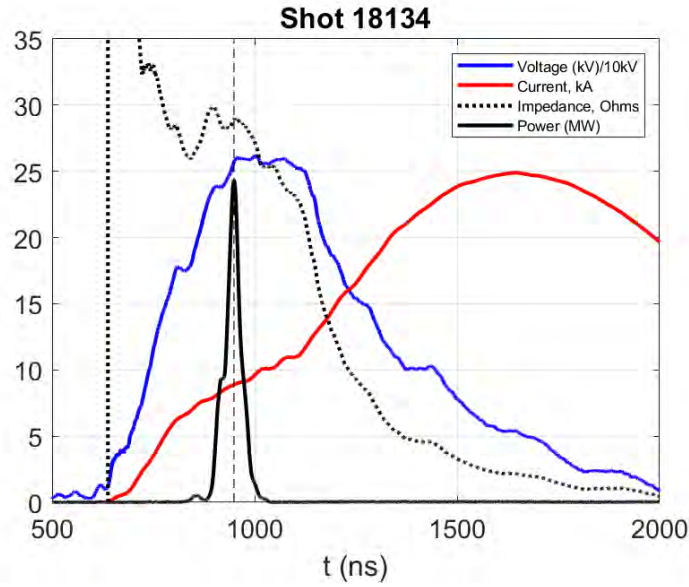


Figure 10: Voltage, current, impedance, and output power for MELBA shot 18134.

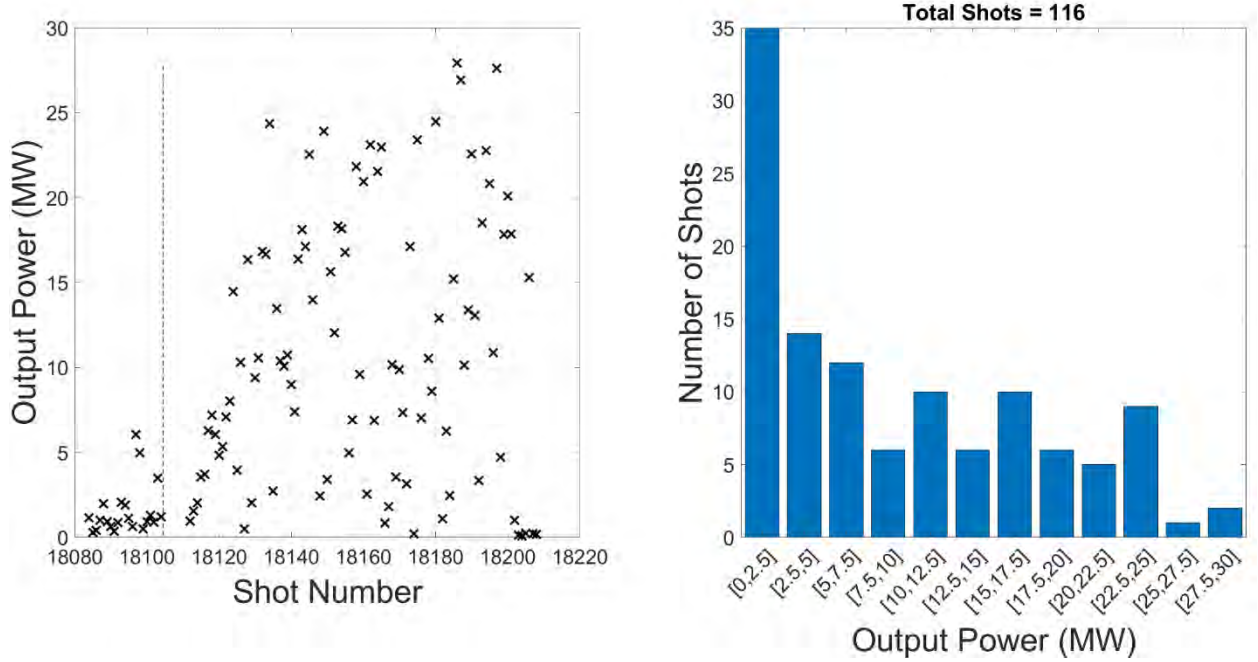


Figure 11: (left) Output power as a function of shot number. Shots to the left of the vertical dashed line are for $r_d = 0.8$ cm, and shots to the right are for $r_d = 1$ cm. (right) Histogram of all shots, sorted by output power.

Several features can be gleaned from Figure 11. Notably, power generation was significantly improved after increasing r_d from 8 mm to 10 mm. A possible explanation for this is that operation within the SWS region is very sensitive to the current drawn in the downstream diode. However, the current was not significantly different in the two experiments; 9.3 ± 0.8 kA and 9 ± 1.6 kA for $r_d = 8$ mm and $r_d = 10$ mm, respectively. This makes the implementation of a downstream current monitor of significant importance.

Focusing on the experiment with $r_d = 10$ mm, there appear to be three distinct zones in terms of the quality of output pulses that were generated. The first ~ 10 shots seem to condition the cathode and remove it of contaminants. The power generation in these shots was consistently higher than it was for $r_d = 8$ mm, but all of them produced < 10 MW. On shot 18124, 14 MW was extracted, which was a record for the MELBA MILO up to that point. Over the course of the next 80 shots, this record was reset numerous times. The power generation over the course of this experiment was extremely irreproducible, where one shot would output 20 MW and drop down to 3 MW on the next. It is speculated that this is because of the presence of triple points on the emitters within the downstream diode and in the SWS region, which can result in inconsistent formation of a Brillouin hub in the SWS region. In comparison with relativistic magnetron experiments on MELBA, there is also volatility in the output power, but not to this degree. The primary difference between the two is the magnetron's magnetic field exists prior to the formation of the electron hub, whereas in the MILO, the insulation and synchronism of the electron hub depends heavily on the quality of emission in the downstream diode. In the last several shots, the quality of the injected voltage pulses was substantially worse, and output power dropped precipitously, possibly indicating that the cathode had failed. In the experiment with $r_d = 10$ mm, the average output power, efficiency,

impedance, and voltage were 11 ± 7.9 MW, $0.53\% \pm 0.41\%$, $26.2 \pm 4.5 \Omega$, and 232 ± 45 kV, respectively.

Multi-Frequency Harmonic MILO

Following our successfully demonstration of the high-impedance L-band MILO, we designed and simulated a multi-frequency harmonic MILO (MHMILO). The current design (**Figure 12**) consists of 6 L-band Oscillator (LBO) cavities at ~ 1 GHz, and six, S-band Oscillator (SBO) cavities at ~ 2 GHz; 2 choke cavities are also designed for each band. This design will allow us to reuse the previous L-band hardware, and simply machine additional S-band slow-wave structures.

Initial simulations indicated 2 MW of microwave output power in S-band. Adjustments to the cathode design and SWS have increased that to ~ 20 MW. Simulations indicate the optimal cathode radius is 7 mm, with that radius maintained throughout the length of the cathode (i.e. without the large downstream cathode radius seen in our previous single-frequency MILO design).

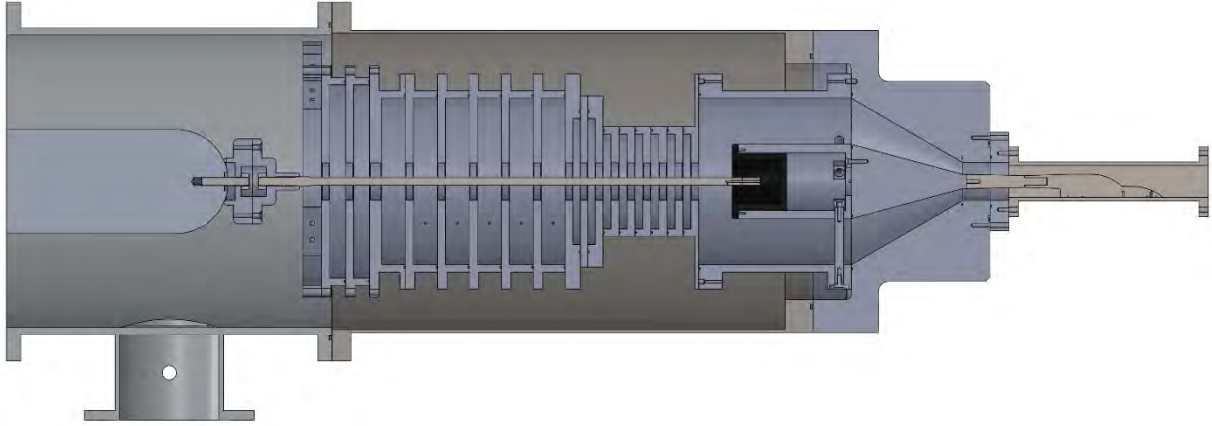


Figure 12: Chamber design for harmonic MILO. A redesigned output taper allows a full set of L- and S-band cavities to fit within the vacuum chamber.

Broadband Output Coupling

We have been investigating methods for simultaneous extraction of 1 and 2 GHz signals. One solution we are exploring is to avoid the transition to rectangular waveguide entirely, keep the output coaxial, and sample via a coaxial directional coupler. While coaxial directional couplers exist as commercial products from Mega Industries⁵ and Myat Technologies⁶, we have determined these will not meet our cost and schedule requirements. Consequently, we are designing a pair of single frequency couplers optimized to our particular experiment.

⁵ <https://www.megaind.com/coaxial/directional-couplers/>

⁶ <https://www.myat.com/products/view-more-products/19-directional-couplers>

In the meantime, we will conduct experiments with the Harmonic MILO where we measure either 1 or 2 GHz via either the WR640 or WR340 mode converters used in previous experiments. This will provide an indication of the power output in each band, though simultaneous, calibrated power measurements will not be possible.

3. Findings and Conclusions

We have designed, simulated, fabricated, and tested a high-impedance L-band MILO. In experiments with a 240-kV, 10-kA generator, the 1 GHz MILO operated at 25-30 Ohms and produced up to 25 MW at 1.017 GHz.

We have produced a broad theory of the flow of crossed field devices, which applies to several geometries of interest. Using this theory, the Buneman-Hartree condition for the coaxial MILO geometry has been derived for the first time. In addition, the Brillouin flow profiles produced have yielded important analytic results that were very useful in the design of the L-band MILO.

4. Plans and Upcoming Events

In the first quarter of FY22, we will machine the slow wave structures and waveguide adapters for the S-band MILO, then conduct initial experiments. Having established the baseline operation of both the L- and S-band MILOs, we will assemble and test the full multi-frequency harmonic MILO. The output taper will be redesigned to allow this structure to fit within the existing experimental chamber.

5. Transitions and Impacts

Three PhD students were directly supported by this grant, but discussion of MILO theory and experiments in group settings expanded education on this topic to 6 graduate and 3 undergraduate students.

Drew Packard, formerly the primary graduate student on this project, completed his PhD defense on May 12th, and left UM in late summer for a position at General Atomics. Ryan Revolinsky has taken the lead role, with Stephen Langellotti and Emma Guerin providing simulation and design assistance and Levi Welch assisting experiments.

6. Collaborations

We have several active HPM projects within the DoD which are closely related to this effort:

- “High-Power Microwave Generation by Compact Linear Transformer Driver Technology”, Ryan McBride ONR Young Investigator, 6/2018 – 5/2021
- “Multipactor and Breakdown Susceptibility and Mitigation in Space-based RF Systems”, Multi-University Research Initiative (MURI), AFOSR #FA9550-18-1-0062, 8/2017 – 7/2022
- Y.Y. Lau, “Integrated model for design optimization and manufacturing tolerance analysis for vacuum electron devices”, DARPA # HR0011-16-C-0080, 4/21/16 - 12/31/20
- “Exploration of Fundamental Limits to High Power Electromagnetic Amplification” Multi-University Research Initiative (MURI), AFOSR, 7/15/20- 7/14/25
- Y.Y. Lau, "Study of Electrical Contact under AC and Nonlinear Conditions," AFOSR# FA9550-18-1-0153, 02/15/18 - 02/14/22

- “HPM Frequency, Phase, and Mode-Locking of Recirculating Planar Magnetron”, AFOSR # FA9550-21-1-0184, 4/15/21 - 4/15/26

7. Personnel

Principal investigator Ronald M. Gilgenbach, 0.27 person months, National Academy Member (N)

Co-PI YY Lau, 0.27 person months, National Academy Member (N)

Co-PI Nicholas M. Jordan, 2 person months, National Academy Member (N)

8. Students

3 graduate students (funded from this ONR grant) and 1 undergraduate students assisted work on this project.

9. Technology Transfer

We have attempted to plan laboratory visits for Yeong-Jer “Jack” Chen, John Kreger and Matt McQuage from NSWC Dahlgren as well as Walter Sessions at Georgia Tech Research Institute (GTRI), but COVID interrupted these plans. We will work to reestablish these connections when possible. To increase opportunities for collaboration with Navy partners, UM has joined the Naval Surface Technology Innovation Consortium (NSTIC).

10. Products, Publications, Patents, License Agreements, etc.

Ph.D. Dissertations

D.A. Packard, “*Innovative Crossed-Field Devices for the Generation of High Power Microwaves*”, doctoral dissertation, University of Michigan, Ann Arbor, MI, 2021.

Peer-reviewed journals:

D. A. Packard, Y. Y. Lau, E. N. Guerin, C. J. Swenson, S. V. Langellotti, A. Jassem, D. Li, N. M. Jordan, J. W. Luginsland, R. D. McBride, and R. M. Gilgenbach, “Theory, simulation, and experiments on a magnetically insulated line oscillator (MILO) at 10 kA, 240 kV near Hull cutoff condition,” *Physics of Plasmas*, vol. 28, no. 12, p. 123102, Dec. 2021, doi: [10.1063/5.0071455](https://doi.org/10.1063/5.0071455).

Y. Y. Lau, D. A. Packard, C. J. Swenson, J. W. Luginsland, D. Li, A. Jassem, N. M. Jordan, R. D. McBride, and R. M. Gilgenbach, “Explicit Brillouin flow solutions in magnetrons, magnetically insulated line oscillators, and radial magnetically insulated transmission lines”, vol. 49, no. 11, pp. 3418–3437, Nov. 2021, doi: [10.1109/TPS.2021.3092606](https://doi.org/10.1109/TPS.2021.3092606).

D. Chernin, A. Jassem, and Y. Y. Lau, “Thermal Electron Flow in a Planar Crossed-Field Diode,” *IEEE Transactions on Plasma Science*, vol. 48, no. 9, pp. 3109–3114, Sep. 2020.

Packard, Cooleybeck, Jordan, Sporer, Mazarakis, Lau, Gilgenbach, McBride, “[HFSS and CST Simulations of a GW-Class MILO](#)”, *IEEE Transactions on Plasma Science Special Issue on HPM Generation*, vol. 48, no. 6, pp. 1894-1901, June 2020.

Conference Presentations:

N.M. Jordan, D.A. Packard, C.J. Swenson, S.V. Langellotti, E.N. Guerin, Y.Y. Lau, R.M. Gilgenbach, "Development of a High Impedance Magnetically Insulated Line Oscillator", PPC/SOFE, Denver, CO, Dec 2021. [accepted]

D.A. Packard, Y.Y. Lau, C.J. Swenson, N.M. Jordan, E.N. Guerin, R.M. Gilgenbach, "Experiments on a 10 kA, 240 kV Magnetically Insulated Line Oscillator (MILO)," ICOPS 2021, Sept 2021. **[Invited]**

D. Li, D. Chernin, Y. Y. Lau, "Electromagnetic and Relativistic Corrections to the Ramo-Shockley Theorem", ICOPS 2021, Sep 2021. **[Best Student Paper]**

D.A. Packard, Y.Y. Lau, C.J. Swenson, N.M. Jordan, and R.M. Gilgenbach, "Theory, Simulation, and Experiments on Moderate-Current Magnetically Insulated Line Oscillators", IVEC 2021, April 2021.

N.M. Jordan, B.J. Sporer, D.A. Packard, R.V. Shapovalov, R.M. Gilgenbach, R.D. McBride, "Driving a Magnetically Insulated Line Oscillator with a Linear Transformer Driver", IVEC 2021, April 2021.

Y. Y. Lau, "The Child-Langmuir Law and the Physics of Diodes," ICOPS 2020, Dec 2020. **[Invited Plenary]** [virtual]

D.A. Packard, N.M. Jordan, A. Cooleybeck, C.J. Swenson, R.D. McBride, Y.Y. Lau, R.M. Gilgenbach, "External Magnetic Field Effects in Magnetically Insulated Line Oscillators", ICOPS 2020, Dec 2020. [virtual]

D. Packard, YY Lau, C. Swenson, N. Jordan, B. Sporer, R. Shaparov, R. McBride, R. Gilgenbach, "Theory, Simulations, and Experiments on Magnetically Insulated Line Oscillator (MILO) at the University of Michigan", APS-DPP, Virtual, Nov 2020.

N.M. Jordan, D.A. Packard, S.C. Exelby, P.C. Campbell, B.J. Sporer, A.P. Shah, G.V. Dowhan, T.J. Smith, C.J. Swenson, Y.Y. Lau, R.D. McBride, R.M. Gilgenbach, "High Power Microwave and Pulsed Power Development at the University of Michigan", IPMHVC 2020, Knoxville, TN, May 2020. **[Invited]** [conference cancelled]

Drew A. Packard, Christopher J. Swenson, Anna Cooleybeck, Brendan J. Sporer, Alexander E. Mazarakis, Nicholas M. Jordan, Y. Y. Lau, Ryan D. McBride, and Ronald M. Gilgenbach, "Simulations and Experiments on Magnetically Insulated Line Oscillators at the University of Michigan", International Vacuum Electronics Conference 2020, Monterey, CA, Oct 2020. [Accepted] [Virtual]

D.A. Packard, N.M. Jordan, Y.Y. Lau, R.M. Gilgenbach, B.W. Hoff, “Experimental Investigations of High Power Microwave Sources at the University of Michigan”, DEPS Directed Energy Student Workshop, West Point, MD, Mar 2020.

N.M. Jordan, D.A. Packard, C.J. Swenson, Y.Y. Lau, R.M. Gilgenbach, “Axial Magnetic Field Effects on Magnetically Insulated Line Oscillators (MILO)”, 61st APS-DPP, Ft. Lauderdale, FL, Oct 2019.

11. Point of Contact in Navy

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Date of last contact: January 8, 2020.

12. Acknowledgement/Disclaimer

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Comprehensive Investigation of Advanced Inductor Materials on Addressing Opportunities to Benefit the Navy's HPPG Systems

Grant No. N00014-20-1-2861

Annual Summary Report for Fiscal year 2021

Period of Performance: October 1, 2020 to September 15, 2021

Prepared by:

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Grant or Contract Number: N00014-20-1-2861/GRANT13169109

Date Prepared: March 7, 2022

Project Title: Comprehensive investigation of advanced inductor materials on addressing opportunities to benefit the navy's HPPG systems

Annual Summary Report: FY21

Principle Investigator: Vincent G. Harris, 617 901 8186, v.harris@northeastern.edu,
Northeastern University

Section I: Project Summary

1. Overview of Project

1.A Introduction:

Nanosecond and sub-nanosecond pulses of high power can be used in many Navy applications in areas of sensing, communication, and EW measures and countermeasures. Recent developments in semiconductor device technologies, such as Drift Step Recovery Diodes (DSRDs) give rise to a new generation of solid-state systems capable of producing megawatts of power over nanosecond pulses with 100,000s of pulses per second. However, the system efficiency is degraded by the energy storage limitations of the inductor components and specifically by their limited bandwidth and efficiency. At high power and high frequencies, in applications such as High-Power Pulse Generators (HPPGs), magnetic and dielectric losses result in copious heat dissipation. The excessive heat places not only limits on the operating flux density of power inductors and their form factor but also overall system efficiency. The constraints in the operating flux density limits size reduction maintaining power inductors as the largest and most lossy components in the system. Optimized performance of HPPGs, requires high power and pulse repetition rates, time stability, long lifetime, high efficiency and reliability.

1.B Objectives:

Principal Objectives

To identify the principal roles of inductors in NAVY DSRD-based HPPG systems and to quantify limitations imposed upon energy storage dynamics from intrinsic magnetic properties in order to optimize pulsed power performance in extreme environments while minimizing SWAP+C² and cost of ownership.

Quantify the role and identify limitations imposed by the inductor's cut-off frequency, saturation induction, permeability, and losses in power handling and overall HPPG system efficiency.

Identify desired properties and investigate potential COTS inductor materials to optimize performance of HPPGs.

Predict improvement to system efficiency offered by replacement inductor materials. Conceptualize advanced materials to meet the needs of the NAVY's HPPG systems in enhanced efficiency, performance, and form factor (SWAP+C²).

Specific Objectives

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1. Identify specific impact of magnetic material properties upon system efficiencies including:
 - a. Cut-off frequency, f_c (inductor bandwidth)
 - b. Saturation induction, B_s (maximum inductor current) and saturation magnetization, M_s (highest allowable power by the inductor)
 - c. Permeability, μ (tunable for specific needs)
 - d. Magnetic and dielectric losses (heat generated by inductor from power dissipation)
2. Identify limitations of COTS inductor materials currently available for use in HPPG systems
3. Identify optimal inductor magnetic properties to enhance Navy HPPG system efficiency.

Background and Approach:

The background and approach are articulated by the following tasks and subtasks with accompanying descriptions.

Task 1: Material needs for power inductors used in HPPG systems

Task 1 focuses on the investigation of required improvements to Navy HPPG systems in the area of power inductors used in PG systems. The desired benefits include higher switching frequencies, higher efficiencies, as well as smaller form factors.

1.A. Identify role of inductors and inductor materials in HPPG systems

1.B. Identify limitations and opportunities presented by replacing existing inductor materials

1.C. Identify desired properties and potential material systems if they exist or if they require invention and discovery (i.e., new technologies)

Task 2. Survey of commercial off-the-shelf products to explore viable options as HPPG inductors

Task 2 includes a comprehensive review and investigation using PSPICE simulations of inductor products and magnetic materials as potential HPPG inductors. We systematically explore material intrinsic properties including saturation induction, permeability, cut-off frequency, and resistivity to determine thermal rise, performance factor, and volumetric efficiency, among other performance properties. In order to accomplish these tasks, the NEU Team has considered the most popular HPPG circuits provided by the NRL circuit design group, investigated the role of inductors in these circuit topologies, and performed an extensive survey of commercial off-the-shelf (henceforth COTS) inductor products available for HPPG applications. Furthermore, we created PSPICE models of not only inductor components but created a magnetic materials library that allowed for simulations of magnetic materials not yet studied for such applications and in theory.

2. Activities and Accomplishments

2.A Highest power harmonic that can be stored in the inductor (i.e., Cut-off frequency, f_c)

Figure 1 shows the output voltage of the system as a function of time obtained from a PSPICE simulation of the 3-stage DSRD HPPG circuit illustrated in Figure 2 (b). A 4.6 nanosecond pulse is generated with the repetition rate of 150 kpulses per second. The black curve arises from an ideal inductor (i.e., with no cut-off frequency and unlimited saturation magnetic field) and the blue curve results from the simulation where a commercial TDK inductor model (i.e., $L=100$ nH, $f_c=35$ MHz, $I_{sat}=133$ A, $I_{rated} = 83$ A, where I_{rated} is the current corresponding to temperature rise to 40°C) were

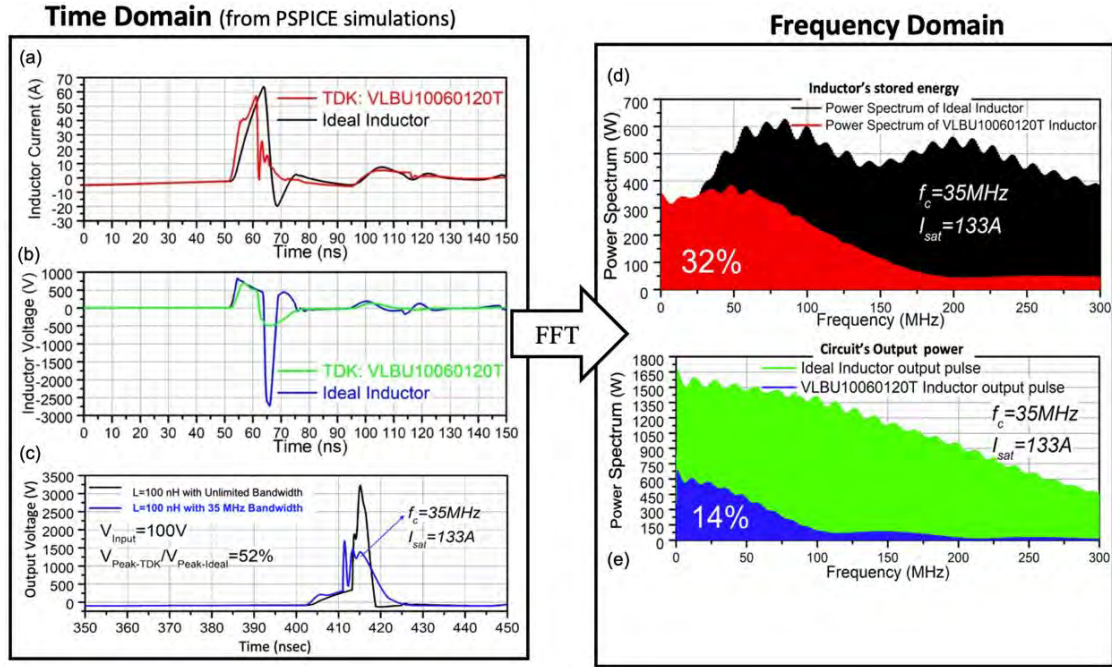


Figure 1. The output voltage of the system depicted as Figure 2 (b) is illustrated as a function of time obtained from a PSPICE simulation for a COTS and an ideal inductor's (a) current and (b) voltage in the time domain. (c) demonstrates the circuit's output pulse using ideal inductor (black) with the amplitude of 3.2 kV and a 4.6 nanosecond pulse width, while using the commercial off the shelf inductor (blue) resulting in the dropping the output voltage to 1.5 kV and a much broader pulse width of 9 nanosecond due to an insufficient cut-off frequency. The pulse width is seen to double and its intensity reduced by 48%. The FFT of these time domain circuit responses, as shown in (d) and (e).

used for the inductors which was chosen as one of the best inductors available in the marketplace. Figures 1 (a) and (b) compare the COTs and ideal inductor's current and voltage in the time domain and Fig. 1 (c) demonstrates the circuit's output pulse using ideal inductor (black) with the amplitude of 3.2 kV and a 4.6 nanosecond pulse width, while using the commercial off the shelf inductor (blue) results in dropping the output voltage down to 1.5 kV and a much broader pulse width of 9 nanosecond due to the insufficient cut off frequency. Therefore, not only pulse width is doubled but also the intensity was dropped by 48%, limiting the efficiency of the overall system. To expand our understanding of the role of the inductor in limiting the efficiency of the system the spectral power density in the frequency domain of the pulses were obtained by taking the FFT of these time domain circuit responses, as shown in Fig. 1 (d) and (e). Figure 1 (d) demonstrates the power spectrum of the inductor component where black reflects the use of the ideal inductor and red reflects the use of the commercial off the shelf TDK inductor under study. This comparison reveals that the inductor stored energy in the commercial off the shelf is only 32% of what was stored in the ideal inductor since the higher harmonics were not stored in the COTs due to the low cut-off frequency. Figure 1 (e) demonstrates the HPPG circuit's output pulse power spectrum, where the blue is the output power spectrum of the circuit using the ideal inductor and green is the output power spectrum of the same circuit using the chosen TDK inductor. This figure demonstrates that using an HPPG circuit with this commercial off the shelf inductor only generates 14% of the power

generated by a circuit using an ideal inductor which has a detrimental impact of commercial of the limitations of the commercial off the shelf inductor.

Figure 2 provides an estimation of the generated output power pulse affected by the insufficient cut-off frequency, that is, the highest power harmonic that can be stored in the inductor. The top figure is the HPPG circuit's output power spectrum obtained using FFT of the circuit response simulated using PSPICE in the time domain for the HPPG circuit under study with a repetition rate of 150,000 pulses per second (i.e., repetition rate (f_r): 150 kHz). The bottom figure is the fractional power captured by the inductor as a percentage and that is plotted against the inductor material frequency response defined by its cut-off frequency. The shaded region, which corresponds to an inductor material with a cut-off frequency of 100 MHz and its intercept to the left, captures roughly 50% of the power available to the inductor. If further mapped onto the plot in the upper panel, i.e., the spectral power density versus the same inductor material's bandwidth, the power density is the fractional integrated area under the curve that is defined by the cutoff frequency and corresponds to $\sim 50\%$ of the total area under the curve. Based on this estimation, an inductor core with a cut-off frequency of 100 MHz can only capture 50% of the power provided by the inductor with an optimal cut-off frequency, i.e., $f_c > 300$ MHz. Likewise, an inductor core with a cut-off frequency of 150 or 200 MHz can capture 70% and 84.6% of the power provided by the inductor with an optimal cut-off frequency, respectively. As a principal conclusion, a cut-off frequency of higher than 250 MHz is recommended for this application for providing the $> 94.3\%$ of the circuit's capacity.

2.B Comprehensive survey of available COTS inductor materials

An investigation of COTS inductor materials was conducted including ferrite and iron-based inductor products. One notices that most of these materials fall into the category of NiZn-ferrites since these materials possess highly insulating properties and lower permeabilities that allow for higher cut-off frequencies. Table 1 lists electric and magnetic (resistivity, coercivity, loss tangent, permeability, magnetization and cut-off frequency) properties for relevant COTS. As can be seen, the NZFO products do not meet the required cut-off frequency to address the necessary bandwidth of the DSRD-based HPPG systems. While iron powder products, despite offering higher cut-off frequencies, become very lossy at MHz frequencies. In the next section, the impact of these characteristics on system efficiency and thermal rise and associated challenges will be presented.

Table 1. COTS power magnetic materials available for MHz frequency operation

Product	Material	μ	f_c (MHz)	B_s (Gauss)	Curie Temp. (°C)	RT resistivity ($\Omega \cdot \text{cm}$)	Loss factor	H_c (Oe)
Nickel Zinc-based Spinel Ferrite Inductor Cores								
Ferronics-P	CoNiZn ferrite	40	100	2150	350	$> 1 \times 10^6$	85×10^{-6}	3.5
Ferronics-K	CoNiZn ferrite	125	35	3200	350	$> 1 \times 10^7$	150×10^{-6}	1.5

National Magn-M5	NiZn ferrite	7.5	300	1750	320	10^7	$< 3500 \times 10^{-6}$	23
National Magn-M3	NiZn ferrite	20	120	2500	520	10^7	$< 500 \times 10^{-6}$	7
National Magn-M2	NiZn ferrite	40	90	2300	430	10^7	$< 150 \times 10^{-6}$	4
National Magn-M	NiZn ferrite	125	30	2400	380	10^7	$< 40 \times 10^{-6}$	1.9
Ceramic Magn.-N40	NiZn ferrite	15	100	2500	600	10^{10}	$< 3850 \times 10^{-6}$	8
Ceramic Magn.-C2075	NiZn ferrite	50	50	3000	420	10^9	$< 3950 \times 10^{-6}$	2.6
Ceramic Magn.-XTH2	NiZn ferrite	80	50	3600	300	10^8	$< 7200 \times 10^{-6}$	2
Ceramic Magn.-C2050	NiZn ferrite	100	20	3700	340	10^9	$< 4250 \times 10^{-6}$	2
Ceramic Magn.-M4	NiZn ferrite	12	60	1800	500	10^9	$< 850 \times 10^{-6}$	12
Ceramic Magn.-M3F	NiZn ferrite	20	90	1800	400	10^9	$< 500 \times 10^{-6}$	9
Ceramic Magn.-XCK	NiZn ferrite	125	40	2500	350	10^9	$< 410 \times 10^{-6}$	0.95
Ceramic Magn.-C2025	NiZn ferrite	175	20	3900	270	10^{10}	$< 1200 \times 10^{-6}$	1.4
Ceramic Magn.-N	NiZn ferrite	250	20	3000	250	10^8	$< 100 \times 10^{-6}$	1.3
Ceramic Magn.-C2010	NiZn ferrite	340	20	3900	245	10^7	$< 1400 \times 10^{-6}$	0.7
Ceramic Magn.-G4	NiZn ferrite	400	~10	4600	250	10^8	$< 35 \times 10^{-6}$	0.8
Fair-Rite-80	NiZn ferrite	600	<10	4700	310	200	10×10^{-6}	0.4
Fair-Rite-46	NiZn ferrite	500	<10	2550	140	10^8	60×10^{-6}	0.53

Fair-Rite-68	NiZn ferrite	16	250	2700	570	10^7	300×10^{-6}	7
Fair-Rite-67	NiZn ferrite	40	90	2300	450	10^7	180×10^{-6}	3
Fair-Rite-61	NiZn ferrite	125	20	2500	370	10^8	10×10^{-6}	1.2
Fair-Rite-52	NiZn ferrite	250	10	4200	290	10^9	45×10^{-6}	0.6
Fair-Rite-51	NiZn ferrite	350	20	3500	180	10^9	30×10^{-6}	0.6
Fair-Rite-44	NiZn ferrite	500	<10	3000	170	10^9	150×10^{-6}	0.45
Ferroxcube-4E2	NiZn ferrite	25	200	3500	500	10^7	4000×10^{-6}	5
Ferroxcube-4F1	NiZn ferrite	80	70	3200	260	10^7	2000×10^{-6}	1.9
Ferroxcube-4M2	NiZn ferrite	140	50	3100	200	10^7	400×10^{-6}	1.2
Ferroxcube-4B3	NiZn ferrite	250	<10	3600	260	10^7	100×10^{-6}	0.5
Ferroxcube-4B1	NiZn ferrite	250	20	3600	250	10^7	90×10^{-6}	1.9
Ferroxcube-4S3	NiZn ferrite	250	20	3600	250	10^7	50×10^{-6}	1.8
Hitachi-ND11S	NiZn ferrite	100	40	4100	330	10^8	65×10^{-6}	Not found
Hitachi-NL12S	NiZn ferrite	120	40	4550	260	10^8	85×10^{-6}	2
Hitachi-NL25S	NiZn ferrite	240	10	4600	230	10^8	30×10^{-6}	1.5
Hitachi-NB25S	NiZn ferrite	250	20	5000	360	10^8	25×10^{-6}	Not found
Iron Powder-based Inductor Cores								
Micrometals-02	Iron Carbonyl Powder	10	>100	14.8k	Not available	Not available	Not available	~0

Micrometals-08	Iron Carbonyl Powder	35	~100	17.6k	Not available	Not available	Not available	~0
Micrometals-14	Iron Carbonyl Powder	14	>100	15.2k	Not available	Not available	Not available	~0
Micrometals-17	Iron Carbonyl Powder	4	170	14.4k	Not available	Not available	Not available	~0
Micrometals-18	Iron Carbonyl Powder	55	~100	17.8k	Not available	Not available	Not available	~0
Micrometals-19	Iron Carbonyl Powder	55	~80	18.2k	Not available	Not available	Not available	~0
Micrometals-26	Iron Carbonyl Powder	75	~20	18.5k	Not available	Not available	Not available	~0
Micrometals-30	Iron Carbonyl Powder	22	~100	16.7k	Not available	Not available	Not available	~0
Micrometals-34	Iron Carbonyl Powder	33	~80	17.1k	Not available	Not available	Not available	~0
Micrometals-38	Iron Carbonyl Powder	85	~30	18.7k	Not available	Not available	Not available	~0
Micrometals-40	Iron Carbonyl Powder	60	~30	18.4k	Not available	Not available	Not available	~0
Micrometals-45	Iron Carbonyl Powder	100	~30	18.9k	Not available	Not available	Not available	~0
Micrometals-52	Iron Carbonyl Powder	75	~60	18.5k	Not available	Not available	Not available	~0

As can be seen in **Table 1**, the cut-off frequency and permeability/magnetization (inductor saturation current) to experience an inverse relationship, consistent with the well-known trends observed in spinel ferrites and alloys called the Snoek's relationship.

As will be presented below, the wider bandwidth (i.e., higher cut-off frequency) comes at the cost of lower permeability and magnetization, which translates to lower power handling capability, higher loss factors and a compromised SWAP+C² (size, weight and power plus cost and cooling). Whereas, samples with higher permeability have lower cut-off frequencies that reduce higher frequency power components, and result in the widening of the output pulse and suppression of its amplitude. This has also been demonstrated in our earlier reports.

Table 2. Commercially available magnetic materials with intrinsic and simulated properties

Mfr. /Product Designation a)	Material b)	μ_i	f_c	M_s	ρ_{RT}	$\tan\delta_\mu$	H_c c)	CPL_{50} d)	ΔT_{rise} e)
			MHz	G	$\Omega - cm$	$\times 10^{-6}$	Oe	W	°C
Micrometals /2	Carbonyl Iron	10	45	14.8k	n.a.	n.a.	~0	42	131
Ferronics /P	CoNiZn	40	100	2150	$> 10^6$	85	3.5	51	141
National Magnetics /M5	NiZn	7.5	300	1750	10^7	< 3500	23	123	252*
National Magnetics /M3	NiZn	20	120	2500	10^7	< 500	7	53	120
National Magnetics /M2	NiZn	40	90	2300	10^7	< 150	4	76	177
National Magnetics /M	NiZn	125	30	2400	10^7	< 40	1.9	470	789*
Ceramic Magnetics /N40	NiZn	15	100	2500	10^{10}	< 3850	8	40	127
Ceramic Magnetics /C2075	NiZn	50	50	3000	10^9	< 3950	2.6	180	383*
Ceramic Magnetics /XTH2	NiZn	80	50	3600	10^8	< 7200	2	279	518*
Ceramic Magnetics /C2050	NiZn	100	20	3700	10^9	< 4250	2	526	875*

2.C A comprehensive survey, evaluation and comparison of available COTs inductor materials

A comprehensive survey, evaluation and comparison of available COTs inductor materials was conducted, and simulations carried out under conditions anticipated for Navy DSRD based HPPG operation.

The magnetic materials were substituted into inductor components in the DSRD-based pulse generator described in previous monthly reports. The HPPG circuitry produces 3.25 kV at 4.6 ns width pulses at a 150 kilopulses per second, shown in Fig. 1(b).

Table 2 presents a listing of those commercially available materials that possess cut-off frequencies (f_c) that are among the highest available and represent the most attractive combination of magnetic and electric properties for the desired frequency and power range to provide insight into their impact on the performance and thermal management challenges of the DSRD-based HPPGs. (Some of the leaders in this area, such as TDK, do not offer magnetic “materials” for this application but provide inductors with ferrite cores that were studied and reported on earlier.)

Each of the materials show to be inadequate in that, not only its cut-off frequency is far below the necessary value for the HPPG application, but also the power dissipation is excessive and manifests as an excessive heat and temperature rise in the component imposing thermal management challenges detrimental to the overall system efficiency and in some instances approaches the materials’ degaussing (i.e., above the Curie temperature, T_c), whereupon the inductor material becomes nonmagnetic, the permeability

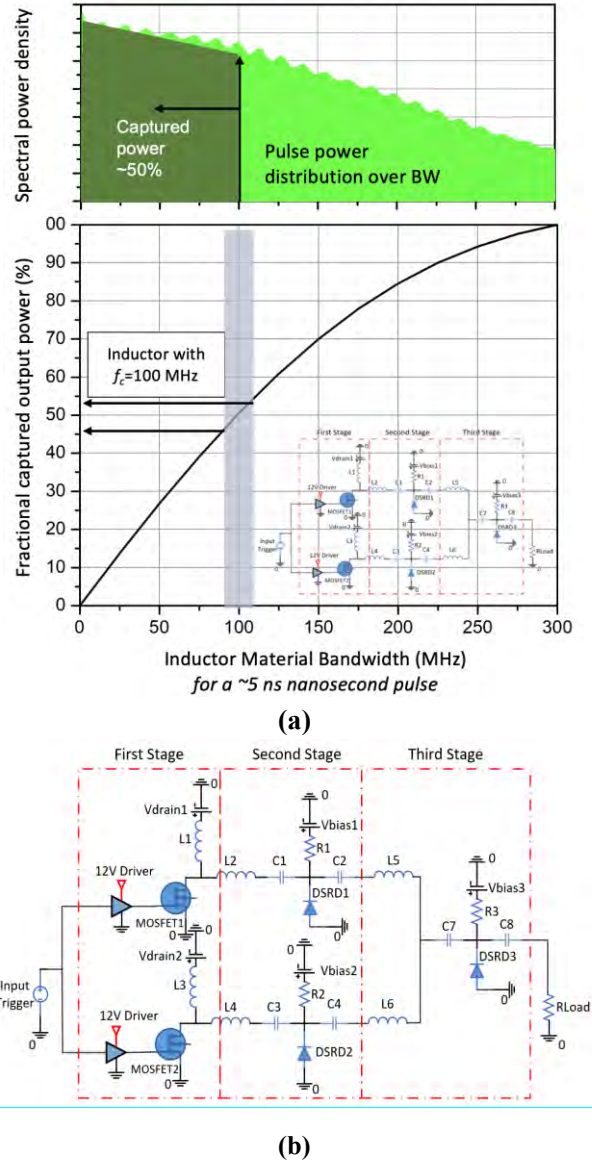


Figure 2. (a-Top) Power spectrum of the output pulse power of an ideal inductor as the storage unit of the 3-stage DSRD-based pulse generator producing 3.25 kV, 4.6 ns width pulses at 150 kHz repetition rate that was studied and presented in the earlier reports (Circuit schematic is shown as the inset). (a-Bottom) The percentage of estimated generated output power pulse affected by the insufficient inductor core’s properties, i.e., cut-off frequency to an inductor with optimal cut-off frequency, i.e., $f_c > 300$ MHz. (c) Circuit schematic of 3-stage DSRD-based pulse generator.

becomes unity, and the core experiences excessive loss.

Evaluation performed based upon our simulations and calculations, indicate that these COTS magnetic materials are ill-suited as DSRD-based HPPG inductor core applications and result in significant power dissipation that generates heat in excess of military and industrial temperature specifications, i.e., -80 °C to 125 °C.

2.D Performance and anticipated thermal rise using representative COTS inductor materials in present and next generation DSRD-based HPPG systems

These studies investigate the total power loss and uncompensated temperature rise of the inductor components of 100 nH (based on a 3-stage DSRD-based circuit under study) with select COTS magnetic cores for a pulse repetition rate of 150 kHz which is the state of the HPPG technology, circa 2020.

The uncompensated temperature rise is a prediction of the generated heat by the inductor component (originating from the identified winding and core power losses of the inductor, see **Fig. 3**, as was presented and discussed in our earlier reports) that must be compensated with appropriate

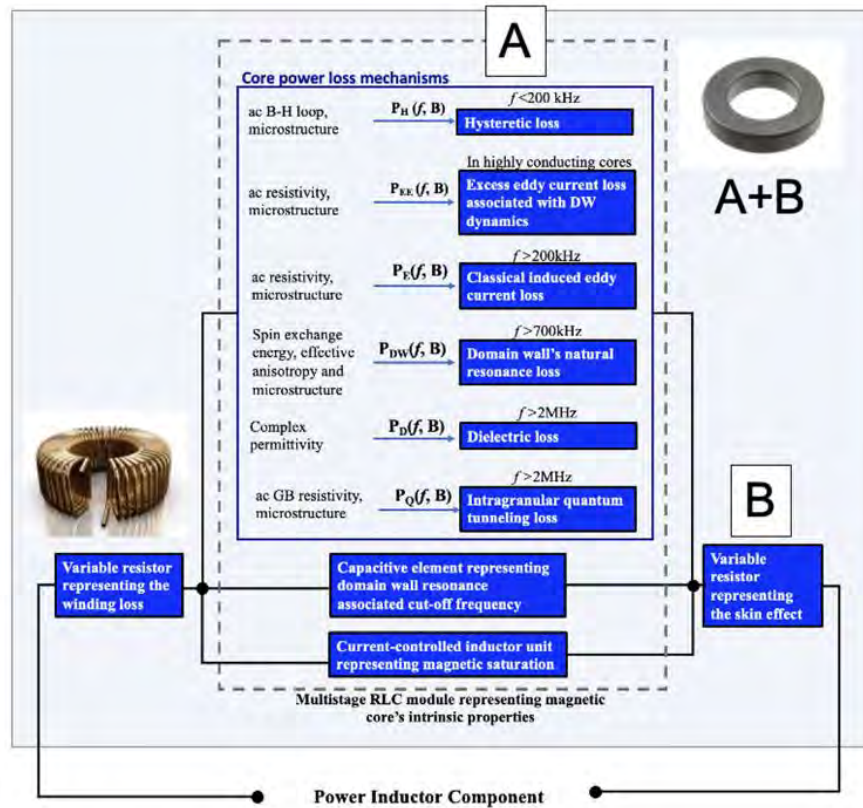
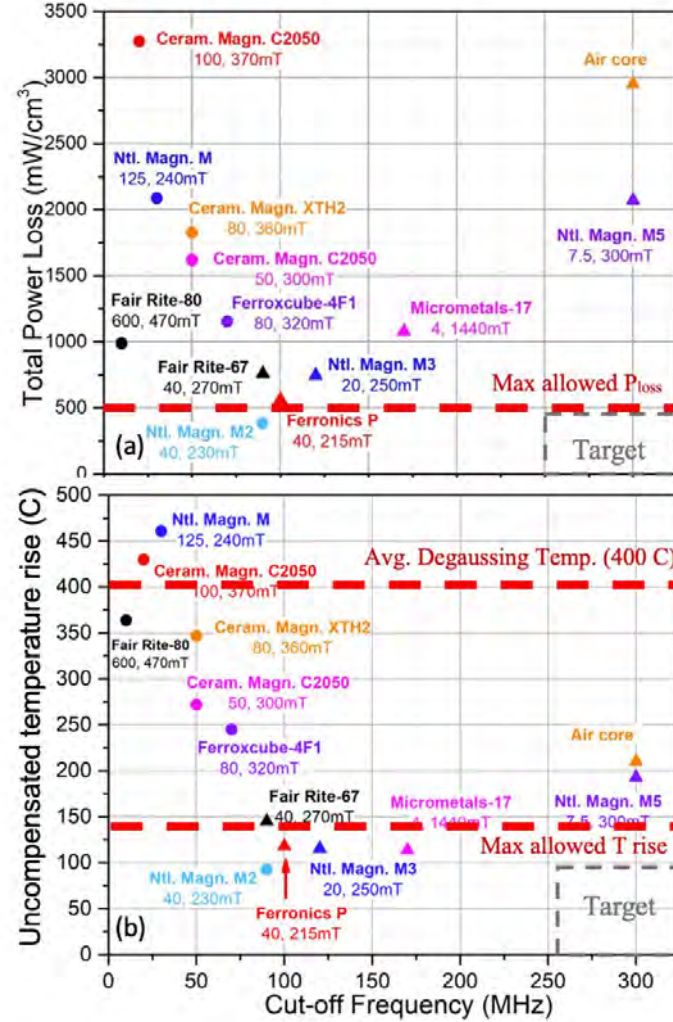


Figure 3. Circuit unit cell representing intrinsic magnetic properties of a high-power inductor cores with high power/frequency power dissipation mechanisms identified. Inductor losses identified: A: The intrinsic core losses as Hysteretic, Eddy current, Domain wall resonance, Dielectric loss and Intergranular quantum tunneling. B: The winding's conductive and skin effect losses.

cooling techniques and protocols. Inductor losses identified in Figure 2 include the intrinsic core losses as Hysteretic, Eddy current, Domain wall resonance, Dielectric loss and Intergranular quantum tunneling. Additionally, the winding's conductive and skin effect losses of both the windings and the magnetic core are included.

These studies present a subset of high power – high frequency candidate inductor magnetic materials from various manufacturers that we compare in terms of their performance in HPPG systems. In particular, extensive simulations have been performed using these materials' magnetic properties to derive the relationship between the intrinsic magnetic properties and system's performance and thermal rise associated with the power dissipation of the inductor components.

It is important to realize that the temperature rise is presented as the uncompensated temperature increase of the inductor components. In some cases, the temperature rise exceeds the *degaussing* temperature (i.e., Curie temperature, T_c) of the magnetic inductor core material indicating that it



Figures 4 (a-b) demonstrate the total power loss density and the associated temperature rise of the inductor in the HPPG circuit under study with the pulse repetition rate of 150 kHz (representing the current generation HPPG systems). In these simulations every attempt was made to isolate and study the inductor materials and not inductor topology, as such for this study the inductor ($L = 100$ nH), the windings remain constant at $N=8$ and the core volume decreases inversely proportional with the core's permeability (the ratio of the cores dimensions, including outer diameter, inner diameter, and height, were kept the same for all samples). As can be observed in Figures 4 (a and b), none of these materials support conditions required for the current state of HPPG operation, i.e., 250 MHz bandwidth and a thermal rise less than 100 °C.

would obtain a permeability of unity (i.e., lose it magnetic character). The Curie temperatures are presented for all materials under study in Table 1 (see Appendix B).

Therefore, the temperature rise is merely a prediction of the generated heat by the inductor component that must be compensated with appropriate cooling techniques. It's important to consider the cooling expenses and associated impact of size and weight of such HPPG systems. The analysis of specific thermal management systems does not fall within the scope this program.

2.E Consideration of higher inductances

In order to not limit ourselves to a single circuit design, we have explored a range of inductance values from 100-1000 nH. **Figure 5** is plotted on a log scale to accommodate very large increases in temperature rise that are in some cases well beyond degaussing limits. As can be seen in **Figure 4**, the temperature rise escalates for higher inductance values. Specifically, for magnetic materials with lower permeability and for the air cores, much higher temperature rise occurs for higher inductances due to topological adjustments such as increases in winding volume and associated conduction losses.

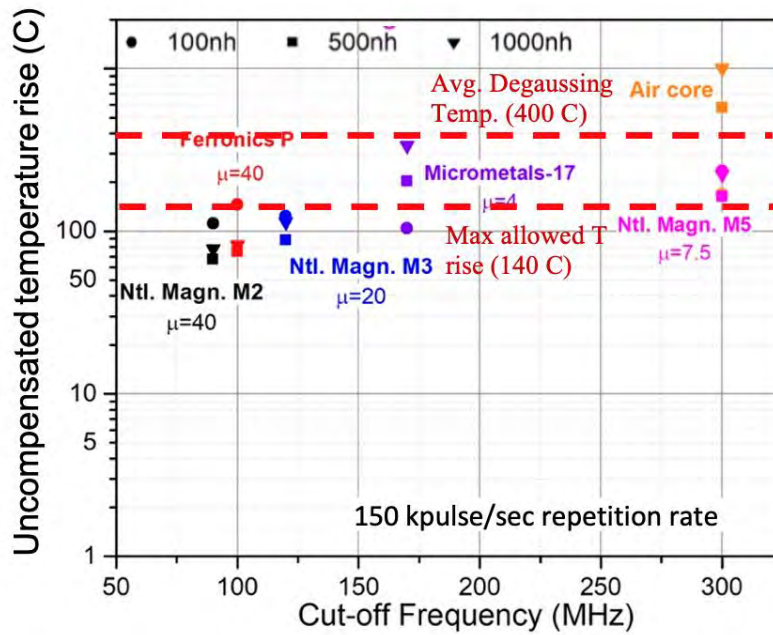


Figure 5. Uncompensated temperature rises of the representative 100 nH (circle), 500 nH (square) and 1 μH (triangle) COTS MHz power inductor materials in the HPPG system under study generating 3.25 kV and 4.6 ns width pulses at 150 kilopulses per second. (Text accompanying symbol denotes permeability and saturation magnetization).

Figures 6 (a-b) presents the same study for COTs materials in a similar HPPG system with 300 kHz pulse repetition rate representing future generations of HPPG systems.

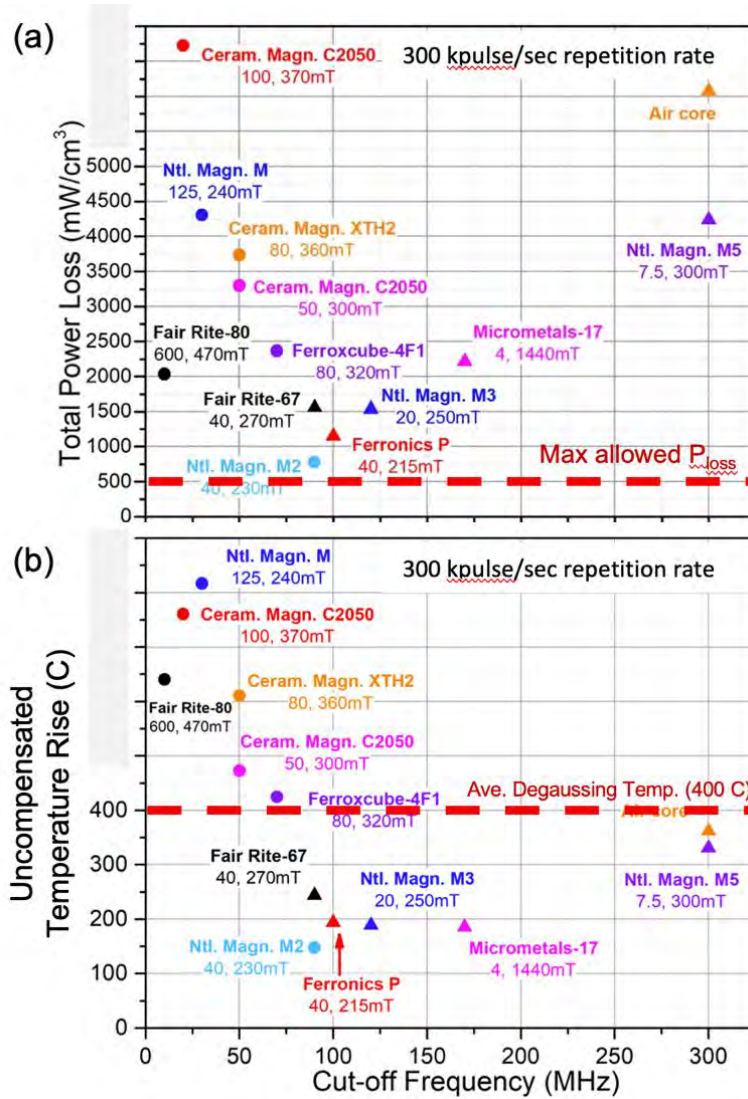


Figure 6. (a) Total power loss and (b) uncompensated temperature rise of the representative 100 nH COTS MHz power inductor materials in the HPPG system under study generating 3.25 kV and 4.6 ns width pulses at 300 kHz pulse repetition rate.

The future generation faces a more critical temperature rise, e.g., 143 °C to 383 °C for these representative samples, which is detrimental to the overall HPPG system efficiency and poses serious thermal management challenges.

2.F Power Handling Capacity, Efficiency, and Size of COTS Inductors

The following three three-dimensional codependent plots compare and contrast COTS inductor materials' suitability for the NAVY's DSRD based HPPG systems.

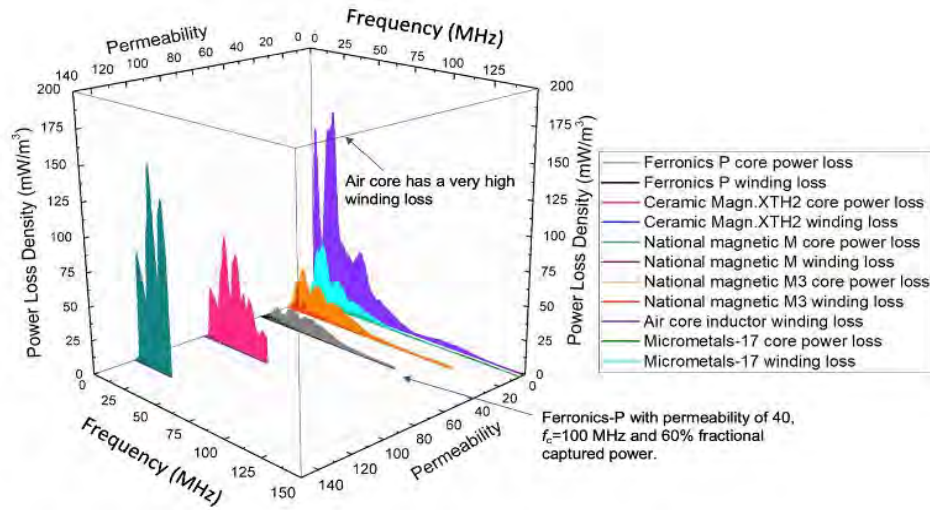


Figure 7. Three-dimensional plot comparing frequency dependance of winding and core power loss density of air core and 5 select COTS products.

Figure 7 is a 3D figure comparing the frequency dependance of winding and core power loss densities of air core and COTS products. The air core curve is shown in purple displaying only a winding loss since no core exists. Other curves demonstrate a dominant core power loss spectra for the ferrite cores and a comparatively negligible winding loss spectra that are barely visible at the front portion of each power loss spectrum. It is important to notice how the total loss density of these representative samples remain smaller than the total loss of the air core along the frequency band which translates into the proportional heat generation and temperature rise in these cores.

The target region has been defined for permeabilities >40 , a high cut-off frequency >250 MHz and low power loss density < 500 mW/cc. Of the COTS ferrite cores, Ferronics-P has a permeability of 40 with a 60% fractional power captured and a cutoff frequency of 100 MHz. Although this COTS product has some acceptable properties, it fails to provide sufficient BW to capture the necessary spectral power for HPPG applications.

There are still other properties to consider in determining the utility of the COTS products, including the efficiency and volumetric footprint. As an example it will be demonstrated in the figure that Ferronics P is not a viable solution when a totality of properties is considered.

Figure 8 compares COTS inductors regarding their *fractional captured power* representing the efficiency and the *performance factor* representing the power handling capacity. **Fractional captured power** was explained earlier and used to explain why COTS samples have inadequate efficiency in storing power due to their low cut off frequencies. **Performance factor** is used here as a comprehensive broadband metric for the evaluation and comparison of power handling capacity of inductor cores at high frequencies where the power dissipation becomes a limiting factor prior to reaching saturation. Performance factor is defined here as the maximum allowed

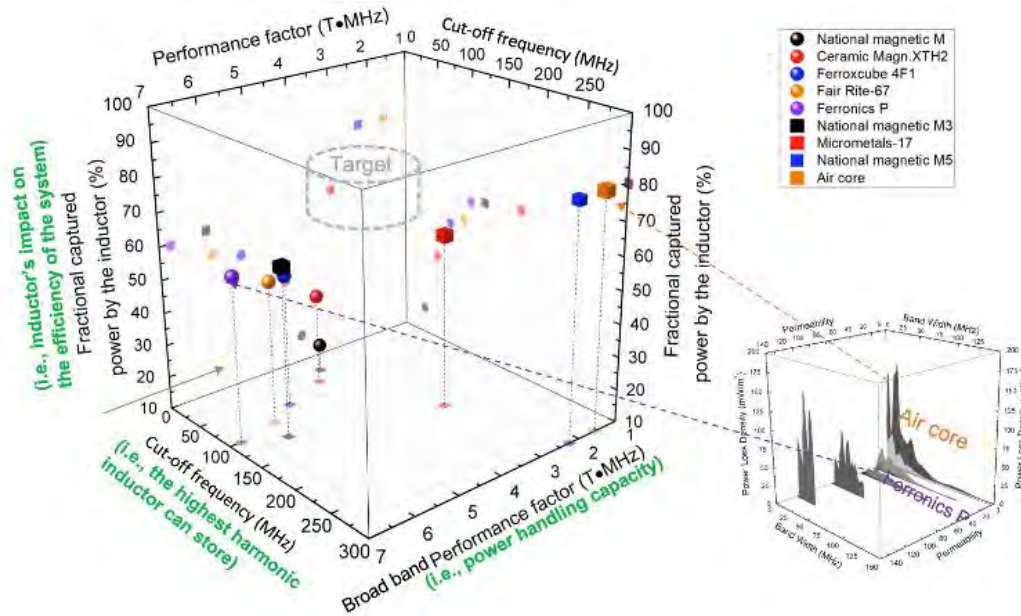


Figure 8. Comparison of COTS inductors' fractional captured power and performance factor as a function of cut-off frequency.

magnetic field in the frequency space, where it is the integrated broadband area defined by the maximum field under which the total core power loss density does not exceed the 500 mW/cc.

Figure 8 compares the performance of the same COTS products and the air core from which important trends were identified (see breakout box). A target region is plotted in the upper quadrant

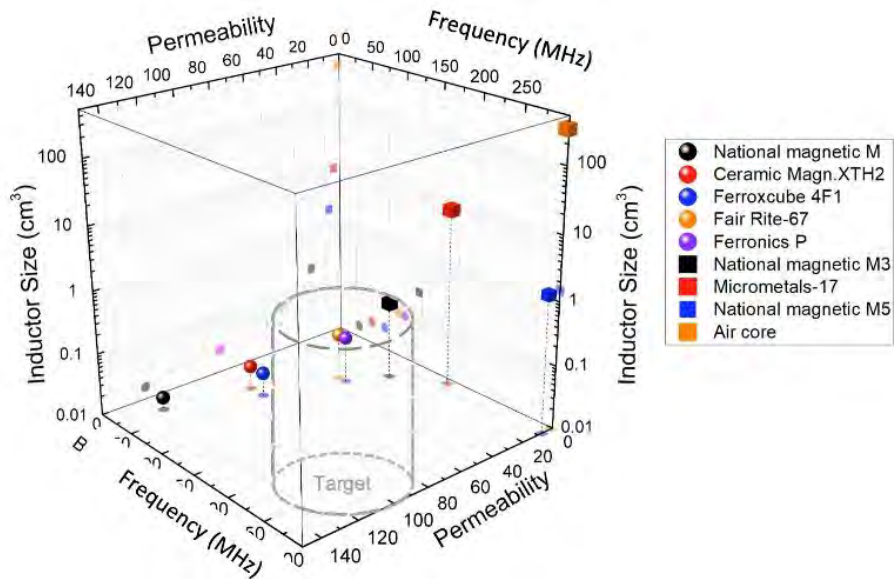


Figure 9. Comparison of COTS inductors' permeability, volumetric efficiency and cut-off frequency.

that corresponds to a high-performance factor, sufficient cut-off frequency and a high fractional captured power.

Figure 9 is the last of the three codependent three-dimensional plots presented in this section. This plot demonstrates a comparison of the volumetric efficiency of the COTS products and the air core under study versus the inductor cores' permeability and cut-off frequencies. As can be seen, as the permeability is reduced and approaches the value of the air core, the inductors' size becomes prohibitively voluminous. Consider that the inductor size axis is of a logarithmic scale, so the air core is 100 to 1000 times larger in comparison to the ferrite cores that have permeabilities of 40 to 100. A target region that corresponds to a high permeability > 40 , sufficient cut-off frequency > 250 MHz, and low inductor size is identified in the figure.

3. Findings and Conclusions

Upon completing this study, we have found that no COTS inductor materials, nor the air core, can satisfactorily address the needs of Navy HPPG systems in terms of power handling, efficiency, volumetric efficiency, and thermal rise. This undeniable conclusion calls for not only new materials but a new design paradigm for ultra-high frequency materials that capture 250 MHz or more of bandwidth (i.e., highest power harmonic that can be stored in the inductor). This should be considered an important challenge to the Navy's pulsed power community moving forward.

Principal findings:

- a. Based on simulations, an inductor core with a cut-off frequency of higher than 250 MHz is recommended for DSRD-based HPPG applications and would provide $> 94.3\%$ of the circuit's power capacity.
- b. The cut-off frequency and permeability/magnetization (inductor saturation current) experience an inverse relationship, consistent with the well-known trends observed in spinel ferrites and alloys (i.e., the Snoek's Relationship).
- c. The wider bandwidth (i.e., higher cut-off frequency) comes at the cost of lower permeability and magnetization, which translates to lower power handling capacity, higher loss factors and a compromise to SWAP+C² (size, weight and power plus cost and cooling design protocols). Whereas, samples with higher permeability have lower cut-off frequencies that curtail higher frequency power harmonics, and result in the widening of the pulse and suppression of pulse amplitude. This has also been discussed in our earlier reports.
- d. Temperature rise is presented as the uncompensated temperature increase of the inductor components. In some cases, the uncompensated temperature rise exceeds the degaussing temperature of the magnetic inductor core material indicating that it would obtain a permeability of unity (i.e., lose its magnetic character). The uncompensated temperature rise is merely a prediction of the generated heat by the inductor component that must be compensated with appropriate cooling techniques. It's important to consider the cooling expenses and associated impact of size and weight of such systems to the overall performance of the HPPG.
- e. The temperature rise escalates for higher inductance values. Specifically, for magnetic materials with lower permeability and for the air core, much higher temperature rise occurs for higher inductances due to topological adjustments such as increases in winding volume and its associated conduction losses.
- f. None of these materials support conditions required for the current state of HPPG operation, i.e., 250 MHz bandwidth, fractional captured power $> 85\%$, power loss < 500 mW/cc, a thermal rise < 100 °C.

4. Plans and Upcoming Events

Recommendations for Future Work:

The program was a 12-month investigative program that has been successfully concluded. Based on the findings, the author has firm ideas on improved inductor materials, morphologies and microstructures, that will lead to significant improvements in inductor performance specific to HPGG applications resulting in improved system efficiencies. These will be included in a 2022 white paper/proposal submitted upon request of the PM.

5. Transitions and Impacts

N/A

6. Collaborations

First Name: Joseph

Middle Name:

Last Name: Croman

Most senior project role: Collaborator

Role: Advised Team on unclassified DSRD-based circuitry important to Navy needs including sharing information on what inductor materials were previously tried and their impact upon system efficiency.

7. Personnel

Principal investigator: Vincent G. Harris, 0.1 person months, US citizen (National Academy, No)

Team: Research Assistant Professor: Parisa Andalib, 2.5 person months, Iranian citizen (H1B filed)

Research Associate (graduate student): Chengju Yu, 6 person months, Chinese citizen

Business Contact: Eva Pasadas, Director, Grants and Contracts, e.pasadas@northeastern.edu, 617-373-7269

Subs: N/A

8. Students

(1) Ph.D. graduate student (research associate)

9. Technology Transfer

N/A

10. Participants (redundant with Collaborations)

Agencies need to know who has worked on the project to gauge and report performance in promoting partnerships and collaborations. Information must be filled out for PI(s), Co-PI(s) and Participants in order to successfully complete and submit the report. Include information on students.

First Name: Joseph

Middle Name:

Last Name: Croman

Most senior project role: Collaborator

Role: Advised Team on DSRD-based circuitry most important to Navy needs (unclassified) including sharing information on what inductor materials were previously tried and their impact upon system efficiency.

11. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

N/A

Conference Papers

N/A

Books

N/A

Book Chapter

N/A

Theses

- a. Title: The role of interfaces in RF materials and devices
- b. Institution: Northeastern University
- c. Author: Chengju Yu
- d. Completion Date: Anticipated, May, 2022
- e. Acknowledgement of Federal Support? Yes

Websites

N/A

Patents

N/A

12. Point of Contact in Navy

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RF Coupling Revisited

Grant No. N00014 -17-1-2932

Annual Summary Report for Fiscal year 2021

Period of Performance: October 1, 2020 to August 31, 2021

Prepared by:

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Grant or Contract Number: N00014-17-1-2932

Date Prepared: 01/27/2022

Project Title: RF Coupling Re-visited

Annual Summary Report: FY2021

Principle Investigator: Anthony N. Caruso, 816-235-2505, carusoan@umkc.edu

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Section I: Project Summary

1. Overview of Project

Abstract:

The problem of undesirable RF coupling to wires and electronics has been receiving high interest for several decades. Coupling can be unintentional, originating from nearby radiators, especially in the rising congestion in the wireless spectrum, or due to the rising threat of High Power Microwave (HPM) weapons. In this work, we developed a combined experimental and modeling approach to quantify coupling to realistic wire systems and we also developed general guidelines to protect wires and electronic circuitry from unintentional and intentional interference.

Objective:

In this project, we developed rules-of-thumb guidelines to predict HPM source dependent effect coupling parameters, for arbitrary collections/geometries of wires/traces/wire-bonds, in a dielectric or metallic enclosure. We also applied such studies to unmanned aerial vehicles (UAVs) using a combined experimental, simulation and theoretical approach.

Most of the previously reported studies in RF effects/coupling focused on the prediction of the statistical coupling properties, which can be set up within arbitrary enclosures. Such efforts do not address the actual coupling to the electronics within these enclosures, which was the main focus of this work.

Introduction:

Electromagnetic weapons in the radio frequency range (700-MHz to 95-GHz) at on-target power densities that induce tenths- to ones-of-volts onto a printed circuit board trace, free wire, or other integrated circuit input (hereafter high-power microwaves or HPM) represent a single event effect (SEE) threat to microelectronics and their downstream applications. Since at least the mid-1960s through today, electronic warfare – and to a lesser extent HPM – testing has been a staple for what is now MIL STD 464C. Empirical testing has been, and will likely continue to be, used as there is no current ability to generate sufficient (i.e., simple, but mostly accurate) models. This effects testing has been employed against assets ranging from motor vehicles to desktop computers to unmanned aerial vehicles to smartphones to instrument landing systems. While with enough detail and empirical feedback data, some models have been developed, but the models are not generalizable. Of those models that seek to be generalizable, they are too complicated to set up, inaccurate and/or ill-pragmatic. A new approach, which stands on the shoulders of this previous work, but harnesses the utility/power of new capabilities, is needed. To meet this demand, in this work, we developed a deeper understanding of how HPM couple to wires, traces, chasses,

integrated circuits, and/or their enclosures, as a function of the source properties. Using this deeper understanding, we developed a hybrid simulation/experimental approach that (a) mapped or predicted the three-dimensional layouts of complex electrical structures (e.g., wiring harness and multilayer printed circuit boards); (b) automatically transferred the physical maps into simulations; (c) ran multi-source-parameter permutations to explore different incident waveforms; and (d) validated the simulations through automated empirical measurements. RF coupling guidelines were then developed and potential Future Work outlined.

Background:

One of the main techniques for predicting interference in metallic enclosures is the Random Coupling Model (RCM). The RCM addresses enclosures or cavities that are much larger than the wavelength of concern. Under this condition, the wave propagation inside the cavity is chaotic, meaning that any small change in the cavity or its components will lead to profoundly different outcomes. Based on the properties of the enclosure or cavity, such as its quality factor, statistical information about the voltages generated at the ports can be induced. In RCM, the ports can represent apertures in the enclosures or the input ports of devices and electronic circuitry inside the enclosure. Therefore, RCM aims to quantify the statistics of the interactions between the enclosures and its constituents. There are a number of other models (e.g., Dynamical Energy Analysis) and their predecessors that are important and form the basis for the work proposed here. We refer the reader to an exhaustive compilation of these works if greater background is desired (<http://anlge.umd.edu/RCM/>) as it is important that we shift gears to describe the background of the new effort proposed here.

The main goal of this work was to develop a joint computational/experimental approach to predict, quantify, and prove the coupling of microwaves to any arbitrary collection/geometry of wires/traces/wire-bonds in different surroundings. The computational approach developed is based on the Characteristic Mode Analysis (CMA) and the Equivalent Circuit Approach (ECA).

If a scatterer is excited by an incident plane wave, currents are excited on its surface based on its conductivity. The CMA decomposes this excited current on the scatterer in terms of a set of fundamental modes [1]. These fundamental modes are independent of the excitation and they only depend on the shape, size, material, and the environment of the scatterer. Moreover, CMA provides the Modal Significance (MS_n) spectrum and the radiation characteristics of each mode. The MS_n spectrum quantifies the importance of each mode at every frequency. The radiation characteristics of each mode identify the optimum directions to excite the mode of interest. Therefore, the knowledge of the MS_n and the radiation characteristics of the modes allows the prediction of the optimum frequencies and incident directions to maximize the coupling and interference to a Devices Under Test (DUT).

The ECA approach is based on the fact that any antenna in the receiving mode, or in our case a wiring system through which back-door RF coupling can occur, can be replaced by the classical Thévenin circuit shown in Fig. 1 [2]-[5]. The Thévenin equivalent circuit involves two main components defined at the receiving port of the antenna or the wiring system: (i) the open-circuit voltage, V_{oc} , and (ii) the input impedance Z_{in} [2]. The input impedance Z_{in} is typically replaced by an equivalent circuit as shown in Fig. 2. For typical antennas, the equivalent circuit consists of a series of parallel RLC circuits. Typically, one RLC circuit is needed for each resonance in the frequency band of interest. The V_{oc} can be calculated by simulating the receiving antenna or the wiring system terminated with a very large load, ideally infinite. If a frequency-domain solver is used, the time domain V_{oc} can be easily achieved via an inverse Fourier Transform.

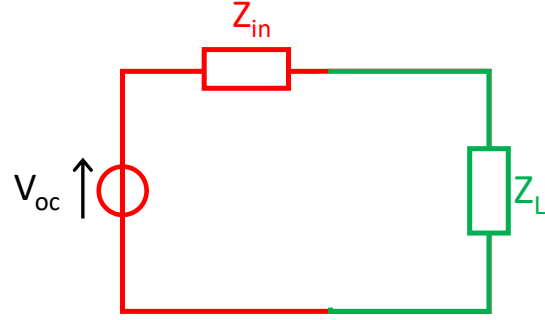


Fig. 1: Thévenin equivalent circuit of coupling to a wire system [3]-[5].

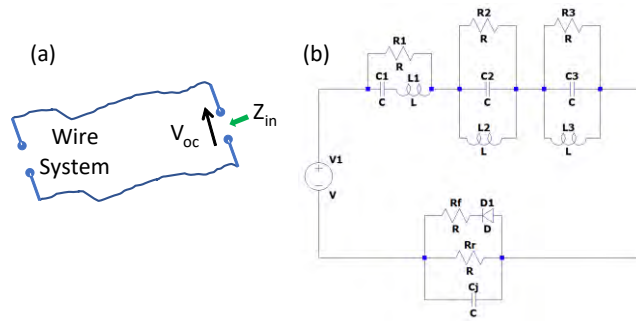


Fig. 2: (a) Dipole-like wire system and (b) the circuit that emulates its input impedance [3]-[5].

The advantages of the equivalent circuit approach in Fig. 1 and Fig. 2 are:

1. It provides physical insight into the response of the wiring system. For example, if the equivalent circuit of a wiring system contains larger capacitance values, then it will quickly discharge the currents and voltages generated by a short pulse high power electronic microwave (HPEM) excitation preventing the buildup of energy in the nonlinear devices.
2. The above approach involves performing one full-wave simulation to calculate the V_{oc} and Z_{in} of the wiring system. After that, we can use much faster circuit simulations to simulate RF coupling to hundreds of possible nonlinear loads that can be connected to the wiring system. These simulations will be much faster when performed using a circuits solver such as LTSPICE than if they were performed using a full-wave solver. Also, this will allow us to simulate, in a feasible computational time, practical electronics and microcontrollers with tens of components.
3. The equivalent circuit approach allows the simulation of excitation of long duration that is infeasible to accomplish using full-wave solvers that enforce a small-time step.

In this work, we will use a novel approach that hybridizes the CMA and the ECA to predict RF coupling to wiring systems with nonlinear loads in realistic environments. All modeling and computational predictions are validated with unique experimental coupling measurements inside a Gigahertz Transverse Electromagnetic (GTEM) cell.

Activities and Accomplishments

2. Activities and Accomplishments

Equivalent Circuit Approach (ECA) Prediction of Coupling to a Wiring System

Consider the configuration in Fig. 3 to test the voltage buildup across a nonlinear electronic component connected to a wire/trace system. The same configuration was studied computationally using FEKO full-wave simulations and the Equivalent Circuit Approach (ECA). We highlight the predictive capability of the ECA to identify the optimum incident waveform to create the desired effect on the nonlinear electronic component of interest. The configuration consists of a square trace printed on an FR4 substrate connecting a 1 M Ω resistor and an RB886CST2R Schottky diode in Fig. 3a similar to [3]. The thickness of the FR4 substrate was 1.7 mm, and its dielectric substrate had a relative dielectric permittivity $\epsilon_r = 4.8$ and a loss tangent of 0.017. The square trace measures 10.5 cm by 10.5 cm, and the thickness of the trace was 1 mm. We can predict the waveform properties that will require the least amount of incident power to maximize the coupling to the diode. The steps of the ECA predictive capabilities are:

1- Remove the diode from the circuit in Fig. 3a and calculate the input impedance seen at the port where the diode is to be connected. The input impedance, Z_{in} , should be calculated over the frequency bandwidth of interest using a full-wave electromagnetic solver. Fig. 3b shows the input impedance of the system in Fig. 3a calculated using the full-wave solver FEKO [6].

2- Represent the input impedance calculated in (1) with an equivalent circuit composed of a series of RLC networks. One RLC series is needed for every resonance in the input impedance, Z_{in} , over the frequency range of interest. As the frequency range of interest increases, additional RLC or different circuit representations needs to be added. But it is important to emphasize that this step is not an approximation. No loss in accuracy will be experienced as long as sufficient circuit elements are used to match the input impedance, Z_{in} , obtained from the full-wave solver. Fig. 3c shows the

equivalent circuit and Fig. 3b shows the close agreement achieved between the impedance calculated from the full-wave solver and the input impedance calculated from the equivalent RLC circuit.

3- Use the full-wave electromagnetic solver to calculate the open-circuit voltage at the port where the diode is to be connected versus frequency. This open-circuit voltage will be calculated due to a waveform at a particular incident direction. The open-circuit voltage due to different incident directions can be efficiently calculated using the Characteristic Mode Analysis [1]. Fig. 3d shows the open-circuit voltage versus frequency for the system in Fig. 3a, and it shows that not all frequencies couple equally to the trace system.

4- The voltage across the electronic component, the RB886CST2R Schottky diode, can be expressed using the circuit voltage divider as $(V_{oc}Z_L)/(Z_L+Z_{in})$, which can be readily calculated using a SPICE solver since it is affected by the electronic component, in this example, the diode. Fig. 3e shows this factor which acts as the transfer function from the incident wave to the diode.

5- The transfer function obtained from step 4 shown in Fig. 3e, provides a plethora of physical insight into the coupling problem. The resonance frequencies in Fig. 3e are the ideal frequencies to couple energy into the electronic component, which is the diode. The main resonance is achieved at 0.477 GHz. Therefore, exciting the system with a pulse centered around this frequency will couple more than any other pulse centered around a different frequency. Fig. 4 shows two different incident waveforms, each a Gaussian Sinusoidal pulse. The

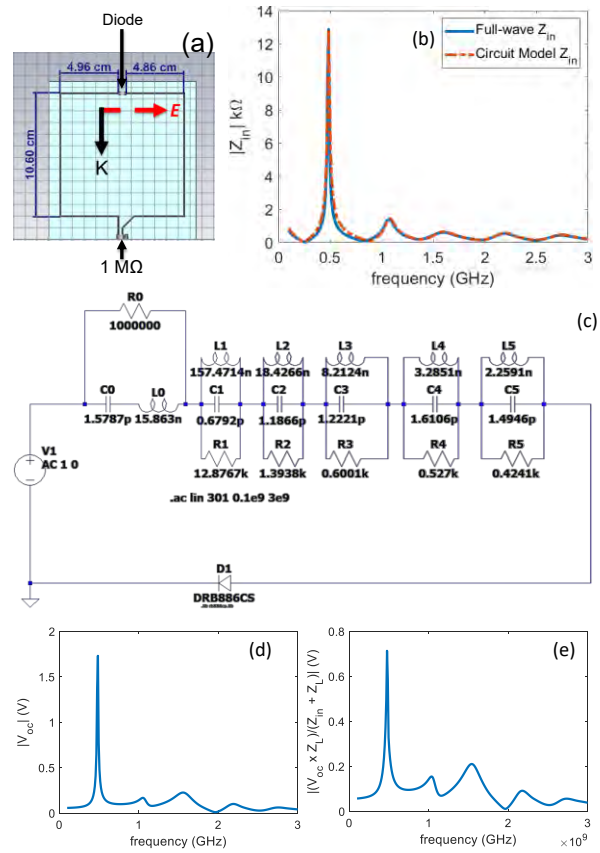


Fig. 3. A representation of the ECA approach to highlight its predictive capabilities (a) An example electronic system showing a square trace connecting a diode and a 1 MΩ load, (b) the simulated Z_{in} at the diode port, (c) the RLC equivalent circuit, (d) the frequency domain open circuit voltage V_{oc} , (e) the transfer function representing the frequency domain coupled voltage to the diode.

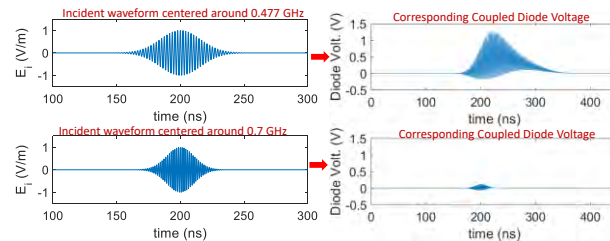


Fig. 4. A comparison between the voltage coupled to the diode in Fig. 2 due to two different Gaussian Sinusoidal pulses centered around 0.477 GHz and 0.7 GHz.

first pulse is centered around 0.477 GHz, and the second pulse is centered around 0.7 GHz. Both pulses had the same amplitude of 1 V/m and a bandwidth of 5%. Fig. 4 shows the coupled voltage across the diode due to the two different incident waveforms and clearly confirms the ECA predictions that the 0.477 GHz Gaussian sinusoidal pulse will maximize coupling. The maximum voltage coupled to the diode for the 0.477 GHz Gaussian sinusoidal pulse was 1.26 V, whereas it was 0.118 V for the 0.7 GHz Gaussian sinusoidal pulse. For the 0.7 GHz, to induce the same maximum voltage on the diode, its incident power needs to be increased by at least 20 dB. Therefore, the previous example shows that the ECA can reduce the power required to create the desired disruptive effect on the diode by at least 20 dB just by identifying the optimum frequency.

The ECA can also predict the minimum Pulse Repetition Frequency (PRF) of the incident waveform to create the desired effect. In between pulses, the voltage buildup across the diode discharges. The ECA can help predict how fast the diode discharge will be, i.e, the time constant of the discharge process, such that we can make sure that the next pulse will arrive soon enough before the voltage across the diode drops significantly. That is, by knowing the discharge time constant of the diode, τ , we can predict the minimum PRF to cause the voltage buildup across the diode to continue to increase.

In between pulses, the incident field drops to zero, and therefore, we can remove the voltage source in Fig. 3c [7]. All the inductors in Fig. 3c can also be replaced with a short circuit during the discharge phase [7]. Therefore, the equivalent circuit can be reduced into the 4 components shown in Fig. 5. The C_j and R_r components represent the junction capacitance and the reverse resistance of the diode, respectively. The C_0 and R_0 components are exactly the same as the ones in Fig. 3c and they physically represent the DC or the low-frequency limit of the resistance and capacitance of the square trace to which the diode is connected. Therefore, C_0 and R_0 can easily be measured or calculated for a complex wire system using low-frequency techniques. The reduced equivalent

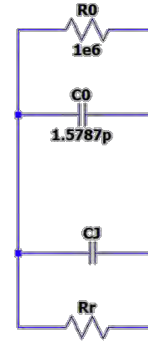


Fig. 5. Reduced equivalent circuit to represent the diode discharge in-between pulses.

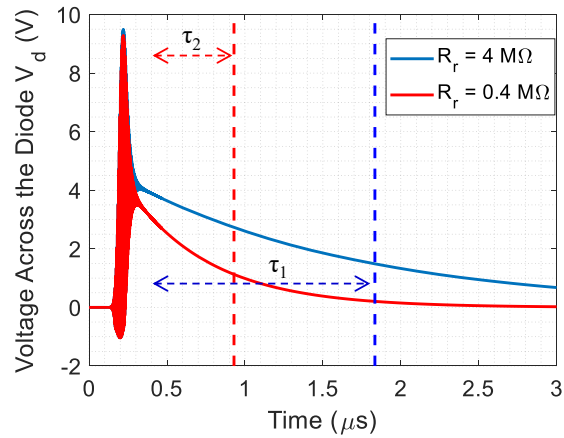


Fig. 6. Coupled voltage to the diode in Fig. 1 after one incident pulse to highlight its discharge time constant for two different reverse resistance, R_r , values.

circuit in Fig. 5 is much simpler than the one in Fig. 3c and yet completely quantifies the discharge of the diode. For example, the time constant of the discharge τ can be expressed using the following simple expression [7]:

$$\tau = (C_0 + C_J) \left(\frac{R_r R_0}{R_r + R_0} \right) \quad (1)$$

To clarify this predictive capability, we repeated the simulation in Fig. 3 but we boosted the amplitude of the pulse to 10 V/m to clarify the discharge process. Fig. 6 shows the discharge of the diode after one pulse for two different values for the reverse resistance of the diode $R_r = 4 \text{ M}\Omega$ and $R_r = 0.4 \text{ M}\Omega$. For both cases, a diode junction capacitance $C_J = 0.28 \text{ pF}$ was used. As expected, the diode discharges slower for the larger R_r value since it leads to a larger time constant according to Equation 1. We measured the time constant from the simulations highlighted in Fig. 6 and found that for $R_r = 4 \text{ M}\Omega$, $\tau_1 = 1.45 \text{ }\mu\text{s}$, and that for $R_r = 0.4 \text{ M}\Omega$, $\tau_2 = 0.53 \text{ }\mu\text{s}$, in perfect agreement with the values achieved from Equation (1) above. To ensure that the voltage across the diode builds up with every consecutive pulse, the PRF needs to obey the following relation:

$$PRF > \frac{1}{\tau} > \frac{1}{R_r R_0} \left(\frac{R_r + R_0}{C_0 + C_J} \right) \quad (2)$$

In summary, the minimum PRF that maximizes the probability of effect by ensuring that the voltage across the diode builds up with every consecutive pulse can be predicted using the ECA as follows:

- 1- Identify the junction capacitance and reverse resistance of the diode, C_J and R_r , by direct measurements or from the diode's datasheet
- 2- Measure, simulate, or calculate the equivalent resistance, R_0 , and capacitance, C_0 , of the wiring system connected to the diode at the low-frequency limit.
- 3- Set the minimum PRF according to (2).

Experimental Validations of the ECA Predictions

We developed the experimental setup in Fig. 7 to test the voltage buildup across the configuration in Fig. 3 that was studied computationally using the Equivalent Circuit Approach (ECA). The goal is to correlate the voltage buildup with any effects caused by the incident pulsed waveforms on the diode. The diode was soldered to a square wire loop at one end, and the other end of the wire loop was attached via a coaxial cable to an oscilloscope. The oscilloscope's input impedance was varied to create different effective impedances, through the coaxial cable, to the wire loop. The GTEM was excited by a waveform generator followed by an amplifier to boost the incident field to the desired level. In the experiments below, the waveform generator was programmed to generate a Gaussian Sinusoidal pulse centered around 777 MHz with a 10% bandwidth. We varied the electric field amplitude over a range that varied from 100 V/m to 1600 V/m and the Pulse Repetition Frequency (PRF) from 1 kHz to 2.5 MHz. This exhaustive parameter scan aims to identify the

waveform properties that will cause an effect on the diode, i.e. change its operating status, and correlate the effect and parameters with the voltage buildup across the diode.

Fig. 8a and Fig. 8b show the coupled voltage across the oscilloscope load, set to $1\text{ M}\Omega$, at incident electric fields of amplitudes 800 V/m and 1600 V/m , respectively. The PRF was varied from 1 kHz to 100 kHz for both incident field levels in Fig. 8. Increasing the PRF was found to increase the voltage buildup as expected. For example, PRF below 10 kHz caused insignificant voltage buildup. Once the PRF reached 50 kHz , significant voltage buildup was achieved for both incident field levels in Fig. 8. In Fig. 8a, the voltage buildup reached 5 V after $900\text{ }\mu\text{s}$ at a PRF of 50 kHz , whereas the voltage buildup reached 8.5 V after $900\text{ }\mu\text{s}$ at a PRF of 100 kHz . Of equal importance, the oscillations or “spikes” around the steady state voltage buildup increased with the PRF. In Fig. 8b, the incident field was increased to 1600 V/m and the voltage buildup reached 7.5 V after $900\text{ }\mu\text{s}$ at a PRF of 50 kHz (the dark green curve in Fig. 8b). When we increased the PRF to 100 kHz , the steady-state voltage buildup decreased to 2.5 V and did not increase as we expected (the light-green

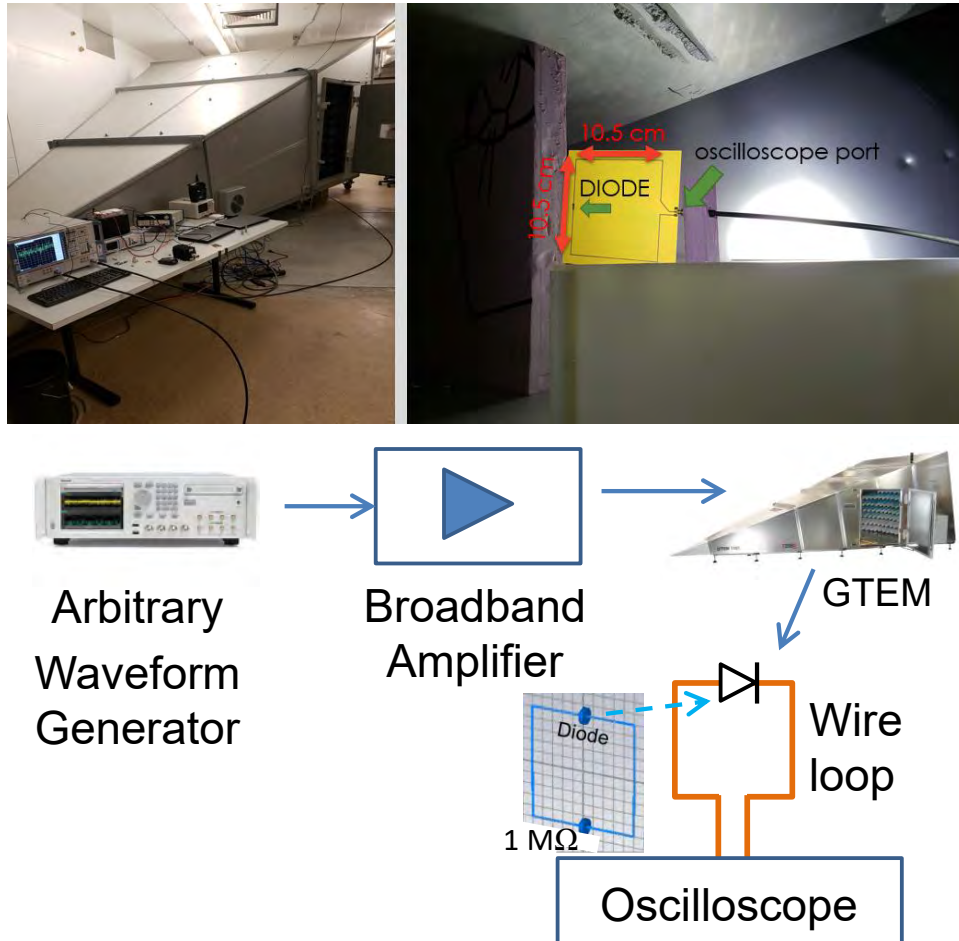


Fig. 7: Experimental setup to measure the voltage buildup across a diode connected to a $10.5\text{ cm} \times 10.5\text{ cm}$ square wire loop due to a Gaussian Sinusoidal pulse excitation.

curve in Fig. 8b). Upon investigating the diode, we found out that it was damaged. To validate that the diode's operation status was changed, we repeated the measurement with the same trace/diode configuration, but we decreased the PRF back to 50 kHz (the yellow curve in Fig. 8b). Clearly, the dark green and the yellow curves in Fig. 8b are different even though they were recorded at the same incident field level and the same PRF, indicating that the diode's operation status was changed between the 2 measurements. Therefore, in conclusion, a PRF of 100 kHz and an incident field level of 1600 V/m were capable of changing the diode's operation status when it was connected to the square trace in Fig. 7. However, the steps employed in varying the incident field level and the PRF were coarse.

The experimental measurements were limited in the sense that we cannot measure the voltage directly across the diode and could only measure the voltage across the 1 M Ω opposite to the diode. Therefore, we used simulations to investigate the voltages and currents at different components/locations, especially across the diode. The experimental measurements in Fig. 8 show that the voltage and currents reached steady-state only beyond 800 μ s. However, a time-domain full-wave solver might take a few days to reach the saturation response for a nanosecond's excitation pulse. Moreover, to perform parametric studies to quantify the effect of different waveforms properties and the effect of various parasitic, the simulations need to be repeated multiple times, requiring a huge computational time in the order of weeks and maybe longer. However, the ECA can perform such simulations in minutes without any accuracy loss. Therefore, another advantage of the ECA is that it allows the simulation of systems and incident waveforms with relatively long Times To Effects (TTE).

We have automated the data collection of RF coupling using the experimental setup in Fig. 7. That is, to verify the ECA predictions for a particular configuration, we can now automatically expose it to hundreds of different pulses of different PRF, center frequency, pulse width whilst keeping the power per waveform constant. So far, the experimental setup can only measure the voltage across

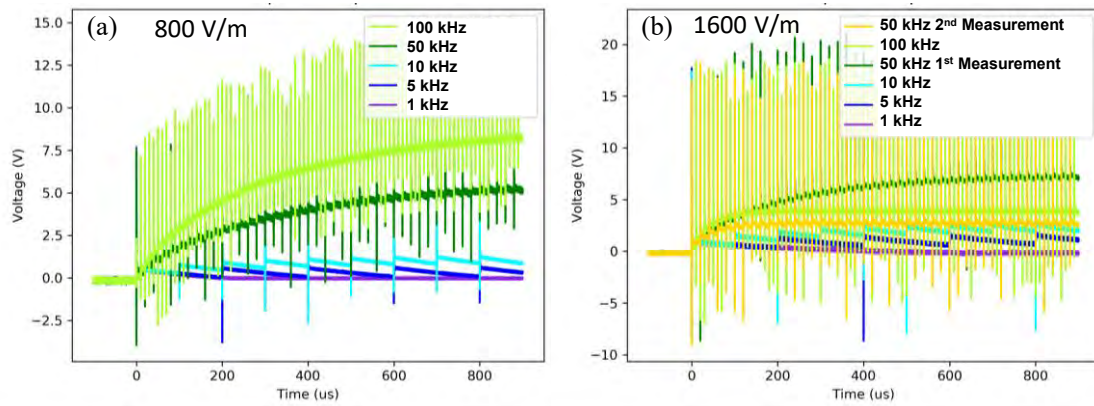


Fig. 8: Experimentally measured voltage buildup across a diode connected to a 10.5 cm $\times$ 10.5 cm square wire loop due to a Gaussian Sinusoidal pulse excitation at different PRF and different peak amplitudes.

the 1 M Ω load and not the diode. However, the voltage across the diode and the 1 M Ω load are correlated. Examples of the test points collected from the automated data collection are shown in Fig. 9 from the same diode/trace configuration.

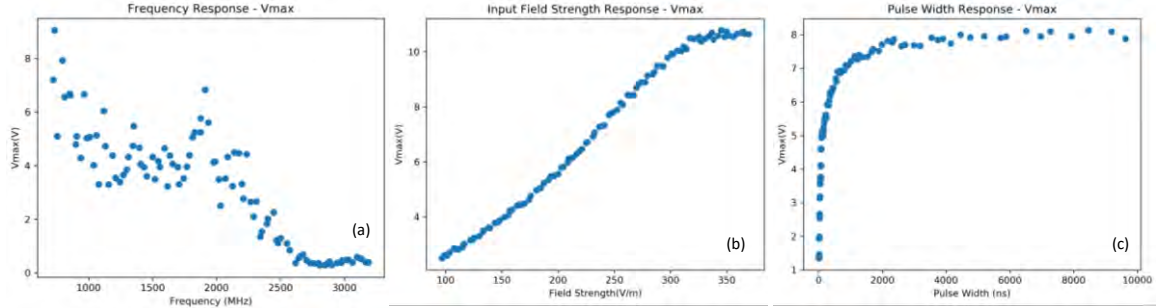


Fig. 9: Experimental RF coupling measurements from the diode trace configuration in Fig. 7 due to different incident waveforms. (a) the coupled maximum voltage versus the center frequency of the incident pulse, (b) the coupled maximum voltage versus the field strength of the incident pulse, (c) the coupled maximum voltage versus the pulse width of the incident pulse. All pulses in the previous 3 subplots had the same power.

Extending the Equivalent Circuit Approach to a Complex Wiring System: An Unmanned Aerial Vehicle (UAV) Case Study

Sadraey *et al.* classified UAVs according to their sizes, where the size is defined as the longest dimension of the UAV [8]. For quadcopters, the size of the UAV is measured from the opposite corner motors. In this work, we studied a quadcopter 54 cm in size. We created a full-wave model of the complete UAV system with all the wires and IC components to use as a numerical platform for studying the RF coupling to the system. The MakerBot Digitizer Desktop 3D scanner was used to scan the Commercial off-the-Shelf (COTS) quadcopter shown in Fig. 10. It uses laser scanning technology to scan the object. Using the MakerBot Digitizer scanner, we developed an accurate representation of the quadcopter, as illustrated in Fig. 10b.

The effect of the frame is negligible since it is composed of a low permittivity dielectric. Thus, we removed the frame and retained the same wire distribution as shown in Fig. 10c and Fig. 10d, which

show two different views of the UAV wiring system. In Fig. 10c and Fig. 10d, the wires' lengths and diameters match the values in the actual scanned UAV, and all the IC components are represented by blue ports to which an arbitrary impedance can be assigned. Twenty-four loads were connected to the wiring system to act as a rough representation of the various UAV devices. Four loads are added at the center of the UAV to represent the input impedance between the pins and the rectangular ground plane of the controller. The controller generates at these four pins the signal that controls the speed of the four motors. The rectangular ground plane is assumed to be $85 \text{ mm} \times 48.5 \text{ mm}$. Without loss of generality, we select the load under test (LUT) to be one of the four loads at the controller, as shown in Fig. 10c. However, the LUT can be varied to be any of the twenty-four loads in the system. Additional loads can be added to the wiring system to better approximate the actual UAV devices. However, the system in Fig. 10 represents a compromise between simplicity and accuracy in representing the UAV. The electromagnetic compatibility of the proposed model will be examined using the ECA in the following subsections.

As shown in Fig. 1, the input impedance, Z_{in} , is a vital parameter in calculating the coupling to the LUT. Therefore, the accuracy of the circuit representation of the input impedance is an important factor to be considered. The input impedance can be represented by different circuit topologies. In this work, we studied two circuit topologies for the input impedance representation. The two representations are categorized as (i) *Circuit 1*: In

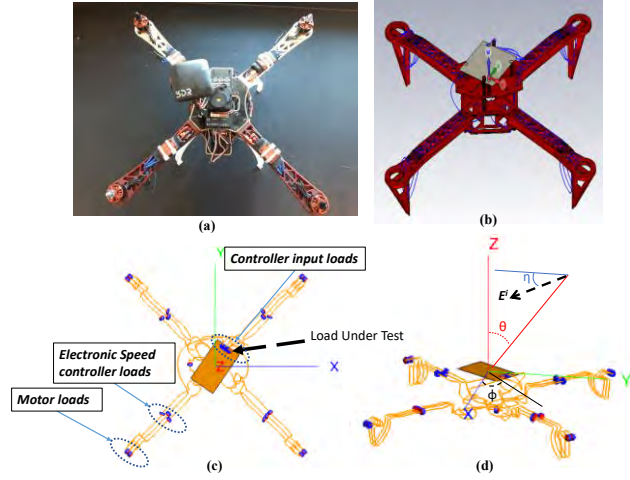


Fig. 10: (a) UAV picture, (b) UAV quadcopter wiring diagram above a dielectric frame, (c) The top view of the proposed model of the UAV wiring system in (a) and (b), (d) side view of the proposed model of the UAV wiring system showing the UAV model orientation with respect to the angles θ , ϕ , and η .

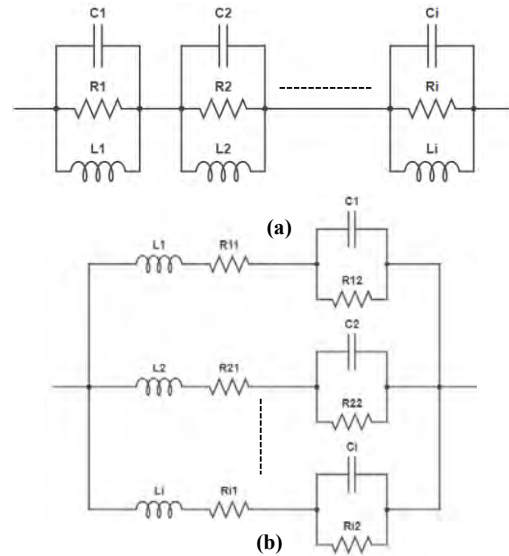


Fig. 11: RLC circuit representation of Z_{in} at the load of interest (a) Circuit 1 (b) Circuit 2.

this circuit representation, each parallel RLC branch of the network shown in Fig. 11a is developed to represent a single resonance of the input impedance of the system [7] (ii) *Circuit 2*: In this circuit representation, the input impedance is modeled as a summation of N arbitrarily weighted poles. Poles typically exist in conjugate pairs. Each pair can be represented by a Second Series-Equivalent-Circuit (SSEC) branch consisting of an inductor, a capacitor, and two resistors connected Fig. 11b [9].

The differences between the two circuit topologies are illustrated as follow:

- (i) Circuit 1: the RLC components' values can be calculated from the input impedance of the system by solving the following two equations [7].

$$B.W_i = \frac{1}{2\pi R_i C_i} \quad (3)$$

$$f_{r_i} = \frac{1}{\sqrt{L_i C_i}} \quad (4)$$

where f_{r_i} is the resonance frequency of the i^{th} peak of the input impedance response, $B.W_i$ is the bandwidth of the i^{th} peak of the input impedance response, R_i is the peak value of the input impedance at the i^{th} resonance. By solving (3) and (4), the corresponding RLC values of the entire input impedance response can be calculated. Next, the parallel RLC branches can be connected in series, as illustrated in Fig. 11a, to form the overall input impedance representation of the system.

- (ii) Circuit 2: Antonini *et al.* illustrated that the rational function $F(s)$ of any given response could be written as follows [10]:

$$F(s) = \sum_{i=1}^N \frac{r_i}{s + p_i} \quad (5)$$

where N is the number of poles, $s = j\omega$ is the complex frequency, r_i and p_i are the residues and poles, respectively. The parameters r_i and p_i can be estimated using the vector fitting technique detailed in [9]-[10]. The values of R_{i1} , R_{i2} , L_i , and C_i in Fig. 11b can be calculated using the values of r_i and p_i as described in detail in [10]. It is worth mentioning that this method might generate negative impedance values, which can be replaced by an equivalent positive impedance and a parallel current-dependent-current-source (CDCS). That is, Circuit 2 is, in general, more complex than the Circuit 1 representation. However, unlike the representation in Circuit 1, the value of N can be smaller or larger than the number of Z_{in} peaks in the frequency range of interest. Moreover,

N can be increased progressively to achieve the desired level of agreement between the Z_{in} calculated using the full wave solver and the Z_{in} calculated using the Circuit 2 representation in Fig. 11b.

For the UAV wiring system shown in Fig. 10, Fig. 12a and Fig. 12b show the magnitude and phase, respectively, of Z_{in} at the port of the LUT. Fig. 12a and Fig. 12b show a comparison between the magnitude and phase of Z_{in} calculated using the Full-wave solver, FEKO [6], and the corresponding values calculated using the two different equivalent circuit representations in Fig. 11. Since there are six peaks in the response shown in Fig. 12a, the Circuit 1 representation will consist of six RLC network branches to represent the full-wave input impedance of the UAV model. For a fair comparison in terms of circuit complexity, we also used 6 branches for the Circuit 2 representation in Fig. 12a and Fig. 12b. Figure 12a illustrates that Circuit 1 agrees better with the full-wave Z_{in} at low frequencies than Circuit 2. For example, at the first resonance 0.15 GHz, the relative differences between the magnitude of the full-wave Z_{in} compared to the Circuit 1 and Circuit 2 representations are 1.4 % and 74.4 %, respectively. Moreover, at the intermediate frequency range, between 0.3 to 0.6 GHz, Circuit 2 missed two consecutive peaks while Circuit 1 response perfectly matched the full-wave Z_{in} . Contrastingly, at the high-frequency range > 0.6 GHz, Circuit 2 provides a better match to the full-wave response.

Since the Circuit 2 representation is based on the fitting technique, the value of N and the number of branches can be increased to improve the Z_{in} representation. Increasing N increases the complexity of the SPICE simulations, but it is still orders of magnitude faster than the full-wave solvers. Figure 12c and 12d show the comparison between the magnitude and phase of Z_{in} calculated using FEKO, and Circuit 2 when using four RLC branches/resonance, i.e., a total of $6 \times 4 = 24$ circuit branches connected as shown in Fig. 11b. The response of the improved circuit representation of Circuit 2 perfectly matches the full-wave Z_{in} . In summary, when the same number of branches are used, Circuit 1 can be better than the Circuit 2 representation up to a certain

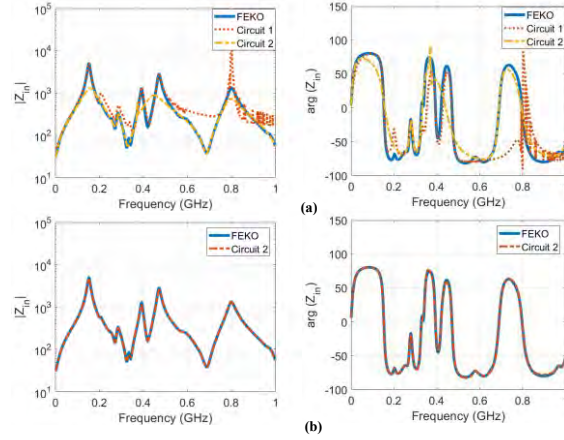


Fig. 12: Comparison between the magnitude and phase of Z_{in} calculated using FEKO, Circuit 1, and Circuit 2 when using: (a) single RLC branch/ resonance, (b) 4 RLC branches/ resonance.

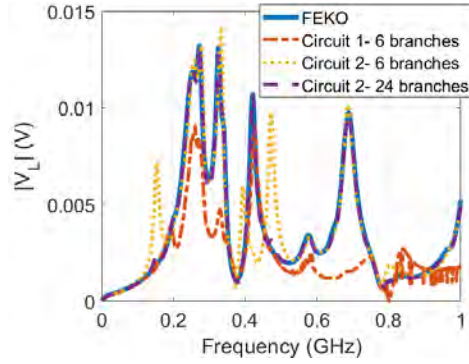


Fig. 13: The induced load voltage across the LUT calculated using different circuit topologies.

maximum frequency value, e.g., 0.6 GHz in Fig. 12. However, the Circuit 2 representation is much better than the Circuit 1 representation in agreeing with Z_{in} , especially when the number of circuit branches is increased.

An accurate representation of Z_{in} is required to ensure better accuracy in calculating the coupled voltage to the LUT. For example, we set all the loads of the UAV wire system to be $10\ \Omega$. The UAV is, then, excited by a 1 V/m plane wave excitation. The excitation angle of incidence is chosen to be $\theta = 45^\circ$ and $\phi = 45^\circ$, and the polarization angle is chosen to be $\eta = 45^\circ$. Figure 13 shows the load voltage at the LUT calculated using the two-circuit representation according to (1). Figure 13 illustrates that V_L calculated using the Circuit 2 representation with 24 branches provides perfect agreement with the full-wave V_L . On the other hand, using Circuit 2 representation with 6 branches provides the worst representation of the full-wave Z_{in} leading to the worst estimation of V_L . Hence, an accurate representation of Z_{in} of the system is essential. However, the ECA evoked in this work indicates that both the input impedance and the open-circuit voltage are important in estimating the electromagnetic compatibility of the UAV. In the next section, the effect of the open-circuit voltage V_{oc} is discussed in detail.

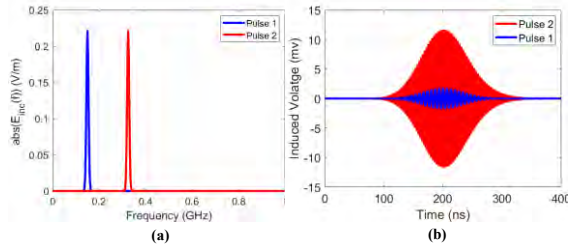


Fig. 14: (a) The frequency domain of the gaussian pulse excitation resonates two different resonance frequencies. (b) the corresponding time domain load voltage due to the gaussian excitation in (a)

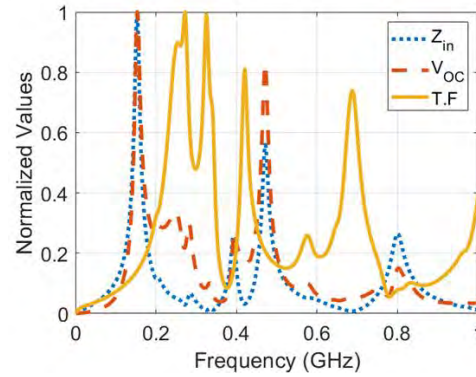


Fig. 15: The normalized values of the open circuit voltage, the input admittance, and the ratio between the two (TF).

This section expands the study to show that the open-circuit voltage plays a significant role in estimating the coupling to the system. To highlight this role, we set all the loads of the UAV wire system to be $10\ \Omega$, and we varied the center frequency of the incident pulsed excitations. That is, all the blue dots in Fig. 10 are set to be $10\ \Omega$. Figure 14 shows the comparison between the time-domain load voltage for a Gaussian excitation with two different center frequencies 0.15 GHz, the first peak of V_{oc} and Z_{in} , and 0.35 GHz. The two Gaussian pulses have the same peak amplitude, 1 V/m, and the same bandwidth of 10 MHz. The excitation angle of incidence is chosen to be $\theta = 45^\circ$ and $\phi = 45^\circ$, and the polarization angle is chosen to be $\eta = 45^\circ$. The magnitude of the induced voltage at the load under test is higher when the Gaussian pulse excitation is centered around 0.35 GHz and not 0.15 GHz. That is, the maximum coupling does not occur at the maximum of V_{oc} or

Z_{in} , but it occurs at the maximum of the voltage-divider Transfer Function, $TF = V_{oc}Z_L/(Z_L+Z_{in})$. Figure 15 shows the normalized Z_{in} , V_{oc} , and the TF. Clearly, the maxima of the TF do not necessarily correspond to the maxima of V_{oc} or Z_{in} , indicating the importance of calculating the TF to predict the critical frequencies that maximize the coupled voltage to a LUT.

As illustrated in the previous section, ECA is an efficient approach to predict the frequencies where the coupling to a load of interest will be high/low based on its TF. However, the load values may also significantly impact the ECA components: Z_{in} , V_{oc} , and TF. Therefore, in this section, we will study the effect of different loads on predicting the frequency ranges of high/low coupling to a particular load of interest. Table I summarizes the load variations

Case	Controller Input Load	All the Other Loads
1	10	10
2	10	2500
3	2500	10
4	2500	2500

in the studied cases. To increase the load variability, the loads were divided into 2 categories: (i) Loads at the input of the controller and (ii) all other loads. In all studied cases, the LUT is fixed to 10 Ω , whereas all other loads are changed as described in Table I. Figure 16a shows the input impedance of the system for the four studied cases. Clearly, the input impedance is sensitive to the load selection. For example, comparing the response of Case 1 with Case 2 shows that the resonance frequencies are quite different because in Case 2 the high load impedances act as open circuits, which shorten the electrical length of the system. However, comparing Case 1 and Case 3 shows no variations in the resonance frequencies but rather on the magnitude of the input impedance. Therefore, the loads representing the UAV devices play an important role in the coupling problem.

Similarly, the load selection can affect the V_{oc} across the LUT. To test the effect of the load selection on V_{oc} , the UAV is excited by a 1 V/m plane wave. The excitation angle of incidence is chosen to be $\theta = 45^\circ$ and $\phi = 45^\circ$, and the polarization angle is chosen to be $\eta = 45^\circ$. Figure 16b shows the V_{oc} of the system for the four studied cases. Clearly, the V_{oc} is also sensitive to the loads. It is worth mentioning that V_{oc} depends on the excitation angle. That is, changing the direction of the incident wave or the polarization will vary V_{oc} . However, Z_{in} is completely independent on the excitation.

Similar to the analysis in the previous section, the TF for all 4 studied cases is calculated. Again, the TF for the 4 studied cases confirms our observation that, for complex wire systems and load distributions, the TF response does not necessarily show the same peaks as the V_{oc} or Z_{in} , and therefore, the TF needs to be explicitly calculated. For example, in Case 1 and Case 3, Z_{in} in Fig. 16a and V_{oc} in Fig. 16b peak at 0.15 GHz, but the TF does not. On the other hand, at 0.7 GHz the

magnitudes of both Z_{in} in Fig. 16a and V_{oc} in Fig. 16b are minimum. However, the TFs of both cases show peaks at this frequency, as shown in Fig. 16c. Similarly, The TF for Case 2 and Case 4 peaks at 0.9 GHz while the magnitudes of both Z_{in} in Fig. 16a and V_{oc} in Fig. 16b are minimum.

An interesting feature of the input impedance response of the 4 Cases is the low magnitudes at the frequency range between 0.2 and 0.4 GHz. For low values of Z_{load} , the TF can be simplified to: $T.F \approx \frac{V_{oc}}{Z_{in}}$. Hence, the TF will peak at the frequencies where Z_{in} is minimum. That is, the frequency range between 0.2 and 0.4 GHz is the most critical frequency range of the system because the TF will always peak at this range. Since Z_{in} is independent of the excitation, this frequency range can be predicted to cause the maximum coupling to the LUT on average when the excitation direction is varied. This prediction was achieved based on the ECA TF with no trial and error, which shows the usefulness of this technique.

To test the ECA TF predictions, the UAV model was excited by a 1 V/m plane wave. Moreover, 325 different angles of incidence, θ , and ϕ were tested where θ varies from 0° to 180° in 15° steps and ϕ varies from 0° to 360° in 15° steps. The polarization angle is fixed at 45° . The induced voltage across the load is averaged over all the incident angles and plotted in Fig. 17. Clearly, all the four studied cases show at least one peak

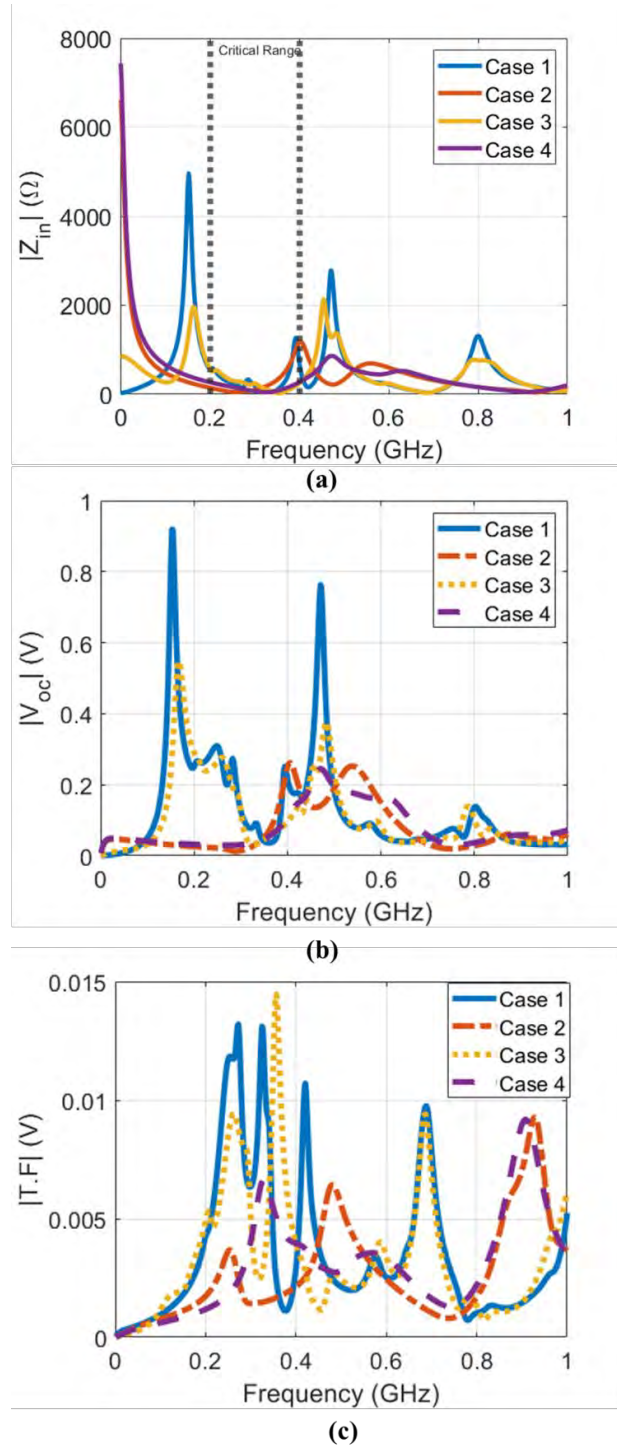


Fig. 16. The input impedance of the system for all 4 studied cases, (b) the magnitude of the open-circuit voltage across the load for all 4 studied cases, (c) the magnitude of the induced voltage across the load (T.F) for all 4 studied cases.

within the critical frequency range predicted by the input impedance of the system shown in Fig. 16a.

The average magnitude of the induced voltage is not the only figure of merit to validate the observations of the ECA. That is, the induced voltage across the load for certain incident angles might dominate the average. Therefore, we tested the probability of the induced voltage exceeding a certain threshold when the direction of the incident wave was varied as previously described. Figure 17b shows the probability of the load voltage exceeding an arbitrary threshold of 5 mV for the four studied cases. The threshold can be tuned to match the value needed to create the desired effect. Each of the four load distribution cases shows a maximum probability of exceeding this threshold at a different frequency range. For example, Case 1, shows the highest probability at ~ 0.25 GHz, Case 2 and Case 4 show the highest probability at ~ 0.9 GHz, and the highest probability of Case 3 is at ~ 0.35 GHz. However, all four cases have a significant probability at the critical

frequency range, 0.2 GHz to 0.4 GHz, as predicted by analyzing the Z_{in} of the wires. That is, the wires are acting as a bandpass filter in this frequency range. Hence, regardless of the load impedance, the load voltage has a very high chance to peak at the critical frequency range.

3. Findings and Conclusions

Over the last few years, we developed a wide range of computational tools to quantify and predict RF coupling to a wide range of wires/traces configurations. These computational tools can be classified into 2 main categories: 1- Characteristic Modes Analysis (CMA) and 2- Equivalent Circuit Approach (ECA). The developed computational tools are combined into a single package for the general benefit of ONR and its contractors. The package is titled “PECNEC: Predictive-package for Electromagnetic Coupling to Nonlinear-electronics using Equivalent-circuits & Characteristic-modes”. The objective of PECNEC is to predict the waveform envelop that will cause electronic upset, by maximizing the coupled voltage and power, to permutations of

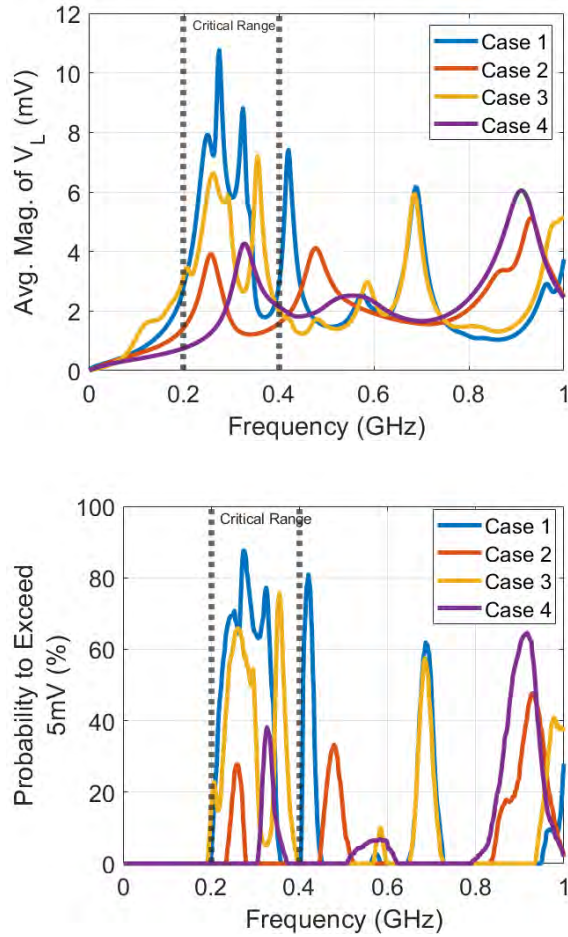


Fig. 17: (a) The average magnitude of the induced voltage over all angles of incidence, (b) The probability of the load voltage, for the four studied cases, to exceed 5 mV.

linear/non-linear loads in any wire topology/geometry. To the best of our knowledge, such a package does not exist and there is a strong need for accurate effects-prediction tools, with a low computational burden, to feed into JREM-like software.

The proposed PECNEC is a hybrid package that combines ECA with CMA to determine the RF-induced overvoltage conditions on linear/non-linear circuit elements using SPICE solvers. ECA is $\sim 100\times$ faster than full-wave simulations with no loss in accuracy. ECA can also predict the optimum waveform to effect, or the overvoltage conditions on a circuit due to a given waveform. On the other hand, CMA can predict the optimum incident angles (θ , ϕ) and polarization (η) for the excitation. The first version of the package will handle a maximum of two nonlinear/linear loads to demonstrate the art-of-the-possible.

Briefly, PECNEC involves three main modules: the Input Module, the Processing Module, and the Output Module, as shown in Fig. 18. The Input Module involves defining the wire geometry, the load characteristics, and the excitation pulse properties. The package will handle arbitrary-shaped wire loops. Thus, wires can be of different types (regular, twisted pair, etc), different sizes (millimeter to meter range), and different shapes (straight, curved, random). The Processing Module involves performing two full-wave simulations for the ECA. After that, much faster circuits simulations can be used to simulate RF coupling to the user-defined nonlinear loads that will be connected to the wiring system. CMA as part of the processing module allows us to predict optimum incident angles (θ , ϕ) and polarization (η) to maximize the coupling to the load. In the Output Module, PECNEC can calculate the coupling quantities (voltage, current, power, energy, etc.) if the user provides a specific excitation. If the user specifies a threshold and/or the “Absolute Maximum Ratings” specified in the loads’ datasheet, PECNEC will predict the following characteristics for the incident pulsed excitation: Optimum center frequency, Optimum angles of incidence/polarization, and a tradeoff between the excitation amplitude and excitation PRF to achieve the desired threshold. The optimization process is computationally efficient since it will require a maximum of 2 full-wave simulations and use instead several highly accelerated equivalent circuits simulations in SPICE.

The user will also be able to add a “Tolerance Level” that will be used to perturb the load characteristics. This will prevent the user from getting false conclusions that will only be valid for a specific unrepeatable configuration.

In terms of the software that the user must have in order to execute the first version of PECNEC, the user is required to have a MATLAB license, A FEKO license, and LTspice (Open Source). The PECNEC package is currently being updated to allow for different solvers and to support more complex wiring configurations with several linear/nonlinear loads.

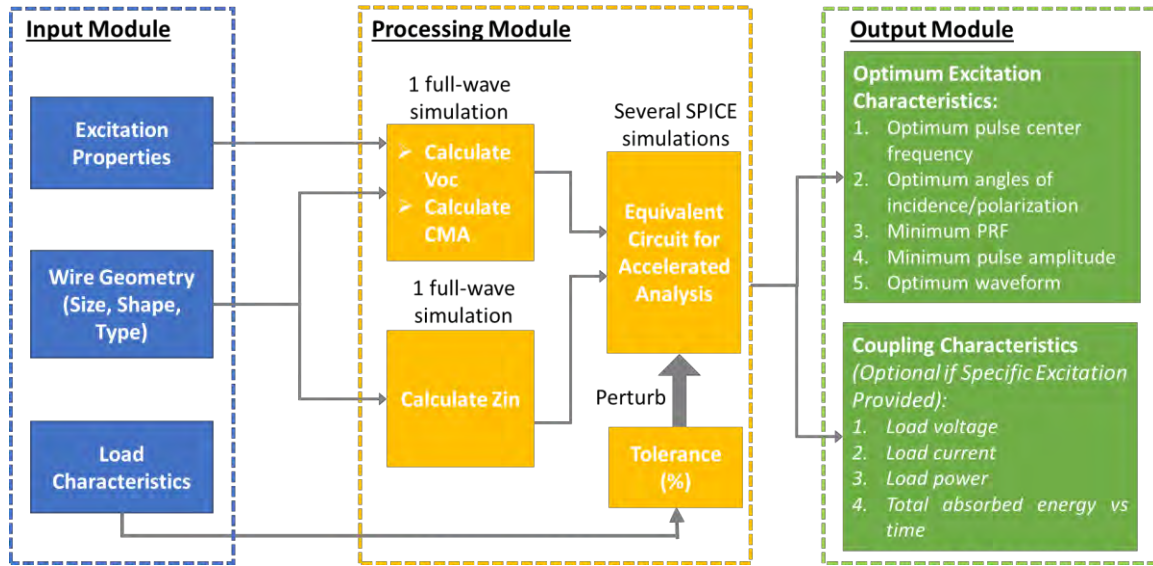


Fig. 18: Flowchart of PECNEC

4. Plans and Upcoming Events

The following improvements are currently planned for PECNEC:

1. Expand the number of solver options based on users' feedback.
 - a. Full-wave solver options: FEKO, CST MWS, COMSOL, and an in-house MOM solver for Arbitrary Thin Wires (ATW)
 - b. Circuit solver options: LTspice, Multisim, etc.
2. Study different equivalent circuits for the ECA to improve the accuracy of the Z_{in} representation.
3. Expand the number of wires and loads
4. Add the effect of the environment e.g. ground planes, enclosures, etc.
5. Build an electronics library compatible with PECNEC by developing black-box equivalent circuits for common electronics. The S-parameters of each component will be measured, translated to impedance/admittance, converted to an equivalent circuit using the black-box macromodeling and the vector-fitting technique [11].

5. Transitions and Impacts

The platform developed in this work, PECNEC, will be augmented with adequate Graphical User Interfaces (GUI) and documentations and presented for the general use of ONR and its defense contractors, e.g. Verus Research (<http://www.verusresearch.net/>). Moreover, the results generated in this work were used as preliminary results for a DARPA WARDEN grant.

References:

- [1] M. Cabedo-Fabres, E. Antonino-Daviu, A. Valero-Nogueira and M. F. Bataller, "The Theory of Characteristic Modes Revisited: A Contribution to the Design of Antennas for Modern Applications," *IEEE Antennas and Propagation Magazine*, vol. 49, no. 5, pp. 52-68, Oct. 2007, doi: 10.1109/MAP.2007.4395295.
- [2] A. Kalantarnia, A. Keshtkar, and A. Ghorbani, "Predicting the effects of HPEM radiation on a transmission line terminated with linear/nonlinear load in perforated metallic enclosure using fdm/vf," *IEEE Trans. Plasma Sci.*, vol. 48, no. 3, pp. 669–675, Mar. 2020, doi: 10.1109/TPS.2020.2968759.
- [3] R. Michels, M. Kreitlow, A. Bausen, C. Dietrich, and F. Gronwald, "Modeling and verification of a parasitic nonlinear energy storage effect due to high-power electromagnetic excitation," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 6, pp. 2468–2475, Dec. 2020, doi: 10.1109/TEMC.2020.2980976.
- [4] M. Kotzev, X. Bi, M. Kreitlow, and F. Gronwald, "Equivalent circuit simulation of hpem-induced transient responses at nonlinear loads," *Adv. Radio Sci.*, vol. 15, pp. 175–180, Sep. 2017, doi: 10.5194/ars-15-175-2017.
- [5] D. Palur Palanivelu, R. Michels, M. Kreitlow, and F. Gronwald, "The response of nonlinearly loaded antennas to repetitive HPEM excitations as obtained from equivalent circuit models," *Adv. Radio Sci.*, vol. 16, pp. 135–140, Sep. 2018, doi: 10.5194/ars-16-135-2018.
- [6] <https://www.altair.com/feko/>
- [7] R. Michels, M. Willenbockel and F. Gronwald, "A Parametric Study of an Energy Storage Effect due to Nonlinear Components and HPEM-Excitation," *2019 International Symposium on Electromagnetic Compatibility-EMC EUROPE*, 2019, pp. 59-64, doi: 10.1109/EMCEurope.2019.8871855.
- [8] M. Sadraey, "Unmanned Aircraft Design: A Review of Fundamentals," *Synthesis Lectures on Mechanical Engineering*, vol. 1, no. 2, pp. i–193, Sep. 2017, doi: 10.2200/S00789ED1V01Y201707MEC004.
- [9] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by vector fitting," *IEEE Trans. Power Delivery*, vol. 14, no. 3, pp. 1052-1061, July 1999.
- [10] G. Antonini, "SPICE equivalent circuits of frequency-domain responses," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 45, no. 3, pp. 502-512, Aug. 2003, doi: 10.1109/TEMC.2003.815528.
- [11] S. Grivet-Talocia and B. Gustavsen, *Passive Macromodeling Theory and Applications*, Hoboken, NJ, USA: Wiley, 2016.

6. Collaborations

- Professor Daryl Beetner, Missouri University of Science and Technology, Electromagnetic Compatibility Lab
- Associate Professor, Victor Khilkevich, Missouri University of Science and Technology, Electromagnetic Compatibility Lab

7. Personnel

Principal investigator

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Co-investigator or Co-PI

Ahmed Hassan, 1 month, National Academy Member (Y/N)

Business Contact

Linda Daugherty, Leta Moler

8. Students

Graduate Student: Mohamed Hamdalla, 12 months, National Academy Member (Y/N)

9. Technology Transfer

None

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Journal Papers

1. K. Alsultan, M. Z. M. Hamdalla, S. Dey, P. Rao, and Ahmed M. Hassan, "Scalable and Fast Characteristic Mode Analysis Using GPUs," *Applied Computational Electromagnetics Society Journal (ACES)*, (In Press), 2022.
2. B. K. Lau, M. Capek, and Ahmed M. Hassan, "Characteristic Modes—Progress, Overview, and Future Perspectives," *IEEE Antennas and Propagation Magazine*, vol. 64, no. 2, pp. 14-22, April 2022.
3. M. Z. M. Hamdalla et al., "Characteristic Mode Analysis Prediction and Guidance of Electromagnetic Coupling Measurements to a UAV Model," *IEEE Access*, vol. 10, pp. 914-925, 2022, doi: 10.1109/ACCESS.2021.3138296.

Journal Papers Under Review/Preparation

1. M. Z. M. Hamdalla, A. N. Caruso, and A. M. Hassan, "Electromagnetic Compatibility Analysis of Quadcopter UAVs Using the Equivalent Circuit Approach," *IEEE Open Journal of Antennas and Propagation*, (Under Review), 2022.
2. M. Hamdalla, W. Al-Shaikhli, J. Lancaster, J. Hunter, L. Yuanzhuo, V. Khilkevich, D. Beetner, A. N. Caruso, and A. M. Hassan, "Field to Wire Coupling: A Characteristic Mode Analysis Approach," *IEEE Transactions on Electromagnetic Compatibility*, (Under Preparation), 2022.
3. M. Z. M. Hamdalla, A. N. Caruso, and A. M. Hassan, "Characteristic Mode Analysis of the UAV Frame Material Effect on its Electromagnetic Compatibility Response," *Progress In Electromagnetic Research*, (Under Preparation), 2022.

Invention Disclosures:

1. D. Beetner, V. Khilkevich, A. Hassan, S. Xia, J. Hunter, A. Harmon, “Rapid Prediction of Electromagnetic Coupling to Electronic Circuits and Harnesses,” *Invention Disclosure (Under Preparation)*, 2022.

Conference Papers

1. S. Xia, J. Hunter, A. Harmon, M. Z. M. Hamdalla, A. M. Hassan, C. Hwang, V. Khilkevich, D. G. Beetner, “A Fast Cascading Method for Predicting the Coupling from External Plane Waves to PCBs,” *Submitted to the 2022 IEEE International Symposium on EMC+SIPI*, Spokane, Washington, August 1-5, 2022.
2. J. Hunter, S. Xia, A. Harmon, M. Z. M. Hamdalla, A. M. Hassan, V. Khilkevich, D. G. Beetner, “A Segmentation Strategy for Structures with Common Mode Coupling,” *Submitted to the 2022 IEEE International Symposium on EMC+SIPI*, Spokane, Washington, August 1-5, 2022.
3. B. Bissen, T. Ory, M. Z. M. Hamdalla, A. M. Hassan, A. N. Caruso, “An Automated Experiment for Parametric Investigation of Voltage Stacking Behavior,” *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Singapore, December 4-10, 2021.
4. M. Z. M. Hamdalla, A. N. Caruso, A. M. Hassan “Predicting RF Coupling to a UAV Wiring System Using the Equivalent Circuit Approach,” *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Singapore, December 4-10, 2021.
5. K. Alsultan, A. M. Hassan, and P. Rao, “Scalable Acceleration of Characteristic Mode Analysis Using Big Data Techniques,” *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, Singapore, December 4-10, 2021.
6. M. Z. M. Hamdalla, A. N. Caruso, A. M. Hassan, “A Predictive-Package for Electromagnetic Coupling to Nonlinear-Electronics using Equivalent-Circuits and Characteristic-Modes (PECNEC),” *Directed Energy Systems Symposium*, Washington DC, USA, 25 - 29 October 2021.
7. M. Z. M. Hamdalla, A. N. Caruso, A. M. Hassan, “The Shielding Effectiveness of UAV Frames to External RF Interference,” *Directed Energy Systems Symposium*, Washington DC, USA, 25 - 29 October 2021.
8. J. Hunter, S. Xia, A. Harmon, A. M. Hassan, V. Khilkevich, D. Beetner, “Modeling and Statistical Characterization of Electromagnetic Coupling to Electronic Devices,” *URSI National Radio Science Meeting*, Boulder, CO, January 4-9, 2021.

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- Ryan Hoffman, ONR, ryan.hoffman@navy.mil, Date of Last Research Progress Meeting: 05/17/2021
- Matthew McQuage, Naval Surface Warfare Center Dahlgren, matthew.mcquage@navy.mil, Date of Last Research Progress Meeting: 05/17/2021

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Fundamental Studies for Nanoscale Vacuum Electronic Emission Devices

Grant No. N00014-18-1-2382

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to September 30, 2021

Prepared by:

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Grant Number: N00014-18-1-2382

Date Prepared: November 30, 2021

Project Title: Fundamental Studies for Nanoscale Vacuum Electronic Emission Devices

Annual Summary Report: FY2021

Principle Investigator: Ravi P Joshi, 806-834-7979, Email: ravi.joshi@ttu.edu

Texas Tech University, Lubbock, TX 79424

Section I: Project Summary

1. Overview of Project

Abstract: The goals and objectives of this project focus on simulations and basic research for understanding fundamental details of processes at the cathode such as electron emission outgassing for vacuum electronics and high power applications. Both can alter the space-charge, (and hence efficiency), of high power microwave (HPM) systems. Optimization of emission currents is objective for robust electron beam generation for HPM devices. In addition, surface changes (e.g., oxide over-layer), can impact emission currents and need to be quantitatively evaluated. The related physics is tied to changes in potential profiles near the surface, which alter electronic wave functions, work function barrier heights, and the tunneling probability. The height distribution and nearest-neighbor separation of emitters can affect total current and needs to be optimized. Such evaluations are important to advance the fundamental physics-based understanding of vacuum field emission, to assess the value of possible surface treatments (e.g., oxide growth, annealing, or plasma etching) for performance optimization and enhanced lifetime. Mutual interactions between emitters in arrays to account for screening (both static and dynamic at the high current densities of interest), field enhancements and effect on safe operating ranges are also important, and merit analyses.

Objectives: Cathode emitters are important components of high power microwave devices. For example, in the magnetically insulated transmission line oscillators (MILOs), quality of cathode arrays have been shown to affect the beam quality, uniformity, stability, and performance. Our project which focusses on physics-based modeling, complements the MILO development both at Texas Tech University (TTU) and the Navy. This effort helps the MILO work with regard to: (a) understanding and optimizing electron emission as the source of microwave power, (b) achieving better electric field uniformity on the cathode surfaces for suppressing cathode flare formation or instabilities, (c) optimal spacing and design of emitter arrays for power scaling, and (d) in evaluating the role of outgassing to mitigate efficiency decreases in HPM systems.

Introduction: Project activities this year have included electron emission, secondary emission, outgassing, current-voltage characteristics for emitter arrays taking account of screening and proximity effects, and the role of surface defects in modifying electron ejection. The possible use of carbon fibers as electron emitters have been analyzed for mitigating outgassing. Collaborative efforts with Drs. M. Sanati (Physics, TTU) and R. Khare (Chemical Engineering, TTU) added a very useful dimension on surface properties, materials issues, and simulations of carbon fibers.

Background: Study of emission from cathodes is important and is being studied at multiple levels:

- (a) Electron emission from surface emitters based on self-consistent calculations of quantum tunneling that include interface barriers and wavefunctions modified by electric fields and photoexcitation.
- (b) Out-gassing driven by temperature-dependent increases in diffusion that can affect space-

charge in HPM systems above the emitting surface, with supporting Molecular Dynamics (MD) analysis.

(c) Modifications in electric fields due to proximity and screening effects based on both three-dimensional simulations based on Molecular Dynamics simulations that include the external electric fields based on Linear Charge Models (LCMs), in addition to many-body Coulomb interactions.

(d) The use of carbon fibers as a material to arrest or reduce outgassing. Molecular Dynamics simulations were used to evaluate both gas diffusion, outgassing, and the reverse process of energy-dependent attachment or sticking at the surface.

(e) Thermal conductivity evaluations for carbon fibers for thermal management and reliability.

2. Activities and Accomplishments

Modeling Electric Fields and Currents for Emitter Arrays

Field emitter arrays (FEAs) are of immense interest as electron sources for high power microwave (HPM) generation [1-5]. In this context, the overall current from emitter arrays based on caesium iodide (CsI) and Cs-coated tungsten emitter arrays were probed through numerical simulations. The melting temperature of tungsten is high, and it is also known to have a low outgassing rate [6, 7] which can be an important consideration for HPM applications. Evaluations of time-dependent currents in uniform multi-emitter cesium (or CsI) coated tungsten arrays arranged in a hexagonal honeycomb pattern were carried out. The hexagonal structure was chosen since reports have shown higher current densities to be possible than a rectangular lattice [8]. Electron transport was modelled based on the kinetic particle-in-cell scheme [9-11]. The Fast Multipole Method [12, 13] was used for treating both the Poisson solution and carrier-carrier interactions. The Scalable Fast Coulomb Solver (ScaFaCoS) package [14] with a best-case $O(N)$ complexity for N -body problems [15] was selected for the electric field calculations. Details of the numerical scheme, and material parameters such as the Workfunction (obtained from Density Functional Theory [16-20]) have been reported elsewhere [21-23]. the metallic boundaries. Geometric field enhancements and screening were included on the basis of Line Charge Model.

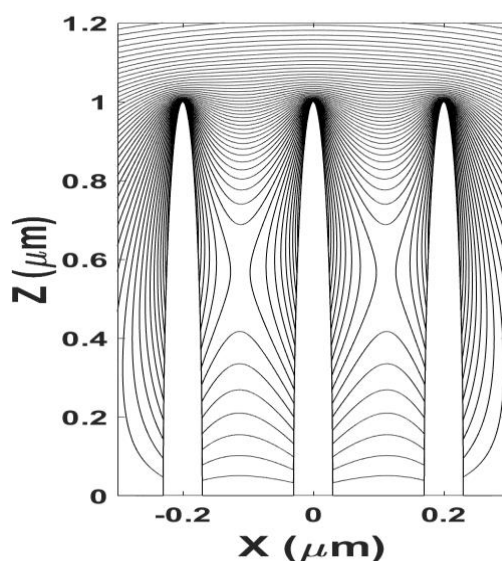


Figure 1. Results showing the potential contour around a simple colinear three emitter array obtained on the basis of the Linear Charge Model.

As an example, Figure 1 shows results of the equipotential contours for a three-emitter structure obtained from the Linear Charge Model discussed above. The separation between adjacent emitters was taken to be 0.2 μm , with a height of 1 μm and emitter tip radius of 0.03 μm . The externally applied average electric-field ($|E_0|$) was taken to be 3.15×10^7 V/m with a cathode to anode plate distance of 2 μm . The field enhancement at the emitter tips is evident.

For an i^{th} emitter subjected to a uniform external field of magnitude F_0 along the z-axis, the potential $V(r, z)$ is given by [24]:

$$V(r, z) = \sum_i \frac{\lambda_i q F_i(r, z)}{4\pi\epsilon_0} - F_0 z \quad , \quad (1a)$$

$$\text{where, } F_i(r, z) = \int_{-L}^L \frac{s}{\sqrt{r^2 + (z-s)^2}} ds \quad , \quad (1b)$$

$$\text{and, } \lambda_i = \frac{4\pi\epsilon_0 F_0 z_i}{[z_i \ln\left(\frac{L_i + z_i}{-L_i + z_i}\right) - 2L_i]q} \quad . \quad (1c)$$

In the above expressions, " L_i " represents the half-length of the line charge associated with the i^{th} emitter, " z_i " is the height of the zero-potential surface at the location of the line charge, " q " the elementary charge, and " ϵ_0 " the permittivity of free space. Equations (1) yield the static electric fields and potentials from an array of emitters of any specified height.

Results Without Emitter Coating: Figure 2(a) shows the honeycomb arrangement with nineteen emitters all with 1.0 μm heights, for which the steady state current shown in Figure 2(b) was obtained. The curve (Fig. 2b) flattens out for distances beyond ~ 2.5 μm in keeping with reports [24] that found shielding to be negligible for separations larger than 2.5 times the emitter height. Figure 2(c) shows electric field scaling factors at different tips of a nineteen-emitter array as a function of emitter separation. The largest reduction is for the central emitter.

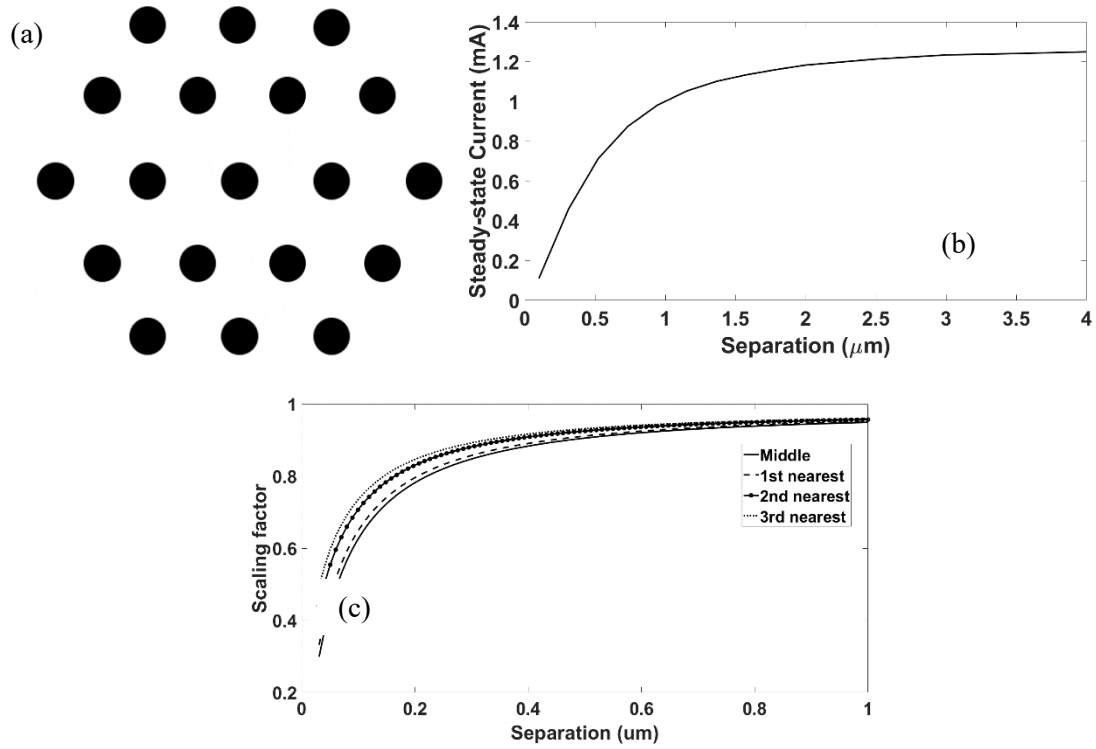


Figure 2. (a) Arrangement for a nineteen emitter structure. (b) Steady state current versus separation between adjoining emitters, in a nineteen emitter array. (c) The electric field scaling factor at the tip for a nineteen emitter array at the central emitter, and at the first, second and third nearest emitters from the center.

Figure 3 shows steady state currents obtained versus number of ($1\ \mu\text{m}$) emitters with emitter spacing as the second variable. Best results are for separations beyond $2.5\ \mu\text{m}$, though the onset of diminishing gains is obvious. Also, current is actually predicted to reduce for emitter spacings below $0.2\ \mu\text{m}$ due to strong screening. Results of time-dependent currents with a bimodal distribution were carried out with one set of emitters of height $1.0\ \mu\text{m}$ and a shorter group with $0.9\ \mu\text{m}$ height. As an example, four possible arrangements for a thirty-seven emitter array are shown in Figures 4(a)-4(d). The resulting currents for the four cases are shown in Fig. 5, with the highest current of $\sim 5.5 \times 10^{-5}\ \text{A}$ seen to result from the structure that did not have three successive emitters of the same length along any of the three primitive axes (termed alternating pattern in Fig. 5) produced the highest current [22].

Results With Emitter Coating: Simulations of emission currents from tungsten arrays coated with either cesium or cesium-iodide were carried out next.

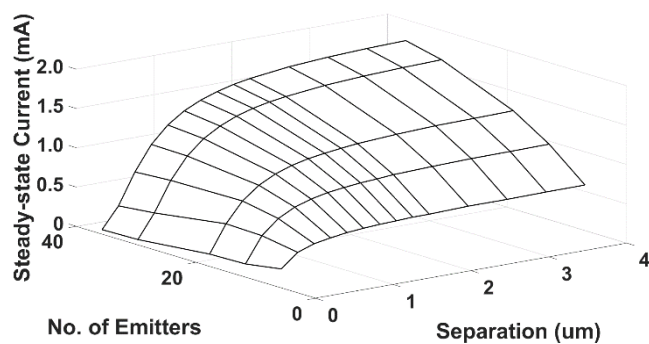


Figure 3. Results showing the total current versus number of emitters in an array, with the nearest neighbor separation as a second variable.

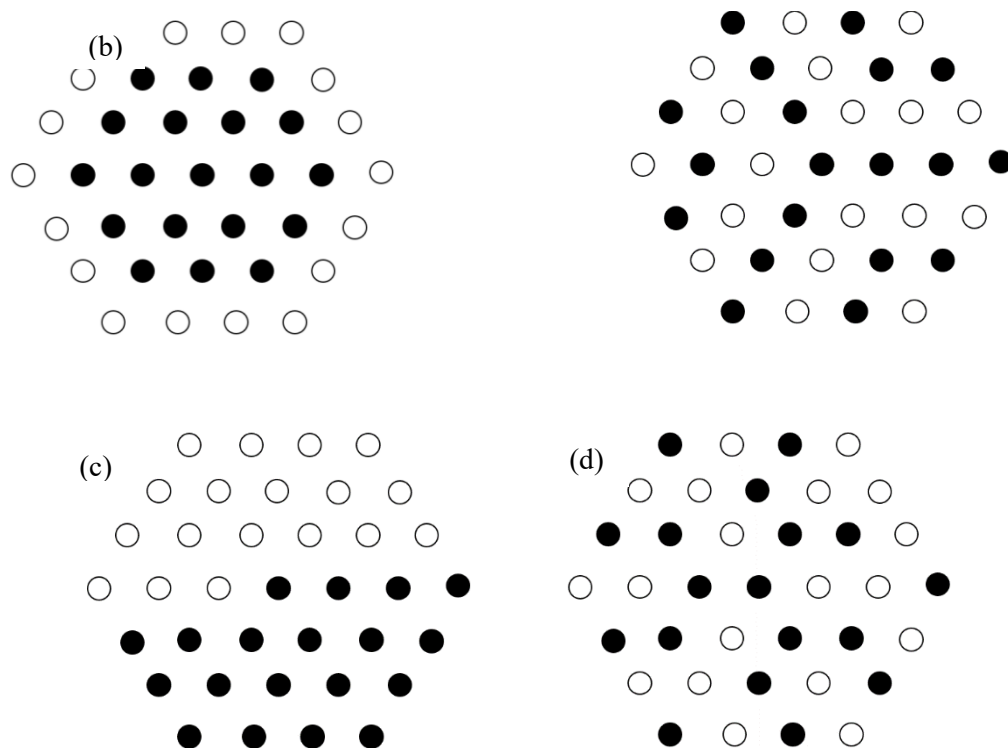


Figure 4. Four bimodal configurations of thirty-seven emitters. Taller emitters are shown as solid circles. (a) An outer layer scheme, (b) alternating pattern, (c) half-and-half scheme, and (d) an alternate-strategy.

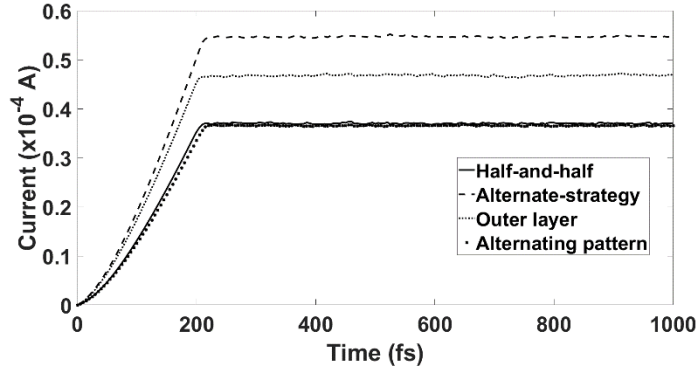


Figure 5. Time dependent total current predicted for the four bimodal thirty-seven emitter array configurations described in Figure 10. The largest current magnitude results from the alternate-strategy.

The average planar potential $\bar{V}(z)$ obtained from DFT calculations for a pure tungsten slab along with results for Cs and CsI coatings are shown in Figure 6. The DFT was used to obtain the workfunction, along with electron transmission probabilities by solving the Schrodinger Wave Equation subject to the potentials.

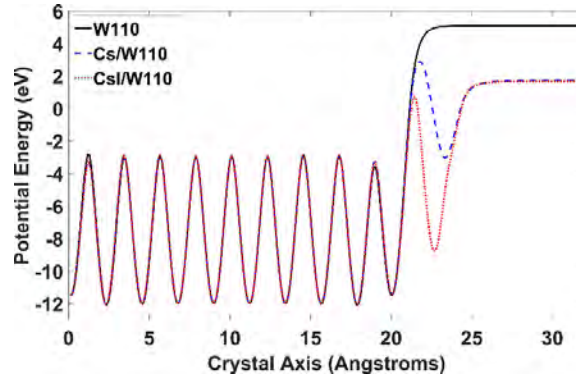


Figure 6. Planar potentials in 110 directions for Tungsten (W), Cesium (Cs) on Tungsten and Cesium Iodide (CsI) on Tungsten. The Fermi Level is taken to be at zero. The adsorption of Cs and CsI lower the work function of W. Results are shown for the: (a) crystalline tungsten W(110), (b) crystalline tungsten with a cesium layer, Cs/W (110), and (c) crystalline tungsten capped with a cesium iodide layer, CsI/W (110).

Result for electron emission current density (J) as a function of external electric field are shown in Figure 7. Currents were also calculated for multi-array emitter systems made of tungsten electrodes with cesium or CsI *coatings*. The time dependent currents obtained for 19-, 37- and 61-emitter hexagonal arrays are shown in Figures 8(a)-8(c). The distance " d " between the bottom cathode plate and the flat anode was taken to be 2 μm , with the height " h " of each cathode emitter set at 1 μm . Thus, the separation between the emitter tip to anode was 1 μm .

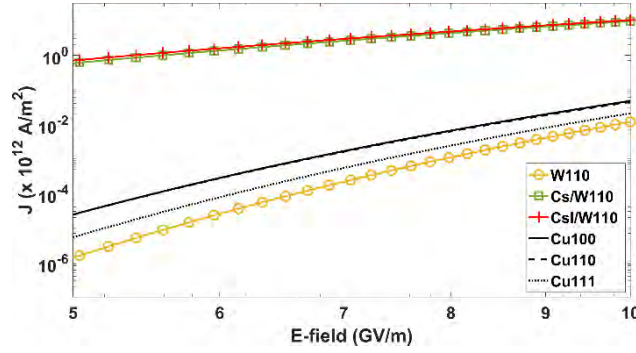


Figure 7. Electron emission current density (J) as a function of external electric field for W(110), Cs/W(110) and CsI/W(110) emitters. For comparison, current densities for pure copper along three different orientations are also shown.

Currents at the smaller 0.1 μm separation were lower as compared to the larger 2.5 μm separation by over a factor of ten. This is the direct result of the proximity effect [24], which leads to electric field screening; however, the screening is nonuniform with the largest effect felt by the innermost emitter that has the highest number of neighbors. While the largest reduction in effective electric field occurs for the central emitter, the effect becomes progressively milder and decreases going outwards from the array center. The results of Fig. 8(a) demonstrate that it is not advantageous to place emitters too close together in an array with short nearest-neighbor separations.

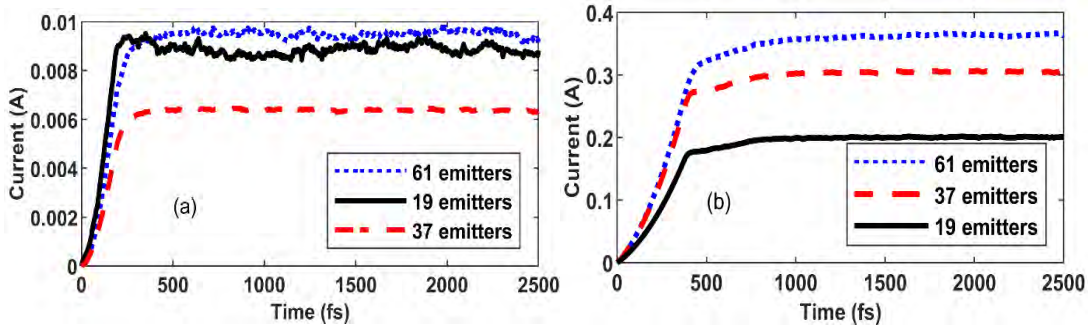


Figure 8. Time-dependent results for the overall currents for the 19, 37 and 61 CsI coated tungsten emitter arrays with different separations of: (a) 0.1 μm between adjacent emitters, and (b) longer 2.5 μm distance between adjacent emitters.

(B) Modeling for Outgassing in Copper and Carbon Fibers

Simulations of temperature-dependent outgassing and sticking coefficients were carried out for copper material. Results for temperature-dependent diffusion coefficients for hydrogen in pure copper and in the presence of a discrete set of vacancies, are shown in Figure 9. For comparison, data reported previously by various groups [25-27] are also shown. An Arrhenius type behavior naturally emerged from the calculations for pure copper, with an activation energy of 0.43 eV and a pre-exponential factor of $2.1 \times 10^{-7} \text{ m}^2/\text{s}$, which are comparable to other reports [28]. Due to trapping of H atoms, the values in Figure 9 with vacancy sites lead to lower diffusion [29]. Simulations for the reflection of hydrogen incident onto the copper surface were also performed at different energies and angles. Results for normal incidence are shown in Figure 10 at 800K. The main feature is that at low incident energy, the ability to bounce back easily is low, and leads to low reflection coefficients. At high energies, the atoms are mainly transmitted through, again

leading to lower reflection. The simulations for adsorption and absorption, presented in Figure 11, predict adsorption for incident energies below 10 eV, and absorption to dominate above 10 eV.

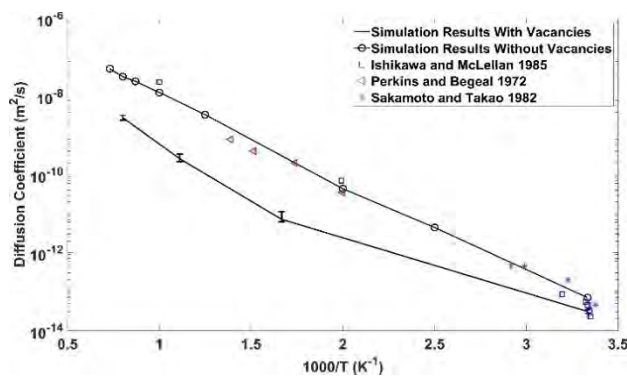


Figure 9. Comparison between the temperature dependent diffusion coefficients for hydrogen obtained from the simulations, and various data points reported in the literature.

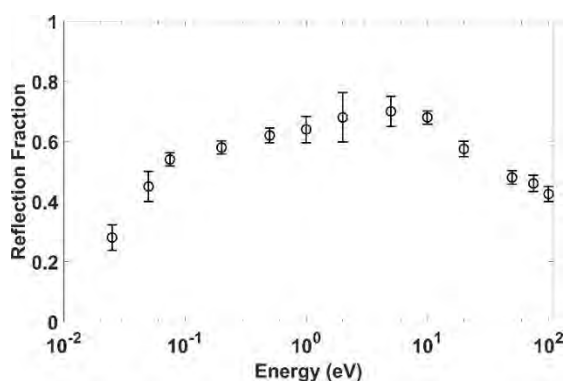


Figure 10. Energy-dependent reflection coefficient at normal incidence of hydrogen impinging on the surface of a copper electrode, calculated from Molecular Dynamics simulations.

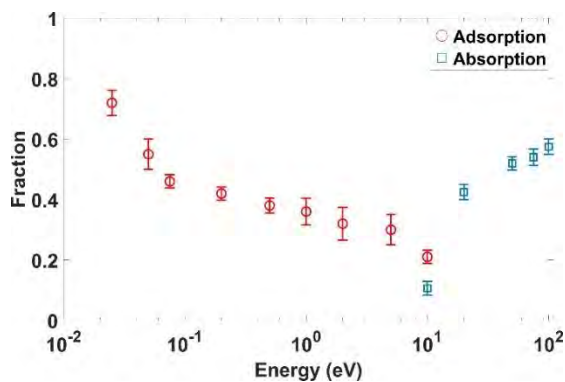


Figure 11. Molecular Dynamics calculations of energy-dependent adsorption and absorption of hydrogen at normal incidence on the surface of a copper electrode.

Carbon fiber cathodes are known to offer advantages over traditional metallic cathodes, in terms of low outgassing [30]. Hence, outgassing from carbon fibers was also studied based on an atomic-level approach using the LAMMPS tool [31]. The diffusion coefficients D obtained for copper and the carbon fiber structure are shown in Figure 12. For copper, reported data [32, 33] is shown for comparison. From Fig. 12, the diffusion of hydrogen in carbon fibers is seen to be lower than in copper by a factor of ~ 15.5 at 400K, and a factor of ~ 86.8 at 1000 K. So, benefits of using CFs over copper for reduced outgassing are further enhanced at higher temperatures.

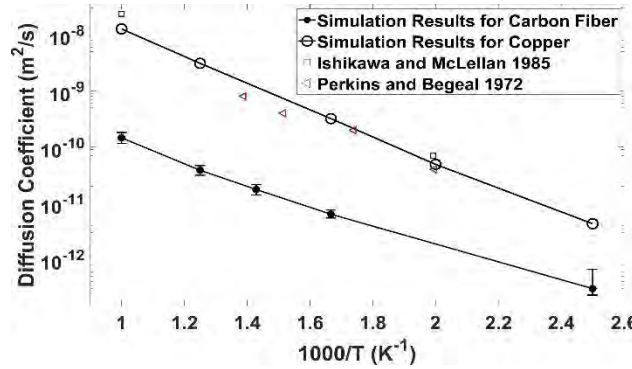


Figure 12. Comparison between the temperature dependent diffusion coefficients for hydrogen in copper and carbon fiber. Some reported data for copper is also shown for comparison.

(C) Thermal Conductivity Calculations for Carbon Fibers

Given the interest and need to drive large currents in such HPM systems to facilitate strong power output, temperature increases in emitters associated with Joule heating, is likely to become an important thermal issue. Heating could be exacerbated by decreases in thermal conductivity due to finite-size effects [34]. However, the carbon fiber system is relatively new and not much data is currently available on its thermal conductivity. So here, calculations were carried out for size dependence of thermal conductivity for carbon fibers. Different carbon fiber (CF) strands of varying lengths had to be built numerically by stitching together graphene sheets of varying sizes [35]. Results for CF thermal conductivity obtained as a function of sample length are shown in Figure 13. Due to the computationally intensive nature of the simulations, only very short dimensions were chosen. Using the same mathematical form of the length-dependent thermal conductivity (i.e., $k(L) = k_{bulk} L/[L + k_{bulk}A]$), a best-fit curve to the data points (Figure 13) was obtained. This led to a predicted thermal conductivity with an asymptotically value around 14 W/m/K in keeping with reported data [36] on long fibers. *The result of Fig. 13 also implies that in order to ensure that thermal conductivity not fall to low values, emitter samples larger than 2 μm should be used.*

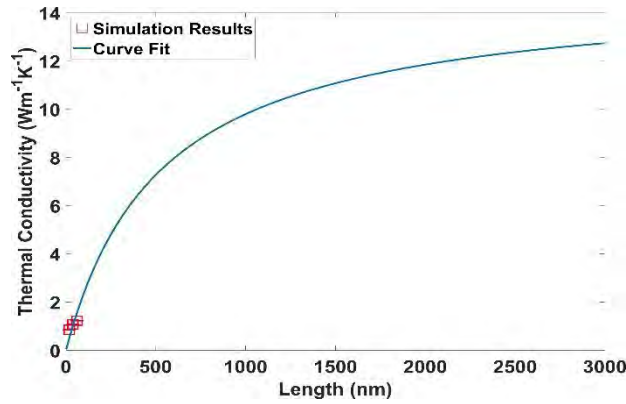


Figure 13. Thermal conductivity of Carbon Fiber as a function of length, with cross section of 5.8 nm x 6.2 nm at 300K. The predicted thermal conductivity value of 14 W/m/K for large samples is in good agreement with a recent report at 300K [47].

3. Findings and Conclusions

The following results and findings emerged this year.

- (i) Molecular Dynamics (MD) simulations of temperature-dependent outgassing were carried out for both copper and carbon fibers, and the latter was shown to have much lower outgassing. Quantitative evaluations of the sticking coefficients for hydrogen gas as a function of incident energy and angle were also performed.
- (ii) Simulations of time-dependent current in emitter arrays were carried out based on molecular dynamics to include dynamic screening and many-body effects. Linear Charge Models (LCMs) were applied to determine electric field distributions and gauge proximity effects in copper, tungsten, and cesium-coated electrodes. This simulation tool can be used to probe newer, promising, and more robust cathode materials such as carbon fibers for HPM systems.
- (iii) Outgassing from carbon fibers was quantitatively assessed. Predictive modeling showed the out-diffusion rates to be over 50 times lower for carbon fibers as compared to copper electrodes.
- (iv) The thermal conductivity of carbon fibers was evaluated. *The results suggest that emitters larger than 2 μm should be used to ensure that thermal conductivity not fall to low values.*

References

- [1] D. Whaley, B. Gannon, C. Smith, C. Armstrong, and C. Spindt, IEEE Trans. Plasma Sci. **28**, 727 (2000).
- [2] D. Shiffler, O. Zhou, C. Bower, M. LaCour, and K. Golby, IEEE Trans. on Plasma Sci. **32**, 2152 (2004).
- [3] A. Thapa, K. L. Jungjohann, X. Wang, and W. Li, J. Mater. Sci. **55**, 2101 (2020).
- [4] N. Li, F. Yan, S. Pang, B. Zeng, and Y. Luo, IEEE Trans. Electr. Dev. **65**, 4369 (2018).
- [5] C. K. Huang, H. L. Andrews, R. C. Baker, R. L. Fleming, D. Kim, T. J. T. Kwan, A. Piryatinski, A. Pavlenko, and E. I. Simakov, J. Appl. Phys. **125**, 164501(2019).
- [6] C. Liu, D. Ryding, R. W. Nielsen, T.L. Kruiy, and T. M. Kuzay, Rev. Sci. Instrum. **67**, 3378 (1996).
- [7] J. Acharjee and R. P. Joshi, Physics of Plasmas **26**, 093504 (2019).

- [8] J. R. Harris, K. L. Jensen, and D. A. Shiffler, AIP Advances **5**, 087182 (2015).
- [9] C. K. Birdsall and A. B. Langdon, in Plasma Physics via Computer Simulation (MacGraw Hill, N. York, 1985).
- [10] T. Takizuka and H. Abe, Journ. Computational Phys. **25**, 205 (1977).
- [11] Y. Weng and M. J. Kushner, Phys. Rev. A **42**, 6192 (1992).
- [12] V. Rokhlin, J. Computational Physics **60**, 187 (1985).
- [13] R. Beatson and L. Greengard, "A short course on fast multipole methods," in Wavelets, Multi-level Methods and Elliptic PDEs (Leicester, 1996), ser. *Numer. Math. Sci. Comput.* (Oxford Univ. Press, New York, 1997), pp. 1–37.
- [14] http://www.scafacos.de/files/pub/libfcs_manual.pdf, library for Fast Coulomb solvers.
- [15] A. Arnold, F. Fahrenberger, C. Holm, O. Lenz, M. Bolten, H. Dachsel, R. Halver, I. Kabadshow, F. Gähler, F. Heber, J. Iseringhausen, M. Hofmann, M. Pippig, D. Potts, and G. Sutmann, Phys. Rev. E **88**, 063308 (2013).
- [16] See <https://www.vasp.at/> for more information about the VASP simulator.
- [17] G. Kresse and J. Hafner, Phys. Rev B **47**, 558 (1993).
- [18] G. Kresse and J. Furthmüller, Phys. Rev. B **54**, 11169 (1996).
- [19] P.E. Blöchl, Phys. Rev. B **50**, 17953 (1994).
- [20] G. Kresse and J. Joubert, Phys. Rev. B **59**, 1758 (1999).
- [21] D. Guo, S. N. Sami, L. Diaz, S. Sanati, and R. P. Joshi, Journ. Of Vacuum Science and Technology B **39**, 054201 (2021).
- [22] D. Guo, W. Milestone, and R. P. Joshi, Journ. Applied Phys. **129**, 173301 (2021).
- [23] S. N. Sami, L. Diaz, M. Sanati, and R. P. Joshi, Journ. Applied Physics **128**, 223302 (2020).
- [24] J. R. Harris, K. L. Jensen, D. A. Shiffler, and J. J. Petillo, Applied Phys. Lett. **106**, 201603 (2015).
- [25] T. Ishikawa and R. B. McLellan, The diffusivity of hydrogen in copper at low temperatures, Journal of Physics and Chemistry of Solids **46**, 445 (1985).
- [26] W. G. Perkins and D. R. Begeal, Permeation and diffusion of hydrogen in ceramvar, copper, and ceramvar-copper laminates, Berichte der Bunsengesellschaft **76**, 863 (1972).
- [27] Y. Sakamoto and K. Takao, The electrochemical determination of diffusivity and solubility of hydrogen in copper, Journal of the Japan Institute of Metals **46**, 285 (1982).
- [28] X. W. Zhou, F. El-Gabaly, V. Stavila, and M. D. Allendorf, J. Phys. Chem. C **120**, 7500 (2016).
- [29] K. Heinola, T. Ahlgren, K. Nordlund, J. Keinonen, Phys. Rev. B **82**, 094102 (2010).
- [30] A. K. Li, Y.W. Fan, B. L. Qian, S. Li, and H. W. Yang, Vacuum **181**, 109723 (2020).
- [31] S. N. Sami, R. Islam, R. Khare, and R. P. Joshi, Journ. Applied Phys. **129**, 213303 (2021).
- [32] T. Ishikawa and R. B. McLellan, Journal of Physics and Chemistry of Solids **46**, 445 (1985).
- [33] W. G. Perkins and D. R. Begeal, Berichte der Bunsengesellschaft **76**, 863 (1972).
- [34] E. Chavez-Angel, J. S. Reparaz, J. Gomis-Bresco, M. R. Wagner, J. Cuffe, B. Graczykowski, A. Shchepetov, H. Jiang, M. Prunnila, J. Ahopelto, F. Alzina, and C. M. Sotomayor-Torres, APL Mater. **2**, 012113 (2014).
- [35] S. N. Sami, R. Islam, and R. P. Joshi, AIP Advances **11**, 105310 (2021).
- [36] K. Dong, G. Bohong, and S. Baozhong, Journal of Thermal Analysis and Calorimetry **124**, 775-789 (2016).

4. Plans and Upcoming Events

Use the data generated and the capability developed in this 3-year effort towards a related research problem of relevance to ONR. Possibly study anode materials that reduce the number of adsorbates

on the surface for enhanced repetition rate and pulse lengths of HPM sources.

5. Transitions and Impacts

None.

6. Collaborations

Dr. Mahdi Sanati, Physics Department, Texas Tech University

Dr. Rajesh Khare, Chemical Engineering Department, Texas Tech University

7. Personnel

Principal investigator Ravindra P. Joshi (US citizen)

Co-investigators Andreas Neuber, John Mankowski, James Dickens (All US citizens)

Person months worked 980 hours (including PI, Co-PI, and students)

National Academy member: None, neither PI, nor the Co-PIs are National Academy members

Business Contact Amy Cook, TTU Associate Vice-President for Research

Team Members None others

Subs None

8. Students

Dong Guo – PhD student -- Graduated in August 2021.

S. Sami – PhD student -- Scheduled to graduate in December 2021.

9. Technology Transfer

None.

10. Products, Publications, Patents, License Agreements, etc.

Archival Publications #1

- a. Article Title: Atomistic Calculations of Thermal Conductivity in Films Made from Graphene Sheets for Electron Emitter Applications
- b. Journal: AIP Advances
- c. Authors: S. N. Sami, R. Islam, and R. P. Joshi
- d. Keywords: Thermal conductivity, Graphene, Simulation, Molecular dynamics
- e. Distribution Statement: Unrestricted distribution
- f. Publication Status: Published
- g. Publication Identifier Type:
- h. Publication Identifier:
- i. Publication Date: October 2021
- j. Volume: 11
- k. Issue: 10
- l. First Page Number: 105310
- m. Publication Location: New York, USA
- n. Acknowledgement of Federal Support? (Yes/No): Yes
- o. Peer Reviewed? (Yes/No): Yes

Archival Publications #2

- a. Article Title: Evaluation of Electron Currents from Cesium Coated Tungsten Emitter Arrays with Inclusion of Space Charge Effects, Workfunction Changes and Screening
- b. Journal: Journal of Vacuum Science and Technology B
- c. Authors: D. Guo, S. N. Sami, L. Diaz, S. Sanati, and R. P. Joshi
- d. Keywords: Electric emission, Tunneling, Array emitters, Molecular dynamics
- e. Distribution Statement: Unrestricted distribution
- f. Publication Status: Published
- g. Publication Identifier Type: <https://doi: 10.1116/6.0001185>
- h. Publication Identifier: <https://doi: 10.1116/6.0001185>
- i. Publication Date: August 2021
- j. Volume: 39
- k. Issue: 5
- l. First Page Number: 054201
- m. Publication Location: New York, USA
- n. Acknowledgement of Federal Support? (Yes/No): Yes
- o. Peer Reviewed? (Yes/No): Yes

Archival Publications #3

- a. Article Title: Simulations of Hydrogen Outgassing from Carbon Fibers
- b. Journal: Journal of Applied Physics
- c. Authors: S. N. Sami, R. Islam, R. Khare, and R. P. Joshi
- d. Keywords: Hydrogen outgassing, Carbon fiber, Simulation, Molecular dynamics
- e. Distribution Statement: Unrestricted distribution
- f. Publication Status: Published
- g. Publication Identifier Type: <https://doi.org/10.1063/5.0054440>
- h. Publication Identifier: <https://doi.org/10.1063/5.0054440>
- i. Publication Date: June 2021
- j. Volume: 129
- k. Issue: 21
- l. First Page Number: 213303
- m. Publication Location: New York, USA
- n. Acknowledgement of Federal Support? (Yes/No): Yes
- o. Peer Reviewed? (Yes/No): Yes

Archival Publications #4

- a. Article Title: Many-Particle Based Evaluations for Maximum Current Output from Bimodal Electron Emitter Arrays
- b. Journal: Journal of Applied Physics
- c. Authors: D. Guo, W. Milestone, and R. P. Joshi
- d. Keywords: Emitter arrays, Field emission, Bimodal size distribution, Simulation, Maximum current
- e. Distribution Statement: Unrestricted distribution
- f. Publication Status: Published
- g. Publication Identifier Type: <https://doi.org/10.1063/5.0047528>
- h. Publication Identifier: <https://doi.org/10.1063/5.0047528>
- i. Publication Date: September 2021

- j. Volume: 129
- k. Issue: 17
- l. First Page Number: 173301
- m. Publication Location: New York, NY, USA
- n. Acknowledgement of Federal Support? (Yes/No): Yes
- o. Peer Reviewed? (Yes/No): Yes

Archival Publications #5

- a. Article Title: Simulations of Hydrogen Outgassing and Sticking Coefficients at a Copper Electrode Surface: Dependencies on Temperature, Incident Angle and Energy
- b. Journal: Physical Review Research
- c. Authors: S. N. Sami, M. Sanati, and R. P. Joshi
- d. Keywords: Hydrogen, Outgassing, Copper electrode, Sticking coefficient, Vacancies, Gas diffusion
- e. Distribution Statement: Unrestricted distribution
- f. Publication Status: Published
- g. Publication Identifier Type: <https://doi.org/10.1103/PhysRevResearch.3.013203>
- h. Publication Identifier: <https://doi.org/10.1103/PhysRevResearch.3.013203>
- i. Publication Date: March 2021
- j. Volume: 3
- k. Issue: 1
- l. First Page Number: 013203
- m. Publication Location: New York, USA
- n. Acknowledgement of Federal Support? (Yes/No): Yes
- o. Peer Reviewed? (Yes/No): Yes

In addition, the following presentations were made at the Pulsed Power Conference (SOFE/PPC-2021) conference in Denver. These talks at the conference will be given remotely in December as the entire conference is now virtual. The specific details are:

T. Buntin, M Abide, J. Dickens, A. Neuber, R. P. Joshi, J. Mankowski, "Evaluation of Explosive Emission of Carbon Fiber Cathodes for High-Power Microwave Devices," IEEE Int'l Pulsed Power Conference and Symposium on Fusion Engineering (PPC-SOFE 2021), Denver, December 12-16, 2021.

M. Abide, T. Buntin, J. Dickens, A. Neuber, R. P. Joshi, J. Mankowski, "Low-Impedance S-Band MILOs," IEEE Int'l Pulsed Power Conference and Symposium on Fusion Engineering (PPC-SOFE 2021), Denver, December 12-16, 2021.

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12. Acknowledgement/Disclaimer

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A High Repetition Rate, Long Lifetime Magnetically Insulated Line Oscillator (MILO)

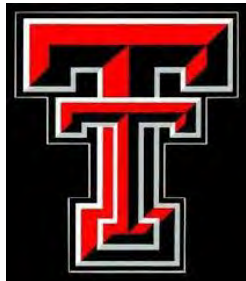
Grant No. N00014-18-1-2384

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to December 31, 2021

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Project Title: A High Repetition Rate, Long Lifetime Magnetically Insulated Line Oscillator (MILO)

Annual Summary Report: CY2021

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Section I: Project Summary

1. Overview of Project

The overall goals of this project are to design, fabricate and test a 1 GW class magnetically insulated line oscillator (MILO) capable of high repetition rates. The MILO source will be a hardtube design with advanced materials for high rep-rate operation. To that end, we are using particle in cell (PIC) simulation code to model the MILO source structure and materials for a prediction of output RF power and efficiency. In conjunction with the MILO development, we are constructing a low impedance ($\sim 10\ \Omega$) Marx generator to drive the MILO and test in single shot mode. Since the project is 9 months in to a 3-year program, the bulk of this report discusses the MILO PIC simulations and Marx generator development.

The fundamental objective of this applied research is to develop an enabling technology for future pre-detonation Counter Improvised Explosive Device (CIED) systems. HPRF system power requirements are primarily driven by range (stand-off), and the pulse repetition frequency correlates to the desired speed of the USMC tactical vehicle. Current conventional microwave tube technology used for such systems is limited by output power to single digit MW and total system weight can exceed 20,000 lbs. By comparison, relativistic High Power Microwave (HPM) sources such as Relativistic Magnetrons (RelMags) and Magnetically Insulated Line Oscillators (MILO) can be driven by short pulse Marx generator pulsed power devices and produced with total weights on the order of 2,000 lbs or less in compact form factors. This reduction in weight by an order of magnitude has potential to enable integration into a wide variety of Marine Corps tactical vehicles to include MRAP and HMMWV. If the size and weight can be further reduced, there is even potential to employ this counter IED technology on small unmanned ground vehicles with on board power. Additionally, there is potential to utilize this emerging technology for countering emerging Unmanned Aerial System threats. RelMags and MILO tube designs offer potential for achieving substantial increases in peak output RF power compared to existing commercial-off-the-shelf (COTS) magnetron and klystron tubes, but at the expense of efficiency. The inherent shortcoming of these relativistic tubes is pulse shortening which is an important factor when operating in the relativistic regime. Additionally, the lifetime of these novel tube design geometries has not been characterized.

Abstract:

This report details the development of a hardtube Magnetically Insulated Line Oscillator (MILO) for testing in the high repetition rate regime. A brief background of the project is first discussed. The narrative portion of activities and accomplishments are divided into three segments. The first part details the completed MILO system components and initial MILO testing. The second part reports on the cathode material testing. The third part reports on a pulse generator for triggering of the Marx. Finally, findings and plans are presented for the upcoming year.

Objective: The objective of this research is to develop a 1 GW class, hardtube MILO that will be capable of high repetition rate operation.

Background:

The program objective is to design and construct a high-power microwave source capable of high RF power (> 1 GW) and high repetition rate. To this end we are proposing the development of a hard tube magnetically insulated line oscillator (MILO). This type of performance can be achieved by fabrication using advanced materials and sealed tube technology as well as design optimization through PIC code simulation. The high diode peak power will induce extreme temperatures within tube components. Advanced materials such as pyrolytic graphite can withstand these conditions which will result in shot lifetimes many orders of magnitude greater than traditionally used materials. These operating conditions will also create plasma within the AK gap which can result in pulse shortening. Sealed tube technology has been shown to reduce plasma generation as well as decrease plasma lifetime. Finally, PIC code simulation will be used to optimize MILO performance resulting in higher power efficiency and lower losses.

2. Activities and Accomplishments

MILO Source –Testing

The MILO center cavity design was based upon a desired S-band frequency of approximately 3 GHz. Equations by Fan were used for numerous parameters including vane width, cathode radius and anode-cathode gap. These are illustrated in *Figure 13*. The selected parameter values are shown in *Table 1*.

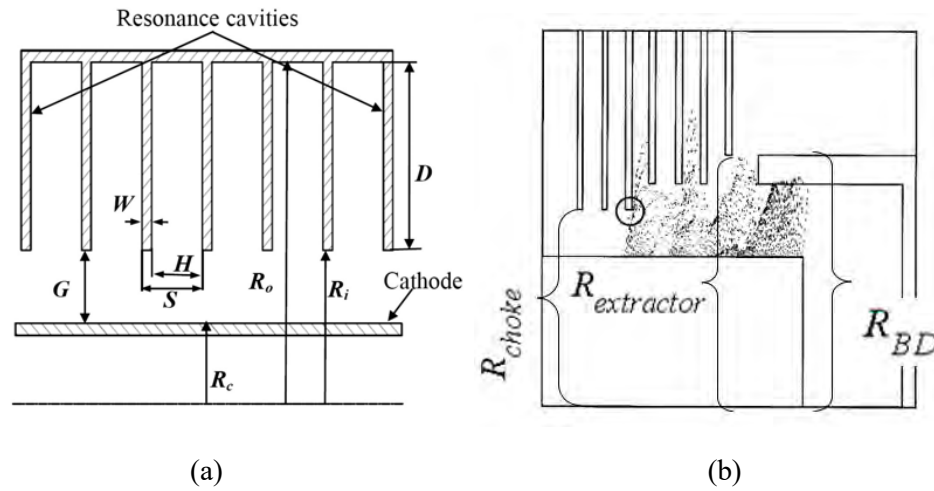


Figure 13. Baseline MILO cavity parameters.

Table 1. Selected parameter values of the MILO cavity.

Cathode Radius (R_C)	25.00 mm
SWS Vane Length (D)	24.98 mm
Exterior Radius (R_o)	63.23 mm
Interior Radius (R_i)	38.25 mm
Cathode-Anode Gap (G)	13.25 mm
Choke Vane Radius (R_{choke})	35.00 mm
Extractor Vane Radius (R_{vane})	41.22 mm
Beam Dump Radius (R_{BD})	39.40 mm
Periodicity of Vanes (S)	21.93 mm
Gap Distance (H)	14.93 mm
Vane Thickness (W)	7 mm

The baseline model was then modeled in CST Particle-in-Cell simulation software, as shown in [Figure 14](#). A major goal was to optimize the MILO output power by varying some parameters which could be mechanically alterable via an external bellows structure. Some of these varied parameters are shown in [Figure 15](#). These include stub distance, overlap and extractor gap. with key components labelled.

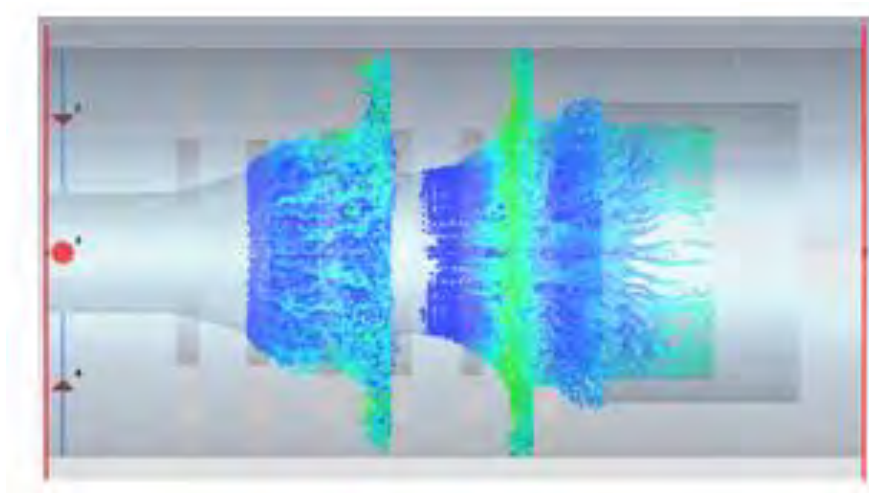


Figure 14. PIC simulation of the TTU MILO.

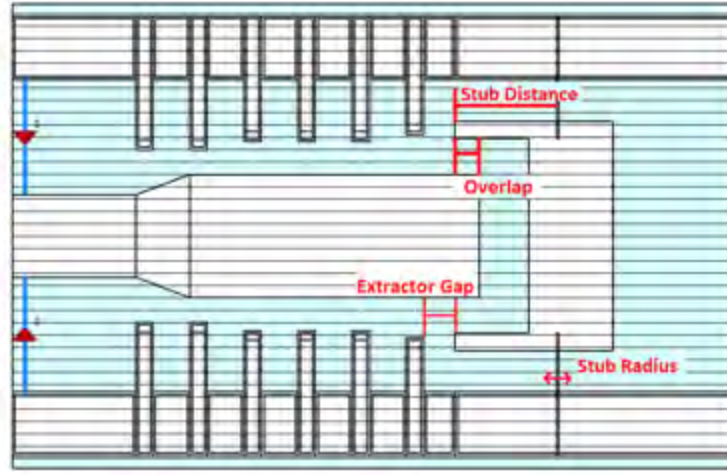


Figure 15. MILO model in the PIC simulation code indicating variable parameters.

The results of the maximum output RF power variation for various parameter sweep ranges are shown in Table 2. Note that the parameter with the resultant maximum output power and largest power range is the overlap parameters.

Table 2. Maximum output power range for various parameter sweeps.

Sweep	Values	Max Output Power
Stub Distance	37.6 – 45.6 mm (2 mm Steps)	3.75 – 4.25 GW (Max @ 45.6 mm)
Stub Radius	0.5 – 2.0 mm (0.5 mm Steps)	3.76 – 4.05 GW (0.5 mm)
Overlap	3 mm – 9 mm (2 mm Steps)	3.74 – 4.48 GW (9 mm)
Extractor Gap	11 – 15 mm (2 mm Steps)	3.87 – 4.05 GW (13 mm)

The simulation model from Figure 14 was then mechanically designed using AutoCad Inventor with the result shown in Figure 16. Some of the key components include the cathode assembly (magenta), cavity vanes and beam dump (gray), and output waveguide (orange). As previously mentioned, a unique aspect of this MILO is the capability of externally varying several parameters which are the beam dump overlap and extractor gap. This has been done by mounting the beam dump and posts to the output waveguide which is mounted to the output window (cyan). The output window is attached to the chamber through a linear translator bellows. By varying the bellows length we can vary the beam dump overlap width between 10 mm and 25 mm.

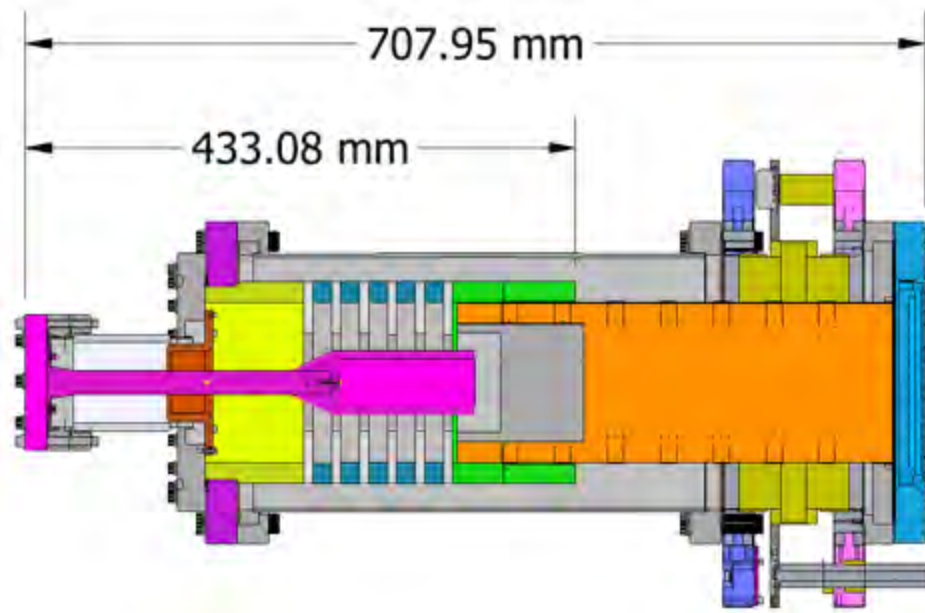


Figure 16. Inventor solid model of the TTU MILO

All components of the MILO have been fabricated and assembled. Additionally, these are all bakeable parts except for the cathode emitter which is fashioned from silk velvet and is shown in *Figure 17*. The completed assembly mounted to the pulsed power Marx generator driver is shown in *Figure 18*.

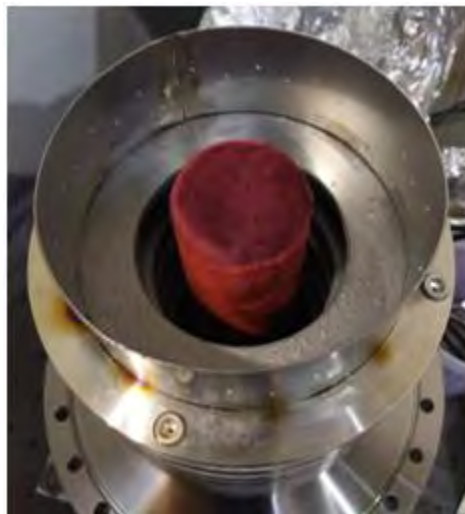


Figure 17. Silk velvet cathode emitter material affixed to the MILO cathode.

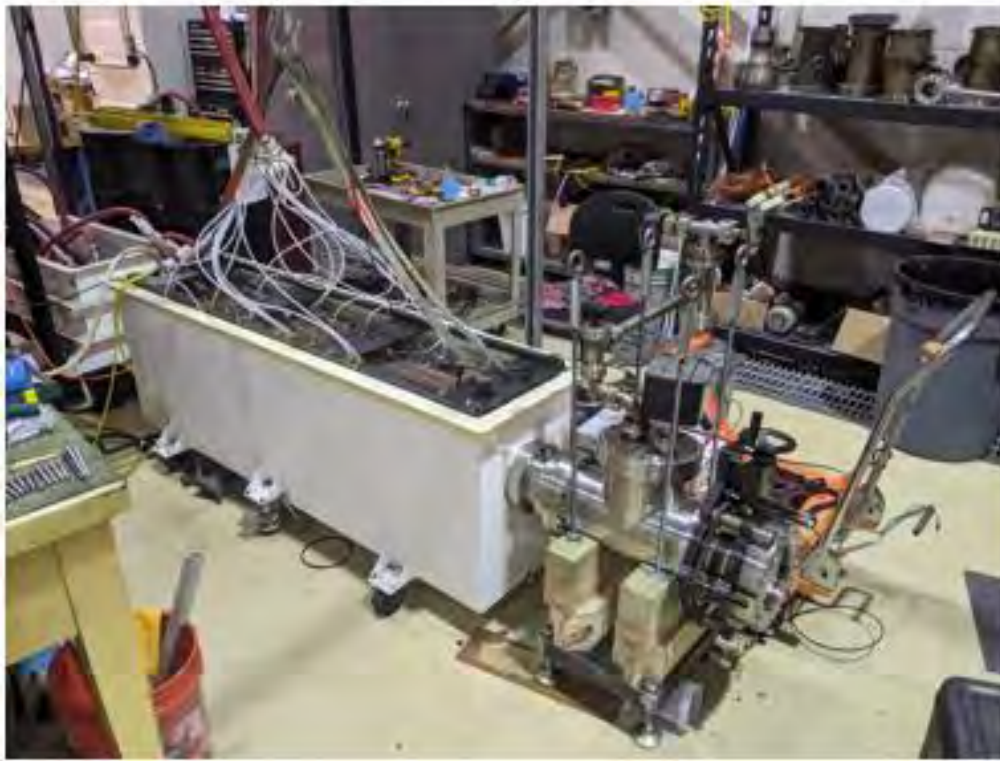


Figure 18. MILO system including the Marx generator and MILO assembly.

The Marx generator is a low impedance pulsed power driver capable of delivering > 50 kA to the MILO. It features two 220 nF, 50 kV Maxwell capacitors at each of the 18 stages. Thus the open circuit output voltage can be as high as 900 kV. The typical output voltage and current into the low impedance MILO is 325 kV and 55 kA.

The output current and voltage at a charge voltage of 30 kV is shown in [Figure 19](#). In this case the voltage peaks at 150 kV and the current peaks at 22 kA. The resultant MILO impedance, in [Figure 19b](#), declines during the pulse from 15 ohm to 5 ohm for an average of 10 ohm. This variation during the pulse is typical.

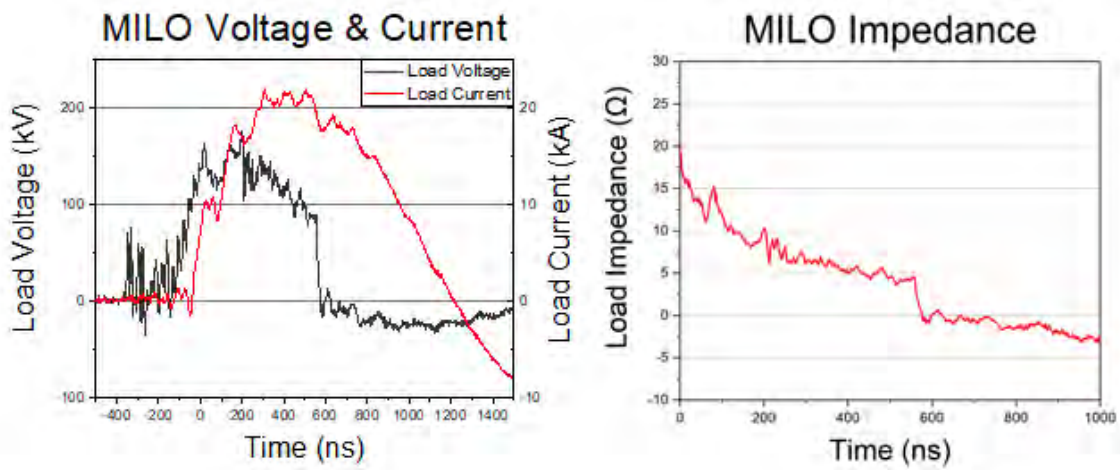


Figure 19. Marx generator output into the MILO charged to 30 kV.

The pulsed power input from Figure 19a resulted in the RF output shown in Figure 20 below. The RF output power is very low, < MW, but it does show MILO beginning to turn on. Frequency analysis shows that this RF output is in the S-band as expected.

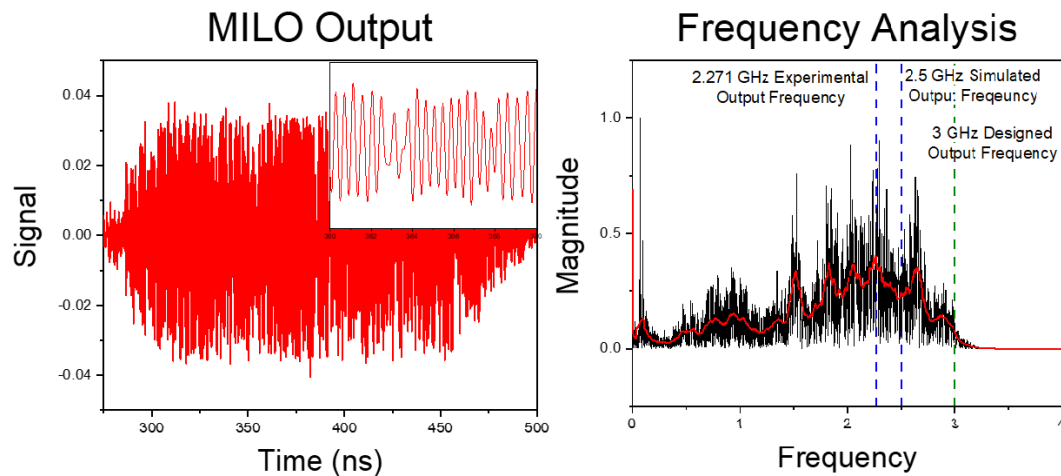


Figure 20. Output voltage and current from the 18-stage Marx at 25 kV charge.

An experimental setup for testing the capabilities of the MILO is shown below in Figure 21. This setup allows for the control of the vacuum pump, HV charger, and pressure control for triggering the Marx from a single location. A horn antenna is set at a height level with the output of the MILO at a 30-degree offset a meter away. This position of the horn antenna was determined by simulation of the MILO, results shown in ---, and is positioned where the output RF signal

theoretically strongest. This allows us to calculate the total output power of the MILO by integrating the measured field strength at the horn.

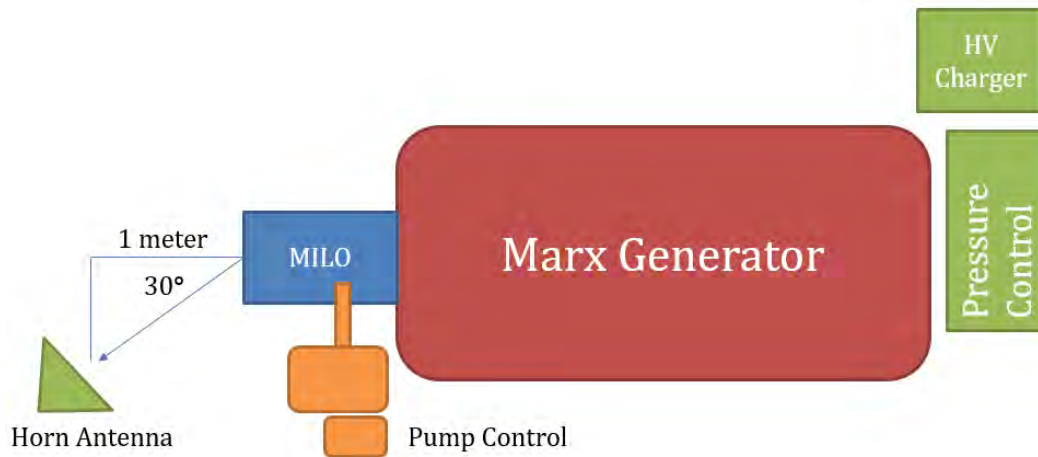


Figure 21: The experimental setup for the MILO with labels indicating the locations of each of the components.

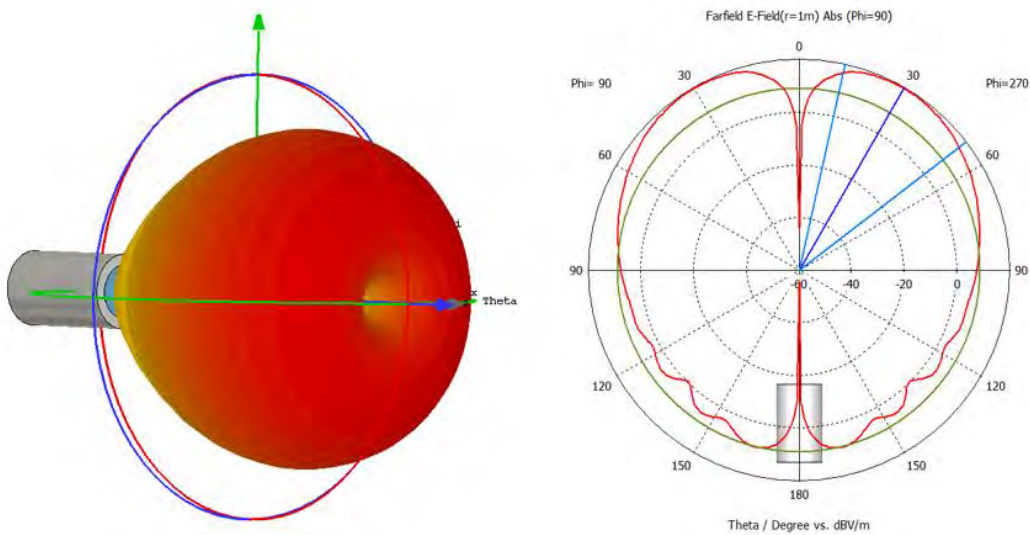


Figure 22: Simulation results of a MILO's RF output and polar plot of the electric field strength. The results show that the electric field is maximized at an offset 30-degrees.

Testing the capabilities of the MILO was performed by a series of tests that varied the charge voltage of the capacitors and the positioning of the bellows. [Figure 23](#) and [Figure 24](#) show the results for a single shot. This test shot set the bellows position such that the cathode and beam dump are overlapped by 2 mm and the capacitors are charged to 45 kV. The Marx was able to provide voltage pulse with a peak of 270 kV with 44 kA. However, the voltage pulse collapsed before rising to its peak at 230 ns. The RF output from the MILO, show in [Figure 24](#), had a peak output power of 85.5 MW centered about 2.785 GHz.

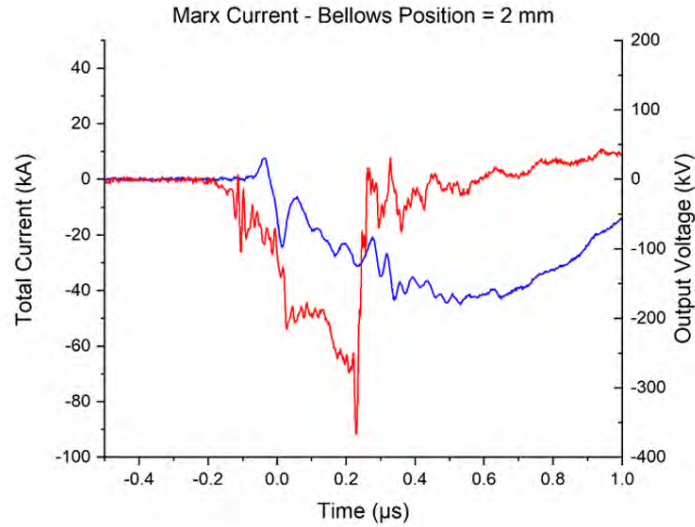


Figure 23: Captured voltage and current waveforms of the Marx generator. Each of the capacitors are charged to 45 kV and the bellows is positioned such that the beam dump overlaps the cathode by 2 mm. The voltage pulse rises to its peak in 200 ns and collapses.

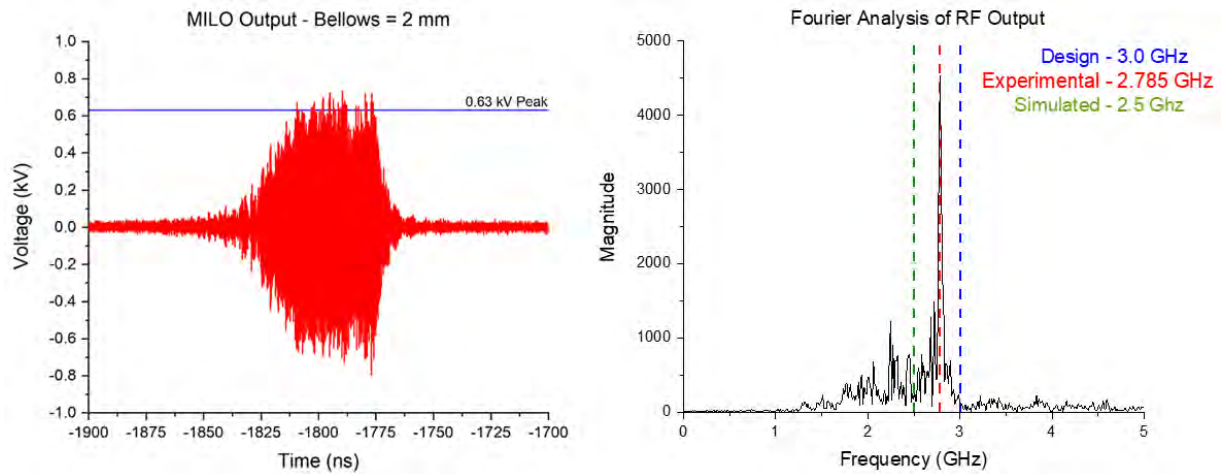


Figure 24: The RF output signal for the test shot described in Figure 23. (left) Analyzing the captured RF output shows a peak of 0.63 kV this correlates to ~85.5 MW output power. (right) The Fourier analysis of the outputted signal show the output frequency is centered about 2.785 GHz.

Testing showed that the voltage collapse was happening because the HV feedthrough attached to the MILO was incapable of holding off the voltage pulse supplied by the Marx generator. A new HV feedthrough, shown in Figure 25, was designed to extend the hold off capabilities. The extended feedthrough required modifications to the cathode such that the cathode would remain positioned in the position relative to the slow wave structure of the MILO. The cathode length was increased during this time to increase the return current as magnetic insulation of the electron beam was not occurring.

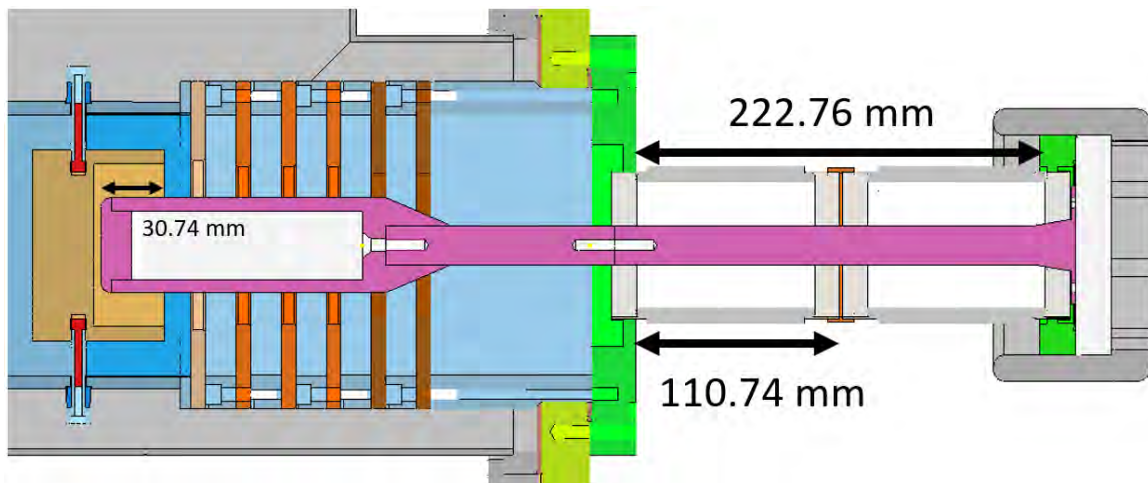


Figure 25: CAD modeling of the changes made to the MILO with the new HV feedthrough.

After continually experiencing arcing to the metal gantry, ground bar, or tank wall when erecting, the Marx generator underwent a series of changes to improve its stability. These changes required that the removal of the metal gantry after once the capacitor bank is set within the tank, replace the ground bar with an aluminum ground plane that is connected to the tank wall, and finally the hose connections at the high side of the Marx generator were removed after a shot broke down to ground over them, show in *Figure 26*.

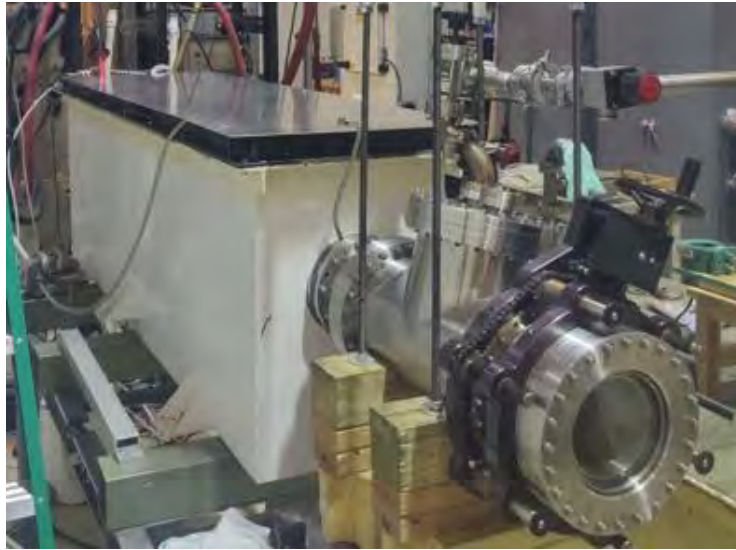


Figure 26: The Marx generator with changes made to reduce the chance of arcing breakdown applied.

An additional water resistor of approximately 4 Ohms was added in series with the Marx generator output to dampen the voltage experienced by the capacitor bank during operation, see *Figure 27*.

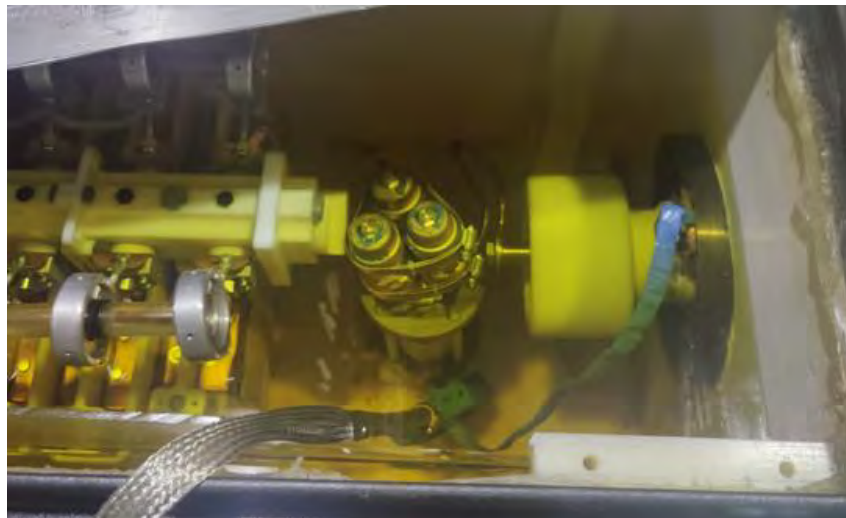


Figure 27: The HV output of the Marx generator and capacitor bank as it sits within the tank. The series resistor.

After resuming testing with the MILO, the Marx generator is stable and the HV feedthrough can hold off for the voltage for the entire duration of the pulse. However, the Marx has experienced a reduction in the total provided current as such the MILO was no longer producing a RF output. As such we investigated the current requirements to achieve magnetic insulation within the MILO. This critical current is determined by the current required to achieve Brillouin Flow for a specific geometry with an applied voltage, the equation is shown in Figure 28.

$$I_c := \frac{I_\alpha \cdot \beta_0 \cdot \gamma_0 \cdot R_c}{d_0} :$$

Solving for concentric cylinders

$$I_c(R_1, R_2, V_0) := I_\alpha \cdot g(R_1, R_2) \cdot \gamma_0(V_0) \cdot \ln\left(\gamma_0(V_0) + \sqrt{\gamma_0(V_0)^2 - 1}\right) :$$

$$I_\alpha := 8500 \text{ A} : \text{ is a constant}$$

$$g(R_1, R_2) := \ln\left(\frac{R_2}{R_1}\right)^{-1} : \text{ is the geometric factor as defined by concentric cylinders.}$$

$$\gamma_0(V_0) := \frac{e \cdot V_0 + m_e \cdot c^2}{m_e \cdot c^2} : \text{ is gamma defined at the position of the Anode}$$

Figure 28: Brillouin Flow equation for concentric cylinders.

Since the critical current required to initiate magnetic insulation is determined by the distance of separation of the anode and cathode two approaches were investigated to increasing the current beyond the critical current. The first approach involved increasing the cathode diameter to decrease the MILO impedance increasing the current through the device, see Figure 29. The original cathode had a diameter of 25 mm, a second cathode of equal length was created with a diameter of 28 mm.

While this increased the required critical current, test show that the increase in the current through the MILO surpassed the requirements, see *Figure 30*.

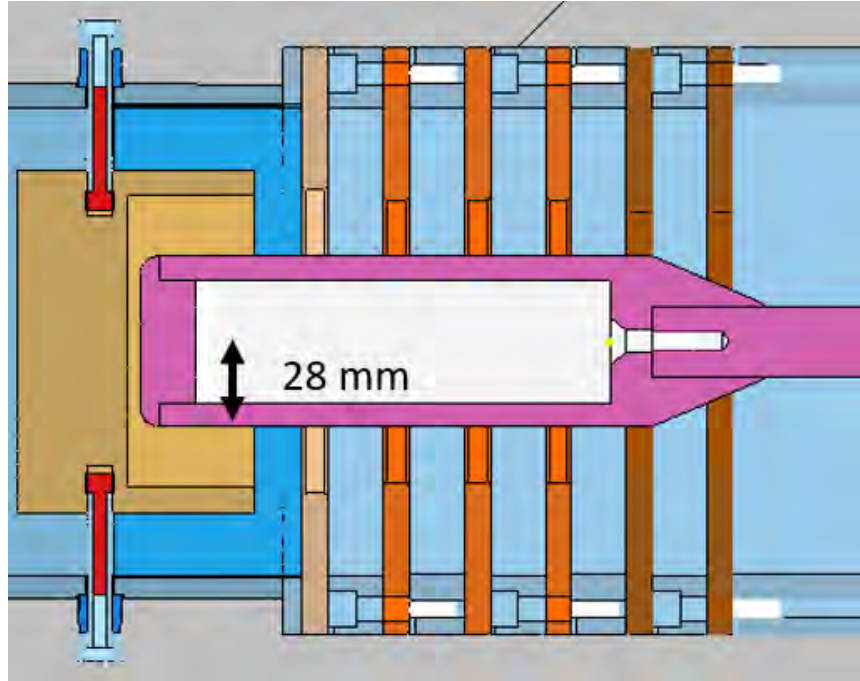


Figure 29: CAD model indicating the radius of the MILO's cathode to be altered.

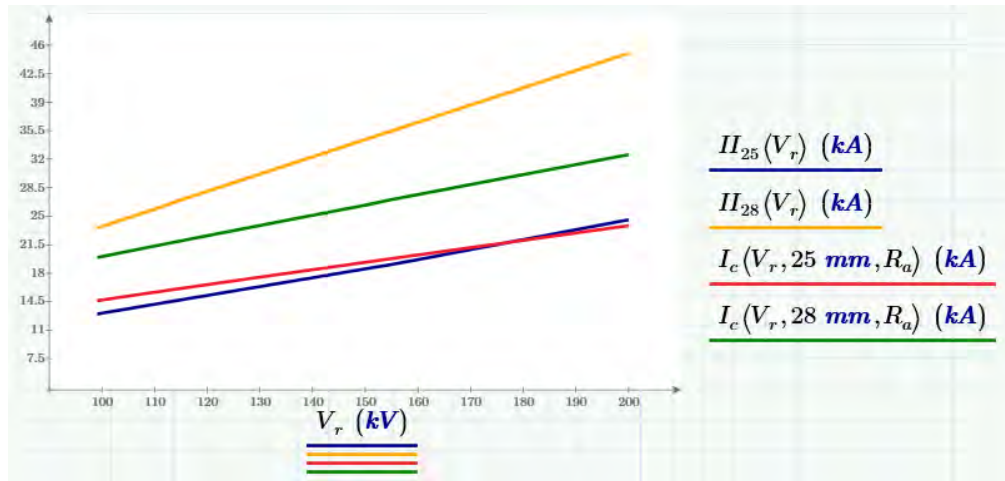


Figure 30: A plot of the experimental currents for cathodes with radius of 25 mm, II_{25} , and 28 mm, II_{28} , and their respective critical currents for a voltage range from 100 kV to 200 kV.

Testing the 28 mm resulted in a lower of the MILO impedance to 4.25 Ohms and increased the current through the MILO to near 22.7 kA with a voltage pulse peaking at 95 kV, shown in *Figure*

31. This met the required critical current for magnetic insulation and while an RF signal was produced its power was extremely low in the tens of kilowatts.

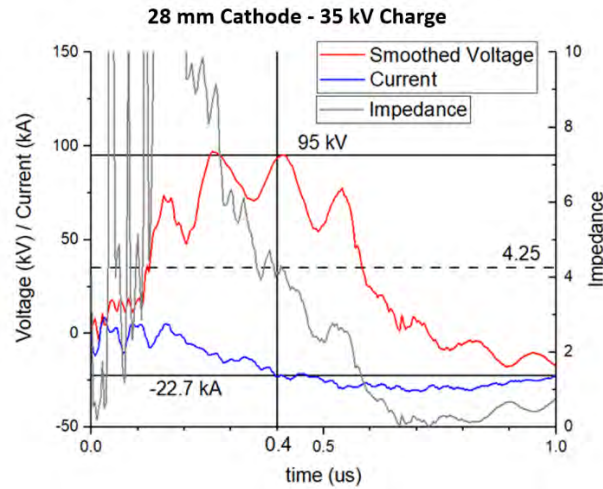


Figure 31: The voltage and current waveform for a shot with the 28 mm cathode with the charge voltage of 35 kV. The current through the MILO is greater than the required 20 kA for the critical current.

The second method was to lower the resistance of the series resistance, shown in Figure 27, within the Marx to 2 Ohms allowing for more current to flow into the MILO. Test shots were taken with the original 25 mm cathode attached, the results were a pulse with a peak voltage of 183.5 kV, current of near 28.8 kA, and a MILO impedance of approximately 10 Ohms. The peak output RF power was measured in the low 100s of kilowatts.

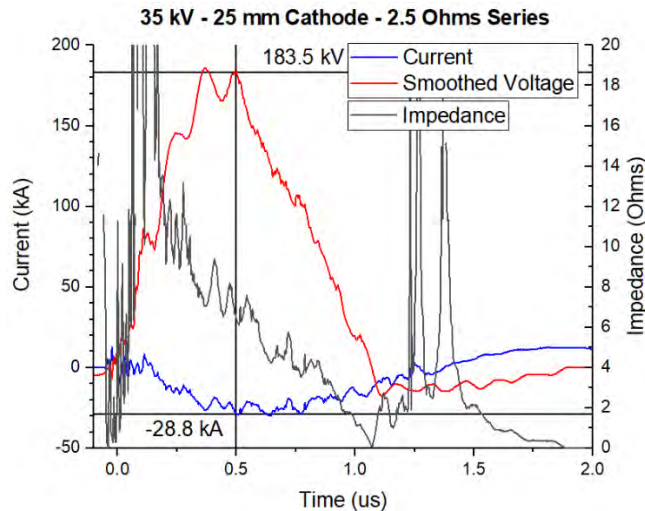


Figure 32: The current and voltage waveform for a shot with the 25 mm cathode with a charge voltage of 35 kV. The series resistance of the Marx was lowered to 2 Ohms. The current increased to 28.8 kA far exceeding the required 23 kA for the critical current.

As testing progressed it was noticed that the voltage waveform tended to collapse early in comparison to the current. Examination of the cathode tip showed that this was due to arcing from the tip of the cathode to the beam dump. By widening the gap between the two pieces the voltage waveform remained on for longer periods of time with little impact to the peak current through the device. The output RF signals for these tests performed with the 25 mm cathode are shown below in [Figure 33](#).

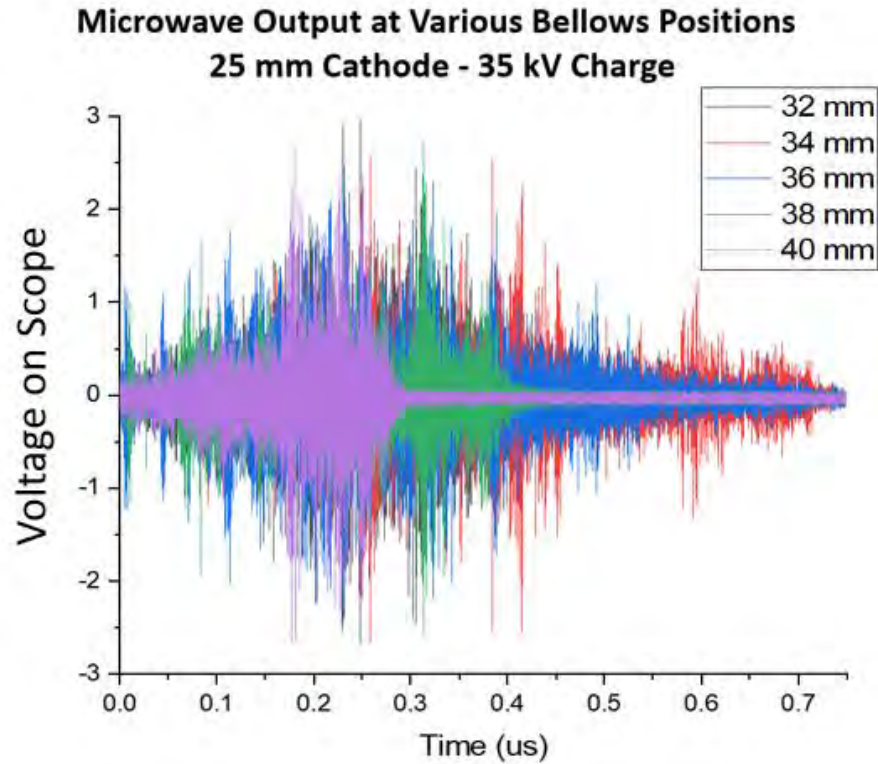


Figure 33: A series of overlaid RF outputs from the MILO comparing the output duration as it related to beam dump position. For each shot the MILO contained the 25 mm cathode, the series resistance of the Marx was 2 Ohms, and the capacitor bank was charged to 35 kV.

Cathode Development

Two in-house cathode materials and one commercially available cathode material have been tested and compared. Critical criteria include high current density ($>100 \text{ A/cm}^2$), turn-on times less than 100 ns, bakeability, and long lifetime. The end use is for MILO cathode development, as pictured in [Figure 17](#). The primary cathode materials under test were Commercially available bi-modal Carbon Fiber Velvet (ESLI) and TTU woven Carbon Fiber Velvet.

In order to manufacture our own carbon fiber velvet a loom was purchased for weaving. The primary carbon fiber thread of choice was a 3000 strand, 7 μm diameter type. This thread was wrapped around the warping board and cut to length. The thread count determines the weave width which for testing was 22 count for a width of 10 cm. The cut thread is then sleighed through heddles in the loom in a predefined pattern. Groups of heddles are then attached to different foot pedals that are raised and lowered individually. After tying the threads to the front and back apron rods, a shuttle is wound with cloth to weave through the threads. After a group of heddles is raised the shuttle is run through perpendicular to the threads, setting the pattern into the weave. An image of the threads on the loom is shown in [Figure 34](#).



Figure 34. Carbon fiber thread mounted on the loom.

Once the cloth has been woven and is cut from the loom the process of weaving the velvet pattern is begun. Needles are threaded through the loops created in the plain weave cloth, shown in [Figure](#)

35. Once all the needles are threaded, a high vacuum rated carbon-based epoxy is applied to the back of the weave. After the epoxy dries, the needles are removed and a surgical blade is used to cut the loops in to upright tufts.

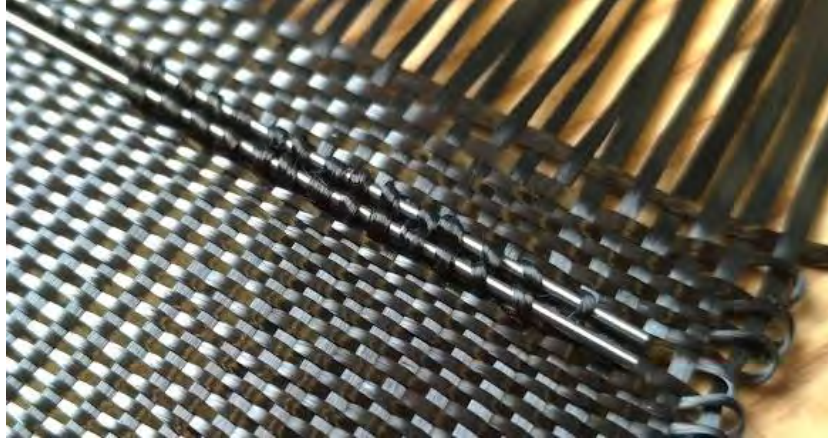


Figure 35. Needles looped through the plain weave.

The velvet cloth is then epoxied to a stainless steel base for testing in the vacuum chamber. Each upright tuft contains approximately 3000 fibers resulting in a total number of fibers of 3.3 million on a small, 5 cm diameter cathode, shown in *Figure 36*.



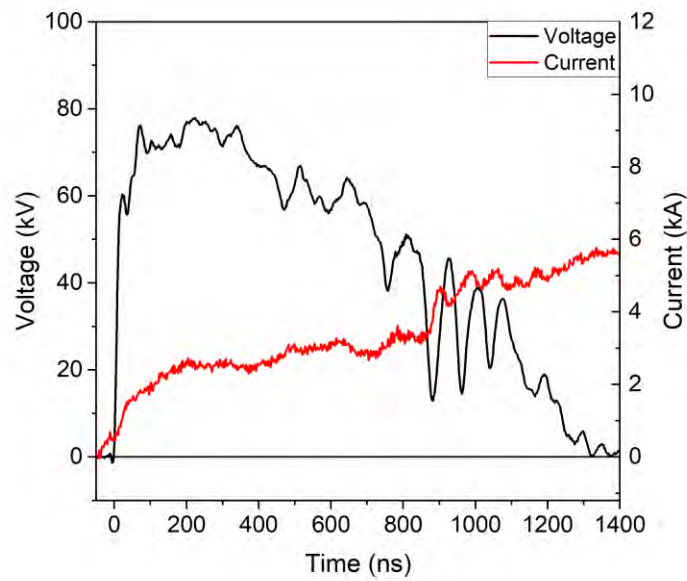
Figure 36. TTU carbon fiber velvet small cathode

The ESLI and TTU carbon fiber cathodes were tested in a vacuum chamber shown in *Figure 37*. The cathode position is variable using a linear translator which appears on the left side of the image. The anode is a honeycomb transparent design fashioned from pyrolytic graphite. The tube is driven with a 1kJ Marx generator.

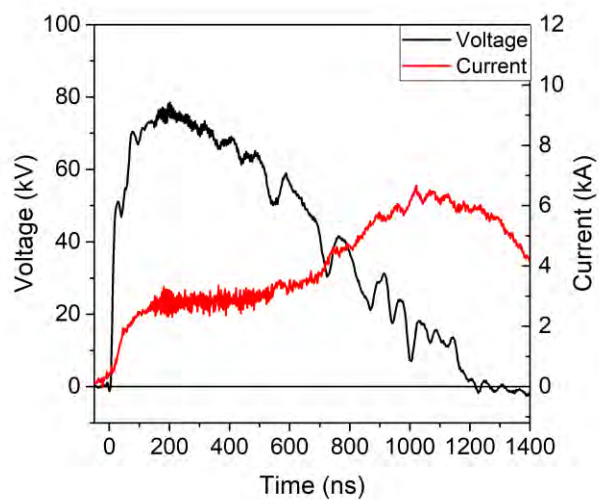


Figure 37. Cathode testing chamber.

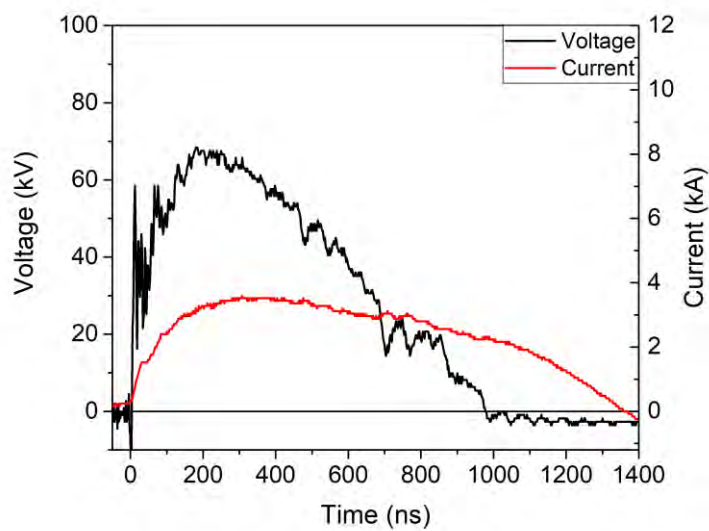
Numerous shots were taken with each cathode type varying the AK gap distance and applied voltage. A typical shot recording the voltage and current on the ESLI cathode and TTU cathodes is shown in *Figure 38*. The resultant impedance at these conditions is shown in *Figure 39*.



(a)

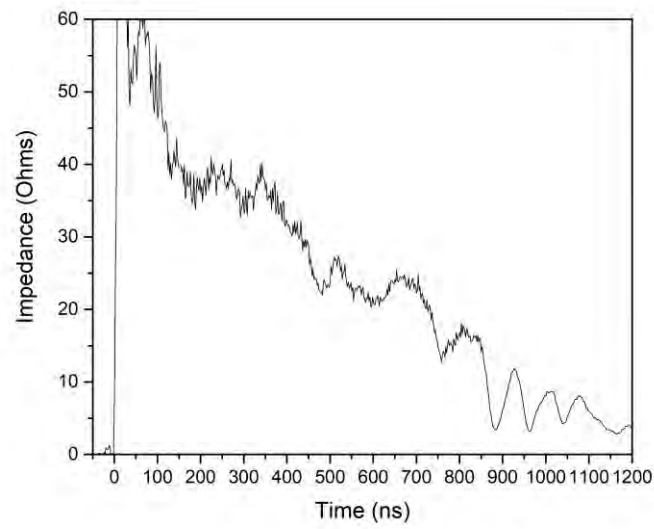


(b)

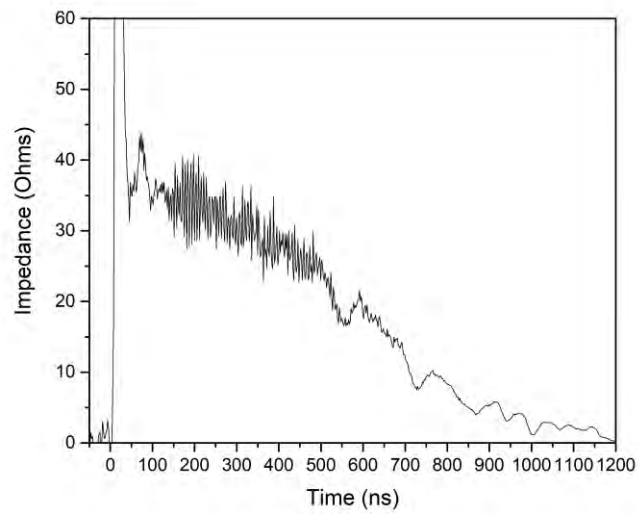


(c)

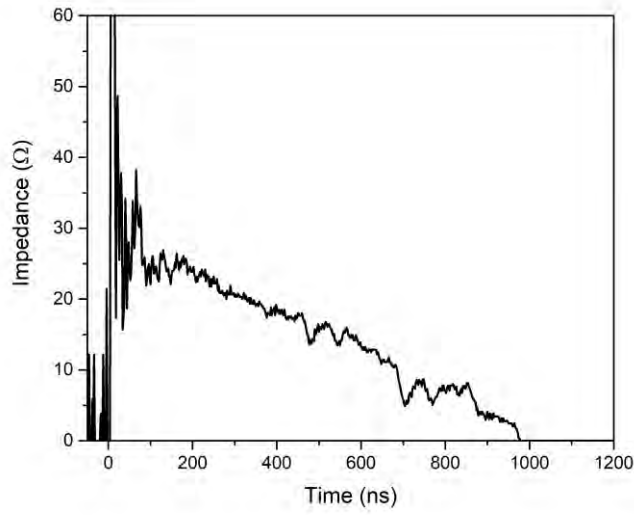
Figure 38. Voltage and current waveforms with the (a) ESLI cathode, (b) TTU monomodal cathode and (c) TTU bimodal cathode tested at a Marx charge voltage of 13 kV and an AK gap distance of 12 mm.



(a)



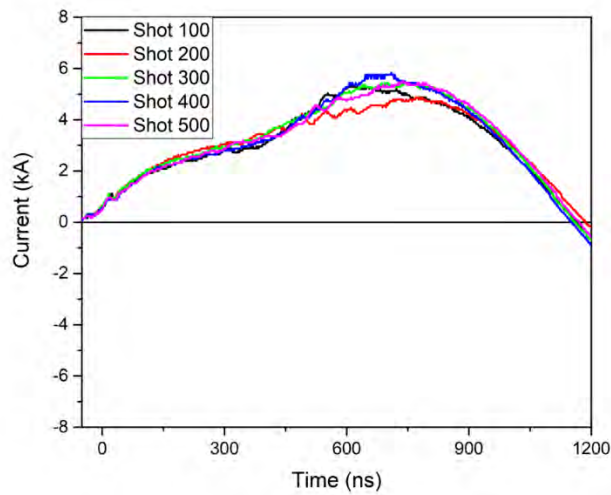
(b)



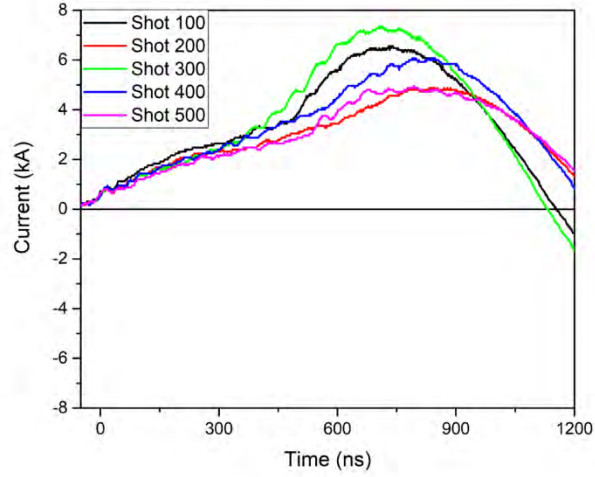
(c)

Figure 39. Load impedance with the (a) ESLI cathode, (b) TTU monomodal cathode and (c) TTU bimodal cathode tested at a Marx charge voltage of 13 kV and an AK gap distance of 12 mm.

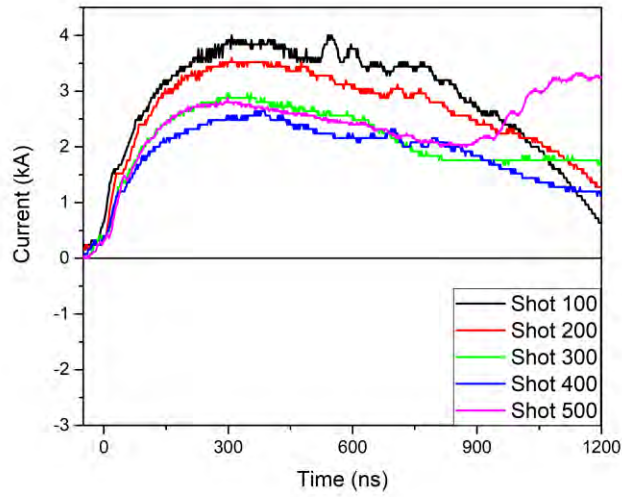
The significant impedance values occur between 0 and 500 nsec. For the ESLI cathode, the impedance starts at 60 ohm and gradually falls to 30 ohm during this time period. The TTU monomodal cathode takes slightly longer to turn on, and starts at 45 ohm and gradually falls to 25 ohm. For the TTU bimodal cathode, the turn on time is slightly faster than the ESLI cathode and starts at an impedance of around 35 ohm, then fluctuates between 30 ohm and 40 ohm for about 75 nsec before gradually falling to around 15 ohm.



(a)



(b)



(c)

Figure 40. Lifetime current over 500 shots with the (a) ESLI cathode, (b) TTU monomodal cathode and (c) TTU bimodal cathode tested at a Marx charge voltage of 13 kV and an AK gap distance of 12 mm.

The TTU monomodal, TTU bimodal, and the commercial bimodal cathodes, had their lifetimes tested by each receiving 500 shots from the Marx generator. The diode currents were compared

across every hundred shots to rate performance as ablation of the carbon fiber occurred. From the lifetime current waveforms, seen in *Figure 40*, the monomodal velvet seemed to be the most consistent, while the custom bimodal has longer pulse widths and a flatter top. The commercially available velvet had the greatest variance across the test regime, with no distinct trend appearing as more shots were fired.

High speed imaging was done both with a scintillator to see the e-beam output and directly at the A-K gap to determine beam uniformity and intensity. *Figure 41* and *Figure 42* show the images with the scintillator and direct imaging, respectively, with both images in each set of pictures on the same scale for image intensity.

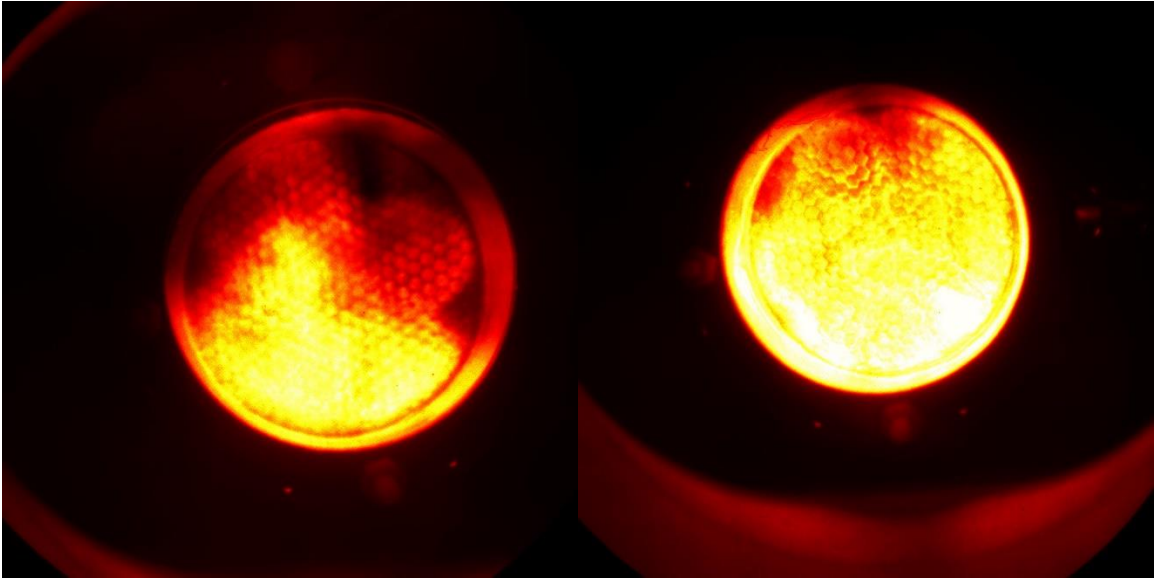


Figure 41. Scintillator imaging of the electron beam output of (left) ESLI cathode and (right) TTU monomodal cathode tested at a Marx charge voltage of 13 kV and an AK gap distance of 12 mm, on the same scale with 500 ns gate width.

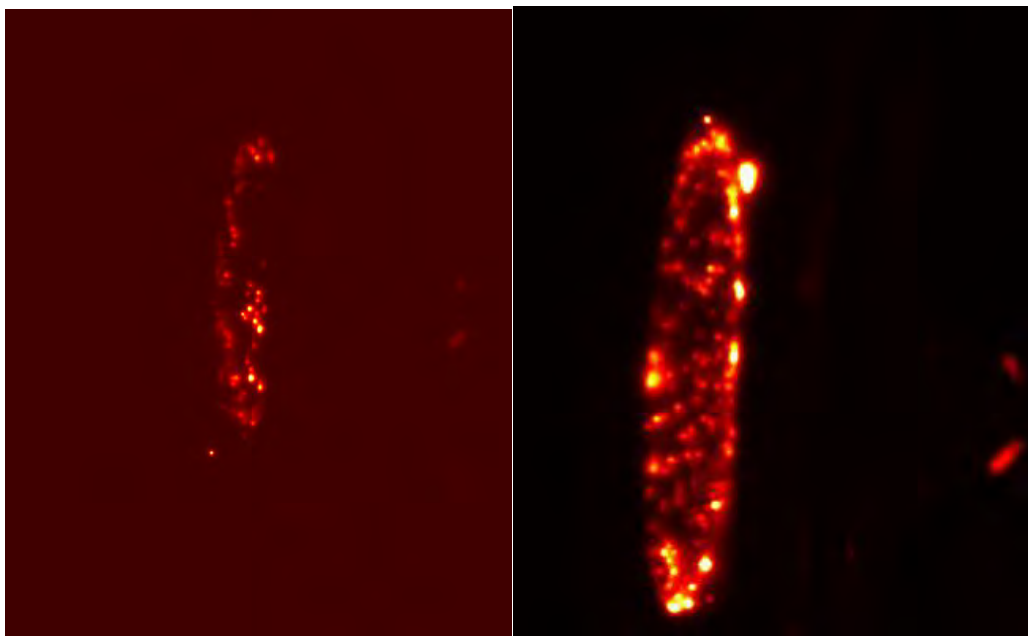
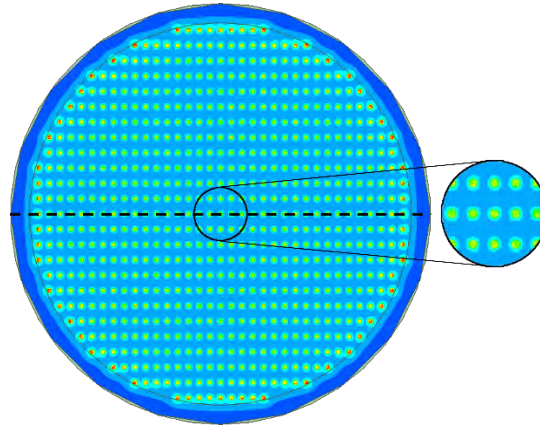
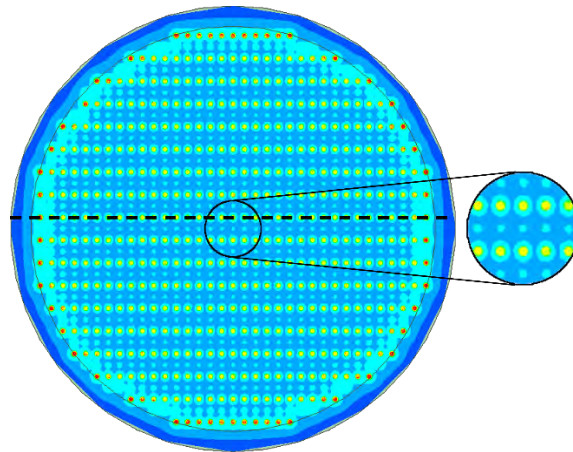


Figure 42. Direct imaging of the A-K gap of (left) ESLI cathode and (right) TTU monomodal cathode tested at a Marx charge voltage of 13 kV and an AK gap distance of 12 mm, on the same scale with 500 ns gate width.

Field simulations were done to determine what effects geometry could have on electron beam generation, looking at first at the electric field. The checkerboard patterned bimodal results in Figure b were interesting, and as such, a checkerboard pattern bimodal cathode is being developed currently for experimental testing.



(a)



(b)

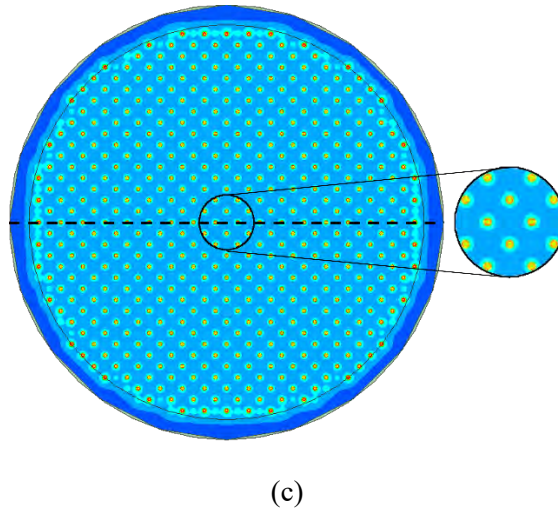


Figure 43. Electric Field Simulations of (a) monomodal cathode, (b) bimodal cathode and (c) bimodal cathode with a checkerboard pattern with 100 kV applied to the A-K gap and a gap distance of 10 mm.

3. Findings and Conclusions

There are several findings and conclusions during CY 2021 of this program. For the MILO testing, the peak output RF power of the MILO thus far has been 85 MW. While this is an appreciable amount of power it is still multiple times lower than the expected output power. We believe the primary reason for this is that the MILO does not fully turn-on until higher input voltage, above 400 kV. Thus, it may not be possible to drive the MILO with a compact pulsed power source such as the Marx generator currently in use.

Regarding the in-house fabricated carbon fiber velvet cathode, the results were very promising. Both the monomodal and bimodal cathodes performed as well or better than the ESLI cathode in all aspects of the testing. Our cathodes showed faster turn-on time, higher current density, and better e-beam uniformity.

4. Plans and Upcoming Events

Plans for the MILO testing are to add a PFL line to the output of the Marx generator. We currently have a large oil-filled PFL with an impedance of 10 Ω . The line is capable of delivering a 70 nsec square pulse into the 10 Ω MILO load. While the PFL is certainly not compact at 23 ft long and 3 ft diameter, it will allow us to deliver a square pulse at voltage levels > 500 kV. We believe we can make these changes and begin testing on the MILO by May 2022.

5. Transitions and Impacts

None

6. Collaborations

None

7. Personnel

Principal investigator: John Mankowski, 1 month effort

Team Members: Machinist, Lee Waldrep, 3 month effort
Technician, Joel Perez, 2 month effort
Technician, Dino Castro 2 month effort

8. Students

2 PhD students, 1 Master's student, 1 undergraduate assistant

9. Technology Transfer

None at this time.

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

- T. Buntin, M. Abide, K. Nagao, J. Dickens, R. Joshi, A. Neuber, and J. Mankowski, "Explosive Emission Cathode Evaluation for a Magnetically Insulated Line Oscillator (MILO)," *2020 IEEE International Conference on Plasma Science*, 2020.
- J. Williams, J. Dickens, A. Neuber and J. Mankowski, "A Solid-State, High-Voltage Pulse Generator with Microcontroller Control," *2020 IEEE International Conference on Plasma Science*, 2020.
- M. Abide, T. Buntin, J. Dickens, A. Neuber and J. Mankowski, "S-Band Magnetically Insulated Line Oscillator (MILO) with Adjustable Cathode/Beam Dump Overlap," *2020 IEEE International Conference on Plasma Science*, 2020.
- T. Buntin, M. Abide, J. Dickens, A. Neuber R. Joshi, and J. Mankowski, "Evaluation of Explosive Emission of Carbon Fiber Cathodes for High-Power Microwave Devices," *2021 IEEE Pulsed Power Conference*, 2021.

Publications in process from this project:

- T. Buntin, M. Abide, J. Dickens, A. Neuber R. Joshi, and J. Mankowski, "Evaluation of Explosive Emission of Carbon Fiber Cathodes for High-Power Microwave Devices," *IEEE Transactions on Plasma Science Special Issue on Pulsed Power Science and Technology*, 2022.

11. Point of Contact in Navy

Contact: Matt Mcquage, NSWCCD, E05, matthew.mcquage@navy.mil Kickoff meeting on 7/31/2018

Distributed Coordination of Aerial Swarms for High-Gain Wireless Transmission

Grant No. N00014-20-1-2389

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to September 30, 2021

Prepared by:

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Date Prepared: January 31, 2022

Project Title: Distributed Coordination of Aerial Swarms for High-Gain Wireless Transmission

Annual Summary Report: FY21

Principle Investigator: Jeffrey Nanzer, 517-432-8089, nanzer@msu.edu,

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Section I: Project Summary

1. Overview of Project

Abstract: This report provides a summary of progress made towards distributed synchronization of separate wireless systems for distributed beamforming operations. Distributed beamforming requires accurate synchronization of the electrical states of the nodes in a distributed array to ensure that transmitted signals arrive sufficiently aligned at the intended destination so that the signals add constructively, yielding significant increases in signal power at the destination. In this report, we summarize the objectives of this effort and report on advancements made in the areas of decentralized electrical state coordination, distributed localization, and experimental implementations of the concepts developed in this effort.

Objective: In this effort, we will develop novel decentralized coordination techniques for high-gain transmission from swarms of hundreds of nodes and evaluate the possibilities of achieving high-gain signal transmission using existing commercial off-the-shelf (COTS) microwave technologies. In particular, we will investigate new techniques for the coordination of large arrays using decentralized consensus algorithms based on physical-layer coordination of array element location, frequency, phase, and time. We will assess the feasibility of achieving high-power transmission under realistic system-level constraints, such as coordination errors, noise, array motion, amplifier efficiencies, and beamsteering errors, among others. The results of this effort will inform future high-gain microwave transmission concepts and identify any technology areas for future development to achieve greater capabilities than COTS technologies can provide. The proposed research directions are two-fold:

Develop a distributed approach enabling the coherent coordination of the spatio-electrical states of arrays consisting of hundreds of nodes, investigate the possibilities of using distributed optimization for high-gain microwave signal transmission, and demonstrate distributed signal transmission in a scaled testbed.

Develop system design rules for achieving specified high-gain signal requirements, determine bounds on achieving high levels of coherent gain given system specifications, provide notional designs based on COTS technologies, and identify areas for future technology development.

Introduction: Current and future wireless applications, including sensing, communications, and high-power transmission, have driven the need for continual increases in transmitted signal gain. However, the ability to achieve high-gain wireless transmission of microwave signals is restricted by the traditional platform-centric model used to develop wireless systems, where single, large platforms are limited by aperture size, device power handling and efficiency, and heat dissipation, among other factors. Achieving increases in signal gain under the current platform-centric model requires redesigns of devices, apertures, or entire systems, an approach that is not only costly but

time-consuming. To overcome these platform-centric challenges, we propose a novel approach to high-gain microwave signal transmission using distributed, scalable arrays of small, low-cost platforms, each with individually low-power transmitters. In particular, coordinating separate wireless systems to create a coherent distributed phased array can yield dramatic system-level gains that cannot feasibly be achieved with a single platform, or even with non-coherent signal coordination on multiple platforms. These benefits include transmit power gains proportional to the number of platforms squared, significant spatial diversity affording robustness to interference and failures, and the ability to directly scale capabilities by simply adding or removing nodes in the array. The ultimate level of flexibility is achieved in an open-loop array, where the nodes self-align without using feedback from the target location. Whereas closed-loop distributed arrays are possible with signal inputs from the target, such approaches are limited in that the array can only direct signals back to the point of the emanating signal. In contrast, open-loop distributed phased arrays can arbitrarily steer beams to any desired angle.

Background: Achieving coherent transmission in distributed arrays requires coordination of the spatio-electrical states of the elements in the array; our group has pioneered efforts in developing technologies for high-accuracy coordination for distributed beamforming in small arrays of 2-4 platforms. Our group has extensive experience developing open-loop distributed phased arrays through our prior efforts developing and demonstrating critical technologies enabling fully open-loop coherent distributed transmission, which have demonstrated the feasibility of achieving and maintaining sufficient phase stability between separate platforms. In prior efforts, a high-accuracy microwave ranging technique using a novel spectrally sparse waveform achieved sub-mm range accuracy and was used to experimentally demonstrate the first open-loop coherent distributed transmission. Other efforts developed a novel one-way wireless frequency locking approach, which was used to demonstrate the first fully wireless open-loop distributed phased array. Current efforts are focused on building cognitive-enabled adaptive coordination algorithms that are robust to changing environmental conditions. The outcome of these efforts is that the basic coordination technology to achieve distributed phase coherence with small array sizes has been largely proven. The challenge for high-gain microwave applications is in creating a framework amenable to coordinating hundreds of nodes or more. The proposed effort is, to our knowledge, the first to investigate approaches to implementing distributed coordination in large-scale arrays of tens to hundreds of nodes, and to explore the implications of array scalability.

2. Activities and Accomplishments

In this reporting period, we made significant progress in the development of decentralized coordination and localization algorithms that will support distributed coherent operation in large arrays, and in centralized localization algorithms that will enable near-term experimental measurements of distributed beamforming. Specifically, in this reporting period we:

- Developed a decentralized approach to localization based on matrix completion of the Euclidean distance matrix and graph realization.
- Explored a centralized node localization based on node-level angle estimation.
- Developed and experimentally demonstrated a channelized decentralized frequency synchronization algorithm amenable to implementation in software-defined radio.

Our results on these topics are described in the following.

Decentralized Localization

For a distributed array to appropriately transmit coherent signals to a destination the nodes in the array must align the phases of their transmitters such that the emitted signals arrive in-phase at the destination. Since nodes are separated by an appreciable number of wavelengths, it is necessary to estimate the relative locations of the nodes with high accuracy in order to estimate the appropriate phase correction. We developed a decentralized consensus averaging allows the array to adequately determine the array Euclidean distance matrix (EDM) by sharing only the distances estimated by nodes to their neighbors (nodes with which they are wirelessly connected). The global variable necessary for phase correction is a global centroid, the estimation of which necessitates a complete EDM, i.e. one that includes range estimates between all nodes. In practice, not all nodes will be connected, thus the matrix completion step essentially estimates the unmeasured distances. We showed that the OptSpace algorithm provides a reasonable matrix completion approach. The algorithm for our case operated better with larger arrays: lower EDM RMS error was obtained with larger arrays and lower connectivity ratios than for smaller arrays with higher connectivity ratios. We investigated the impact of internode ranging errors and determined that the error of the resultant decreased in accordance with decreasing internode range error.

In this reporting period, we investigated the operation of the algorithm in terms of the estimated distance between nodes in the array and the estimated global array centroid. We assume that the array has reached consensus on the array partial EDM, i.e. the partial EDM on each node is identical. Each node estimates the complete EDM independently, from which the global centroid is computed. Nodes then estimate their relative distance from the global centroid. Fig. 1 shows an example partial EDM and an estimated completed EDM. Some errors are apparent, which will cause errors on the phase correction step; however, the goal is to ensure that the majority of the nodes in the array are sufficiently phase coherent, thus some errors in the process are tolerable.

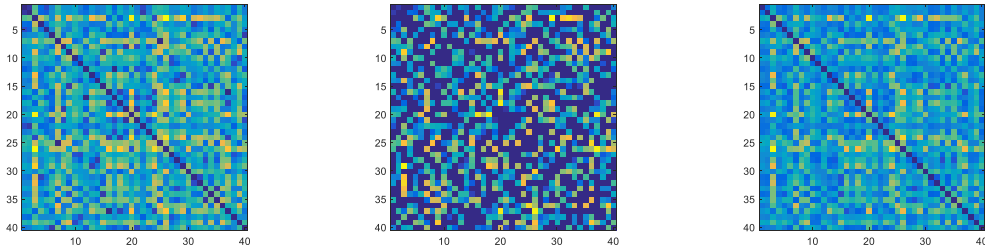


Figure 44. (Left) Actual EDM. (Middle) Partial EDM with 50% connectivity. (Right) Estimated EDM after matrix completion.

Fig. 2 shows the average error in estimating the relative position of each node to the global centroid (in m). The error scales inversely with the array size and the connectivity. While providing reasonable position estimates, the impact on angle estimation of the matrix completion and consensus EDM will be evaluated in our future work to determine the phase error impact.

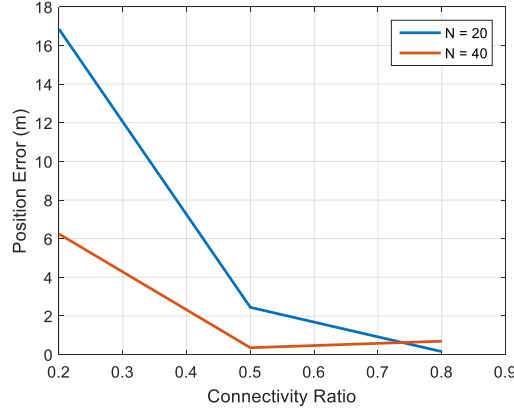


Figure 2. Average global centroid distance error (100 Monte Carlos) for arrays of 20 and 40 nodes versus connectivity ratio.

Centralized Localization Via Multilateration

Decentralized coordination requires the local exchange of ranging information that, while feasible, necessitates additional communication. While we work towards implementing this approach, we also explored a centralized localization approach that will provide the opportunity for nearer-term distributed beamforming experimentation. We consider centralized systems such as the one shown in Fig. 3.

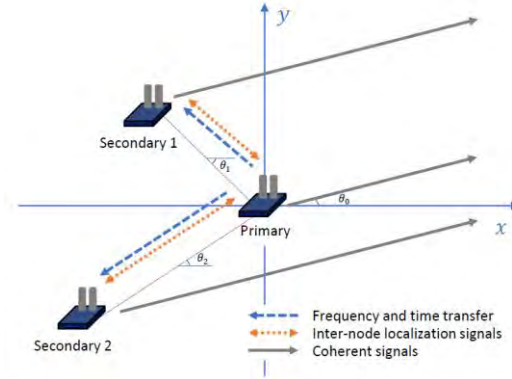


Figure 3: Hierarchical open-loop distributed array with one primary and two secondary nodes. θ_0 is the beamforming angle, θ_1 and θ_2 are the angles of the primary node relative to the planes of the secondary nodes.

In centralized systems, it is sufficient for the secondary nodes to localize themselves relatively to the primary node. Previously we assumed that the relative angle of the primary node to every secondary node was given, and we evaluated the ranging accuracy needed to achieve high coherent

gain. The coherent gain G_c represent the received power at the target from the synchronized CDA (with some synchronization errors) over the received power for the ideal case where perfect synchronization is achieved. For a given relative angle of the primary node, and when the effects of wireless frequency synchronization are not considered, a ranging root mean square error (RMSE) of $\lambda/15$, where λ is the wavelength of the carrier, is needed to obtain 90% of the ideal coherent gain level at a random beamsteering angle with a probability of 90%. When considering the effects of wireless frequency synchronization on the relative phase of the nodes, an RMSE of at most $\lambda/27$ was need to achieve the same level of coherent gain.

In practice, the angle is not known, making localization a much more challenging task. Estimating the range and angle separately to localize the primary node is not a feasible option for the majority of the cases. Thus, we focus in our work on implementing multilateration techniques to localize the nodes. Typically, in a centralized system, the secondary nodes would only need to localize the primary nodes to synchronize their phases. Multilateration can be done between only one secondary node and one primary node as it is going to be shown later in this document. However, utilizing all the secondary nodes in the array to localize the primary node cooperatively, gives much higher localization accuracies.

We previously explored a localization approach that relies on time of arrival (TOA). Instead of using multiple transmitter/receiver pair or nodes, it was possible to estimate the relative location of the primary node with low standard deviation (STD) by using the two-tone stepped frequency waveform (TTSFW) to estimate the time delay between the repeater of the primary node and the receivers of the secondary node. TTSFW is a time-delay estimation waveform that offers both high accuracy and scalability. Since TTSFW is highly ambiguous, and to boost the SNR of the received pulses, a repeater was used on the primary node. By using a repeater, it is possible to observe the target as a point source and it is possible to retransmit the received pulses on other bands, reducing the interference between transmission and reception. Fig. 4 shows the diagram and experimental setup that was used. It was possible to use the time difference of arrival (TDOA) instead of the TOA to localize the primary node, in this case, the transmitter on the secondary node needs to be placed on the primary node, and the repeater on the primary node would need to be removed. Although this reduces the complication introduced by using a repeater and two bands, nevertheless, the proposed approach offers a high flexibility and allows other nodes in the array to use different localization techniques when needed.

The approximate maximum likelihood (AML) estimator was used to localize the primary node once all the time delay or range is estimated between the primary node and the receivers of the secondary node. AML offers a very fast and accurate solution to multilateration, where the TOA equations are linearized before accurate estimates are obtained.

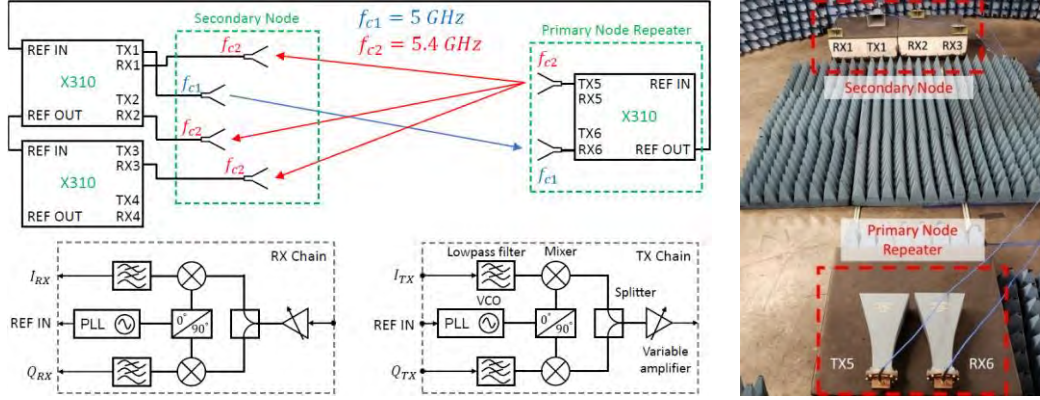


Figure 4: Diagram (left) and experimental setup (right) showing the proposed TOA experiment, where the secondary node transmits TTSFW signals to localize the primary node.

Experimental results were obtained by first setting TX1 (from Fig. 4) as the origin (0,0), as for the receivers RX1, RX2, and RX3, their coordinates in meters were (0.345, 0.384), (-0.408, -0.114), (-0.737, 0.384) respectively. The parameters of TTSFW were set as follows: 2 encoding pulses were used ($N=2$), the lowest tone was set as $f_1 = 500$ kHz, the maximum bandwidth was $BW = 9$ MHz, the time of each encoding pulse was $T = 49.9$ μ s, and the non-zero duration for every encoding pulse was $T_r = 24.95$ μ s. Using these settings, and by using the repeater, the received SNR was at least 30 dB, which is common for cooperative systems with small separation. The accurate range estimates between the transmitter and every receiver were as follows: $\sigma_1 = 6.08$ mm, $\sigma_2 = 6.1$ mm, and $\sigma_3 = 4.58$ mm.

Using these ranging STDs, the Cramér–Rao lower bound (CRLB) for TOA was calculated. Few experimental results are shown in Table 1. The primary node was only moved in front of the secondary node because directive horn antennas were used.

Although this technique showed low STD, it proved to be only feasible when the nodes are very close to each other. The CRLB for the localization is shown in Fig. 5, where it clear that only accurate location estimates are possible when the primary node is close to the secondary node. This shows that a better localization technique is needed to localize the nodes, especially when the nodes are widely scattered. Next we will explore the use of localization using multiple nodes.

Table 3: STD of the estimated locations along with the CRLB in meters. The first column shows the actual location of the primary node compared to the transmitter of the secondary node.

(x, y)	STD(x, y)	$\sqrt{\text{CRLB}(x, y)}$
(0, 3.6)	(0.0495, 0.0058)	(0.048, 0.004)
(-0.15, 3.6)	(0.05, 0.0035)	(0.048, 0.0032)
(0.15, 3.6)	(0.052, 0.0076)	(0.048, 0.0055)
(-0.12, 3.75)	(0.051, 0.0051)	(0.05, 0.0033)

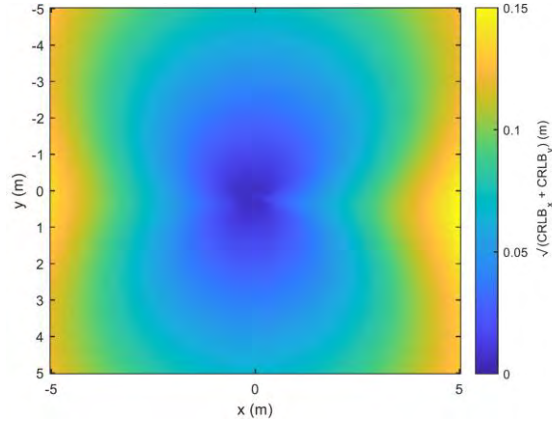


Figure 5: Square root of the summation of lower bounds for estimating x and y coordinates of the target at multiple locations.

Channelized Decentralized Frequency Synchronization

Decentralized frequency synchronization is achieved using a consensus averaging approach. The goal is to have all the distributed wireless nodes in the array reach a consensus value such that each node transmits/receives at the same carrier frequency. The frequency of the LO in each node is constantly changing over time depending on the frequency random walk and drifts of the LOs; however, consensus averaging is tolerant to such dynamics.

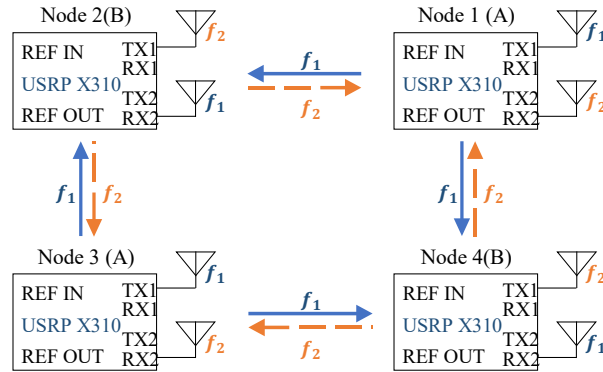


Figure 6. Block diagram of the full-duplex frequency consensus approach.

A channelized approach with multiple frequency bands is used in the presented algorithm to allow continuous and simultaneous transmit and receive of the frequency synchronization signals. We demonstrate the approach through a two-channel model for simplicity. The nodes in the array are separated into groups A and B; group A transmits the synchronization signals at the carrier frequency f_1 , and receives the incoming synchronization signals at f_2 . Group B transmits at f_2 and

receives at f_1 . It is preferable to split the nodes equally between the two groups to reach a consensus over the operational frequency with a minimal number of iterations. For instance, if we have four nodes in the array, such as in Fig. 6, nodes 1 and 3 would be assigned to group A, and nodes 2 and 4 would be assigned to group B. In this case, nodes 1 and 3 can each analyze their individual frequencies and the frequencies of nodes 2 and 4, and vice versa. Given that $f_1 \neq f_2$, the frequency shift is different at these two frequencies. To translate the frequency shift between these two frequencies, we use $\Delta f_1 = \Delta f_2 (f_1/f_2)$, where Δf_1 and Δf_2 are the frequency shifts at f_1 and f_2 observed by a given node. By using this relationship, it is possible for a node n to shift its transmitted frequency by Δf_1 or Δf_2 , based on the desired frequency shift obtained from the frequency consensus algorithm using the received frequency synchronization signals at f_2 or f_1 , respectively. The desired frequency shift Δf_i is added to the baseband frequency given that it is easier to accurately modify it compared to adjusting the carrier frequency. In this work we implement two frequency channels for a four-node experimental demonstration, however the approach can be extended to more channels for larger numbers of nodes.

The frequency synchronization signals are transmitted as follows: the first node transmitting on a given band (either using f_1 or f_2) transmits a continuous wave (CW) signal with a baseband frequency f_0 . The addition of f_0 , which was chosen as 1 MHz in this paper, ensures that the baseband signal is sufficiently far from the LO phase noise to be easily estimated. Consecutive nodes on this band transmit a CW signal at frequency increments of f_{node} , which was set to 500 kHz to ensure separability of the frequencies. It is thus possible to accurately estimate all the frequencies of a certain group of nodes. The values of f_0 and f_{node} depend mainly on the quality of the LOs, and in most of the cases they can be on the order of kilohertz.

The frequency of the incoming CW signals is estimated using a discrete Fourier transform. To refine the peaks in the spectral domain, the captured waveforms are zero padded with seven times the number of samples. The peaks are estimated using a sinc-function nonlinear least squares fit. Once the frequencies of all the received signals are estimated, the mean value of these frequencies (minus f_0 and any added f_{node}) along with the previously applied frequency shift Δf_i is calculated and used as the new frequency.

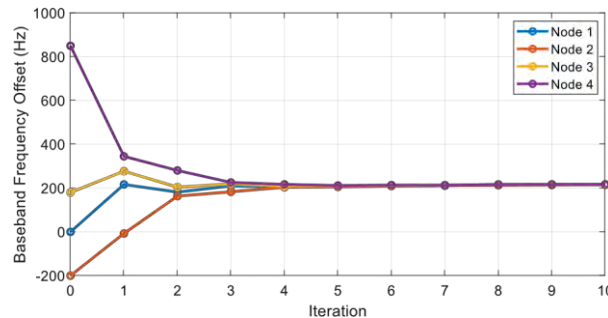


Figure 7. Simulation results showing the performance of the presented averaging consensus algorithm for wireless frequencies synchronization.

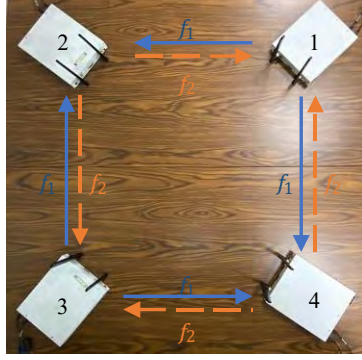


Figure 8. Experimental setup using four SDRs.

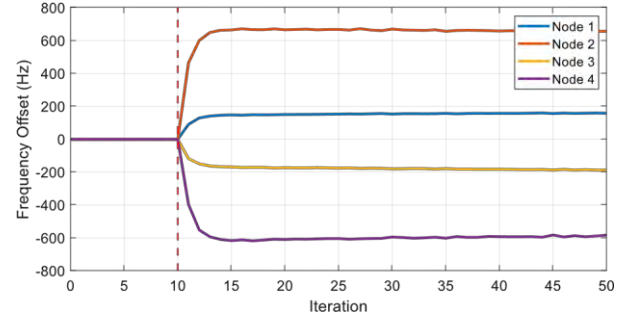


Figure 9. Estimated frequency corrections at each node. The frequency synchronization approach was implemented after the 10th iteration. The iterations had an interval of 3 seconds each.

The approach was evaluated through simulation and experimental validation. The simulated and experimental parameters were set as follows: sampling rate $F_s = 10$ MSps, capture time $t_c = 399.2 \mu s$, $f_0 = 1$ MHz, and $f_{node} = 500$ kHz. Using the network in Fig. 6, the frequency convergence of the nodes with ideal oscillators is shown in Fig. 7. As can be seen, after five iterations from the initial state, the frequencies of all the nodes converged to a mutual frequency.

We implemented the consensus frequency approach experimentally using Ettus Research X310 SDRs equipped with UBX 160 daughterboards (Fig. 8). The carrier frequencies were set to $f_1 = 1$ GHz and $f_2 = 2.7$ GHz. The applied frequency corrections are shown in Fig. 9. The synchronization algorithm was implemented starting at iteration 10. As can be seen, the desired frequency shift for each node reached a relatively stable state after five iterations. Fig. 10 shows the frequencies of the CW synchronization signals as observed by each node in the array, demonstrating that connected nodes reach a converged frequency relative to their offset frequencies.

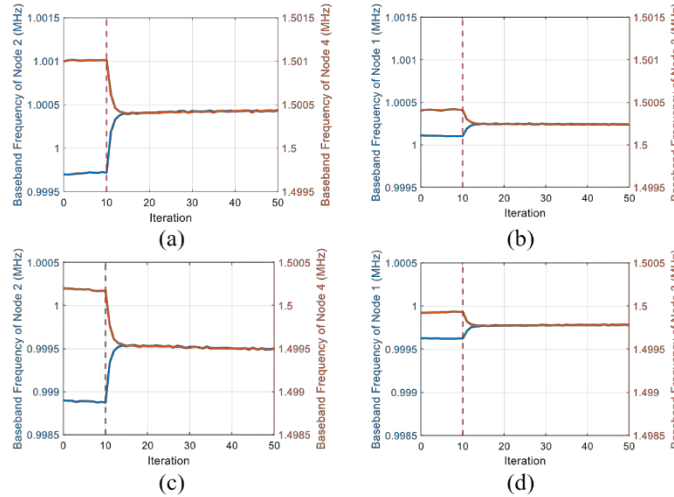


Figure 10. Estimated frequencies at nodes (a) 1, (b) 2, (c) 3, and (d) 4, demonstrating convergence to the intended offset frequency.

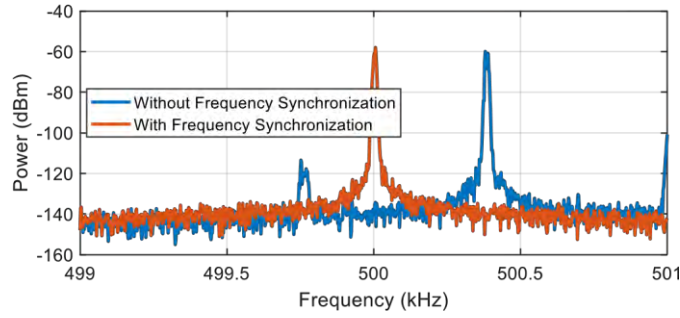


Figure 11. The output frequencies of the mixer that was used to mix the transmitted signals from nodes 1 and 3. Once synchronized, the output frequency is 500 kHz, which represents the intended frequency separation between the transmitted signals from nodes

To demonstrate that all the nodes in the array are operating on the same frequency after convergence, the transmitted signals from nodes 1 and 3 were mixed together and the output frequency was measured. As can be seen from Fig. 11, at first the output frequency was around 500.5 kHz. Once the frequencies of the four LOs were synchronized, the output frequency of the mixer became 500 kHz, which represents the actual separation between the frequencies of the transmitted CW signals from nodes 1 and 3. The same test was done for nodes 2 and 4 with identical results. Knowing that nodes 1 and 3 do not directly transmit or receive any signal from each other, this test proves that these two nodes, along with all the nodes in the array, were able to reach a consensus and synchronize their frequencies.

3. Findings and Conclusions

The results of this reporting period provide critical pieces of the foundation of a distributed approach to phase coherent transmission of microwave signals. In order to evaluate the bounds on high-gain transmission in future systems, we must determine the bounds on the coordination error of the coordination approaches. Furthermore, our intent is to also implement technologies that may support near-term distributed beamforming capabilities to determine transmitter requirements.

Decentralized localization is particularly challenging in practical networks because the process of calculating the locations of vertices in a graph from only the edge lengths is error-prone, particularly when the range estimates have noise and when the graph is not fully connected. Our initial algorithm has demonstrated that localization of the graph geometric centroid is possible with low error when the connectivity is high but not full. The error increases with decreasing connectivity. However, this error must still be tied to system parameters such as noise and range estimation error before its impact on beamforming can be characterized.

Centralized localization based on multilateration is feasible as a near-term solution, but can only provide localization for small arrays. However, we have begun to implement this approach in software-defined radio, and this will provide a basis for characterizing the impact of physical layer technologies as well as processing latencies on localization and therefore beamforming performance.

The implementation of a distributed channelized frequency consensus algorithm provided a feasible approach for experimentation of hardware limitations on distributed consensus algorithms. For

frequency synchronization, we developed a novel channelized architecture that mitigate the impact of oscillator phase noise and frequency resolution challenges.

The results above provide the foundations for determining the error bounds on coordination that will be investigated in the coming months of this program.

4. Plans and Upcoming Events

In the next year we will focus on three principal topics: advanced decentralized coordination algorithms for aligning frequency and phase, hardware implementations of wireless coordination to support distributed beamforming, and investigating bounds and limitations on transmit power.

Our decentralized coordination algorithm will be expanded to include estimation of the frequencies and phases of neighboring nodes to support full phase alignment for beamsteering. This can be accomplished with a similar consensus averaging approach. We will explore the steady-state phase error and approaches to minimizing the error. Hardware-based implementations will be based on software-defined radio implementations. Initially, we will expand our work on frequency consensus, and will add phase consensus. These will be used to implement distributed beamforming experimentation. Once the steady-state error is characterized through theory, simulation, and experiment, we will investigate transmit technologies and their bounds on obtaining high power transmission from multiple nodes.

PI Jeffrey Nanzer was named a Distinguished Microwave Lecturer for the IEEE Microwave Theory and Techniques Society for the 2022-2024 class for his work on distributed phased arrays. Approximately 25 invited talks will be given on this topic, which will include the results of the work in this effort.

5. Transitions and Impacts

N.A.

6. Collaborations

Based on our work in this effort we have begun discussions on distributed high-gain beamforming with engineers at Lawrence Livermore National Laboratories.

7. Personnel

Principal investigator

- Jeffrey Nanzer
- ~1 person month of effort in the reporting period
- National Academy Member: No

8. Students

This project supported two PhD students during the reporting period:

- William Torres

- Serge Mghabghab

9. Technology Transfer

N/A

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Archival Publications

- H. Ouassal, M. Yan and J. A. Nanzer, "Decentralized Frequency Alignment for Collaborative Beamforming in Distributed Phased Arrays," in IEEE Transactions on Wireless Communications, vol. 20, no. 10, pp. 6269-6281, Oct. 2021, doi: 10.1109/TWC.2021.3073120.

11. Point of Contact in Navy

N/A

12. Acknowledgement/Disclaimer

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Ultra-High-Efficiency Relativistic Magnetron and Improved MILO Capabilities

Grant No. N00014 -19-1-2155

Annual Report for Fiscal year 2021

Period of Performance: October, 1, 2020 to September 30, 2021

Prepared by:

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This work was sponsored by the Office of Naval Research (ONR), under grant number N00014 - 19-1-2155. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Grant or Contract Number: N00014-19-1-2155

Date Prepared: January 20, 2022

Project Title: Ultra-High-Efficiency Relativistic Magnetron and Improved MILO Capabilities

Annual Summary Report: FY2021

Principle Investigator: Edl Schamiloglu, 505-277-6095, edls@unm.edu, University of New Mexico, Department of Electrical and Computer Engineering; Salvador Portillo, 505-277-1311, sportil@unm.edu, University of New Mexico, Department of Electrical and Computer Engineering

Section I: Project Summary

1. Overview of Project

The relativistic magnetron is the most compact and efficient high power microwave source. The University of New Mexico (UNM) has been studying relativistic magnetrons for nearly 20 years. We published a review article on the topic in 2019. Our recent work has focused on techniques to mitigate axial leakage current, and through a very productive collaboration with our colleagues at The Technion, we have made substantial progress through the introduction of the split cathode. In addition, the split cathode has made it possible to perform joint studies with the Naval Surface Warfare Center Dahlgren Division (NSWCDD) using their superconducting magnet.

UNM has also been developing a magnetically insulated line oscillator (MILO) over the past few years to study plasma formation and evolution in the device, and mitigating such plasmas to achieve higher efficiency operation. Additional funds were requested and received to construct a transmission line to facilitate MILO experiments. In addition, collaborations are ongoing with several partners on cathode development, theoretical studies of desorption, and spectroscopic diagnostics.

In terms of the Navy relevance of the project, this project extends the UNM/University of Michigan (UM) successful HPRF partnership to MILOs, that were largely developed in the USA (1980's-2000), but recently have seen intensive research and development by near-peer adversary nations. Our goal is to address, via focused and transitional HPRF research, some of the critical problems facing Navy operations due to asymmetric electronic threats, such as those faced by Marine warfighters in forward operating bases to those in littoral waters, and protection of high value targets, such as U.S. embassies in potential hot spots around the globe. These asymmetric electronic threats can come in the form of small airborne electronic drones, perhaps even COTS-type devices, employed in boat or automobile-sized machines.

Abstract: This annual report summarizes activity on the recently awarded ONR grant “Ultra-High-Efficiency Relativistic Magnetron and Improved MILO Capabilities,” covering the period October 01, 2020 – September 30, 2021. We present progress on the incorporation of the split cathode in the magnetron with diffraction output (MDO) and the traditional relativistic magnetron with radial extraction. The split cathode has enabled experiments at NSWCDD where the NSWC MDO utilized a cryomagnet with a long uniform magnetic field. In addition, the work on the UNM MILO has been progressing with significant advances in simulation space and progress on hardware construction.

Objective: The objectives of this research are to i) increase the HPRF power/electron beam power efficiency of relativistic magnetrons and explore the MILO to further improve its performance. The MILO portion of this research is in collaboration with UM.

Introduction: The University of New Mexico (UNM) group excels in designing novel HPRF source concepts of relevance to the Navy, and then validating the source designs in experiment. We are pushing the boundaries on the relativistic magnetron through the use of a split cathode, an idea originally proposed by our colleagues at The Technion but investigated jointly. In addition, UNM is seeking to further the magnetically insulated line oscillator (MILO) through basic studies of surface plasmas within the device. This project seeks to continue this basic research program that has been in collaboration with our colleagues at UM. Investigating frequency agile magnetrons with diffraction output (MDOs) and MILOs will be an important consideration of our work.

Ultra-High-Efficiency Relativistic Magnetron

The thrust of our relativistic magnetron and MDO work has changed since FY20 Q4. The use of a “split cathode,” first proposed by collaborators at The Technion but investigated collaboratively with UNM, allows for trapping of the electrons in a squeezed state but without requiring the formation of a virtual cathode (Fig. 1 left). This suppresses all leakage current and is a much simpler implementation than a magnetic mirror field. After a comprehensive series of PIC simulations, UNM manufactured a split cathode and had it anodized and shipped to NSWC in summer 2021. It turns out that the split cathode is the silver bullet to enable testing UNM’s MDO at NSWC. The cryomagnet that NSWC acquired has a very long magnetic field and there is concern that electrons might follow the magnetic field lines and destroy the output window (Fig. 1 right). The split cathode solved this problem and enabled testing at NSWC in FY22 Q1.

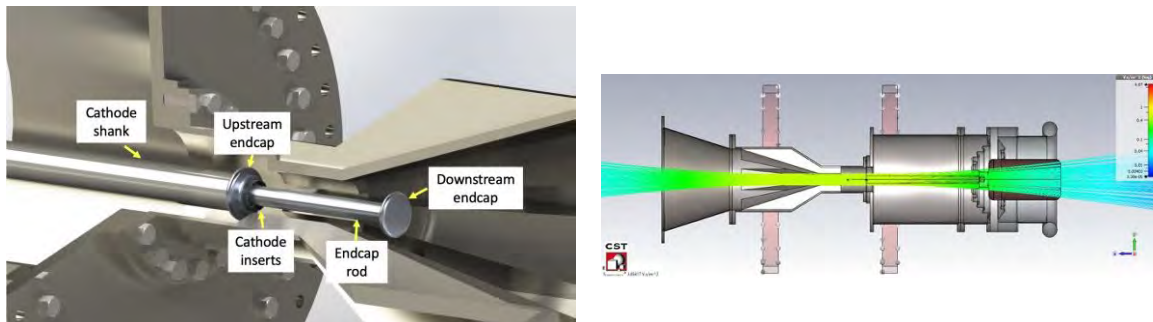


Figure 1. Left: The split cathode with its downstream endcap prevents electrons from traveling to the output window. Right: Magnetic field lines from the NSWC cryomagnet go straight into the output window of the MDO.

UNM performed another comprehensive series of PIC simulations to guide the NSWC experiments and shared the results with them. UNM provided voltages, values of magnetic field, and other key parameters for NSWC to explore. The experimental campaign took place FY22 Q1.

UNM also explored the relativistic magnetron (radial extraction) with split cathode, as well as the MDO with split cathode in a collaboration with The Technion. In FY21 all the effort at UNM was

in theory and PIC simulations. UNM did manufacture a split cathode and had it anodized for its own use in FY21 Q4. Experiments at UNM commenced FY22 Q1. Two journal articles were published in FY21 that derived from the UNM/Technion collaboration.

The fruitful collaboration with The Technion also led us to investigate a relativistic magnetron where the anode block is segmented, allowing for rapid penetration of a short pulse magnetic field. Two journal articles were submitted based on this work and the publications appeared in FY22.

The Magnetically Insulated Line Oscillator

The MILO is a crossed field HPM generator comprised of two structures; an inner conductor that serves as an electron field emitter, and an outer conductor that contains the slow wave structure and is ultimately where the electromagnetic energy is generated. Figure 2 (repeated from last year's report for convenience) shows a schematic of the AFRL hard tube (HT) MILO.

Our MILO overall goals are to develop solutions to allow the MILO to deliver the highest possible energy and peak powers possible. To this end we are approaching the problem in a multipronged manner. First, we are collaborating with AFRL/RX colleagues and with a small business (DexMat) to develop high current density cathodes based on carbon nanotubes that can meet the current required by HPM sources with fast turn on at low fields and with little outgassing. Second, we are heavily invested in numerical simulations to solve the essential problem of frequency agility/variability and gap closure. Our models have successfully showed that we have solved the former and have applied for a patent on this solution. Third, we are conducting fundamental research on plasma evolution from desorbed neutrals. These neutrals, mostly hydrocarbons, are adsorbed into the first few monolayers of all materials and, when heated, are liberated and then become ionized which in turn leads to gap closure and ends the production of radiation (analogous to poisoning of the beam and turning the device off).

These problems are key to fundamentally changing the path to providing the naval warfighter an asymmetric capability to engage multiple disparate targets and thus dominate the battlefield. This will be done via an HPM source that is compact, long pulse, high peak power and frequency agile.

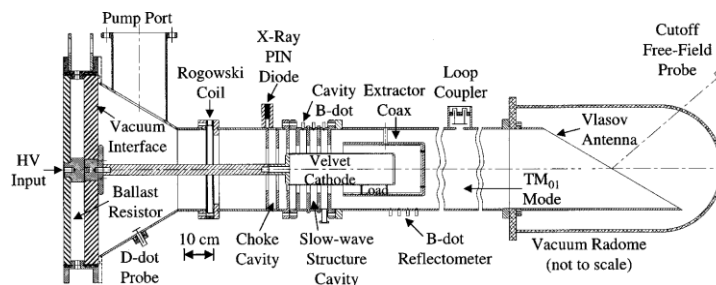


Figure 2. Schematic of the AFRL HT MILO.

Background: The approach that is being followed in the research under this grant is to i) utilize comprehensive PIC simulations using UNM's various virtual prototyping tools (ICEPIC, MAGIC, and the Large Scale Plasma (LSP) code – which can handle surface plasmas in the MILO) and then validate the simulations using experiments. A modified PI-110A accelerator is used for the MDO and relativistic magnetron experiments, and a Marx/PFL will be used to drive the MILO. Additional funds were requested and received for a transmission line build for the MILO. The MILO will be

fitted with spectroscopic diagnostics to compare experimental results with LSP simulations. Novel cathodes are also being developed for the MILO.

2. Activities and Accomplishments

Ultra-High-Efficiency Relativistic Magnetron

UNM and NSWC have been meeting periodically. UNM and The Technion meet biweekly.

Figure 3 presents MAGIC simulation set-up of the UNM MDO with a split cathode. (NSWC uses the identical MDO.) Figure 4 presents the simulation results. During a biweekly meeting with our colleagues from The Technion we discussed these results. A question then came up. Why is it that the high efficiency and high powers we observed and published in simulations and experiments for the MDO with a transparent cathode are not manifest with the split cathode? The conclusion that we drew is that the MDO with a split cathode is a very different device than the traditional MDO with transparent cathode. It seems that the optimized design of the MDO with the transparent cathode might not be the optimum for the split cathode, particularly the angle of the diffraction output.

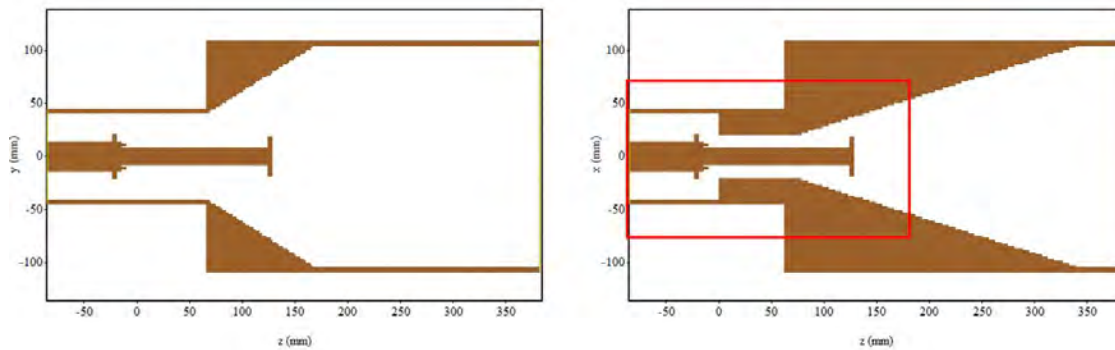


Figure 3. MAGIC simulation set-up for the UNM MDO with split cathode.

The split cathode parts were machined at Continental Machining and anodized at the vendor recommended by Continental. Ph.D. student Artem Kuskov noticed some fine cracks in the anodization and will meet with the vendor. Our collaborators in Israel recommended a 120 μm -thick coating, but the vendor could only go to 100 μm . Two sets of these parts were made, one for NSWC and one for UNM. We decided to go ahead and ship a set to NSWC while Artem works with the vendor to discuss the coatings. We decided to proceed with the NSWC experiments and UNM can work on its hardware to improve and will send to NSWC if needed. Figure 5 (left) presents photos of the parts and Figure 5 (right) presents photos from a microscope.

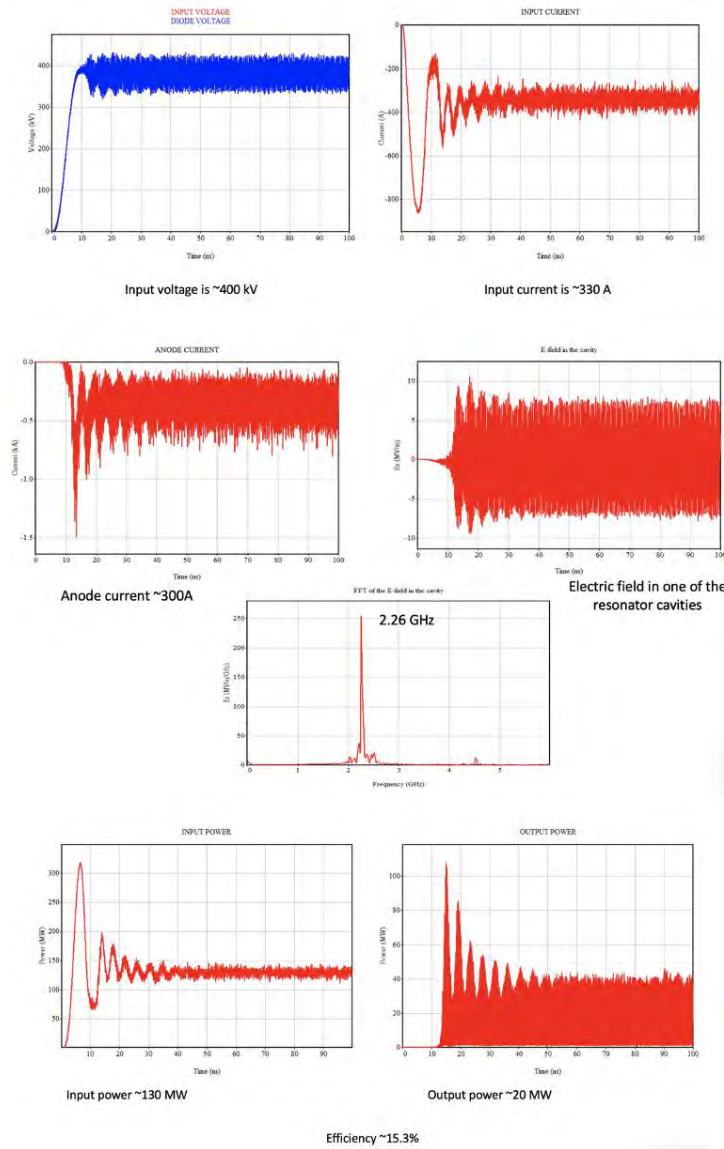


Figure 4. MAGIC simulation results for the geometry in Fig. 3.

UNM performed a comprehensive series of PIC simulations to guide the NSWC experimental testing plan. UNM also performed a comprehensive series of PIC simulations to guide UNM experiments in early FY22.



Figure 5. Left: Photograph of the anodized split cathode parts that were shipped to NSWC. Right: Photograph of the anodization taken through a microscope.

The Magnetically Insulated Line Oscillator (MILO)

We completely rebuilt our Marx generator. The transmission line we are building is receiving additional updates in numerical space so as to ensure that our models provide the correct output for the MILO. This means that we are paying very close attention to the peaker switches as these are crucial to having a fast risetime and, thus, will improve the efficiency of the MILO.

Our cathode test bed, based on a Linear Transformer Driver (LTD) of NRL design, is functioning and various cathode materials have been tested.

We received additional cathode material from our DexMat/Drexel partners. This necessitates a new configuration for the target holder, which we modified. The two new configurations will be characterized not just for current density capability at different operating voltages, but we will have our spectroscopic and interferometric diagnostics on these shots as well, measuring desorption of neutrals. Recall that this is a critical radiation stopping issue when the neutrals are ionized and in turn neutralize the beam. The nature of the neutrals (are they hydrogen or perhaps hydrocarbons?) as well as the depth of ionization and the location of these plasmas are critical measurements. Figure 6 shows the “as-received” cathodes. The white material is PVA that is used for support and was removed during final bake out at 500 Celsius.

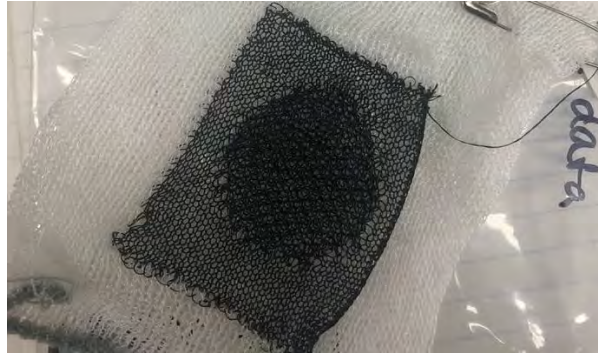


Figure 6. Photograph of the “as-received” DexMat/Drexel cathode material.

Our simulation work in FY21 has shifted from ionization work to modeling of a new ~ 550 MHz MILO. As part of this work we are varying the number of cavities to find an optimum configuration, aside from the typical three or four that are commonly used for radiation production. It is our goal to generate a governing law for maximizing this quantity. Additionally, this will also allow us to work on improving the efficiency of the device by varying the cathode-to-anode geometry which was one of our stated goals at the onset of this grant. We believe that there are realizable gains that will have an impact on the lethality of HPM sources. Finally, although early in our work, we are working on numerical simulations that can have a chirped effect on the output of the device. This chirping will generate not the typical train of monochromatic waveforms, but variations in the amplitude and spectral content, perhaps useful for irradiation experiments. More of this will be presented in FY22.

Finally, the spectroscopic diagnostics in support of the MILO and outgassing is continuing in a new collaboration with Ken Hara (Stanford) and ongoing collaboration with Yitzhak Maron (Weizmann Institute of Science).

3. Findings and Conclusions

For the ultra-high-efficiency relativistic magnetron work, the split cathode and related work has been a major breakthrough that is enabling experiments at NSWC and advancing the relativistic magnetron and MDO work at UNM. The collaboration with colleagues at The Technion has been extremely fruitful.

For the MILO, the Marx has been refurbished and the transmission line build has commenced. Various cathode materials have been received and are being tested using the LTD. LSP simulations are ongoing, both for the 2.4 GHz MILO, and for the 550 MHz design. Spectroscopic diagnostics are being tested in preparation for MILO experiments in FY22.

List of Abbreviations

A-K – anode-cathode gap
CsI – cesium iodide
ECE – Electrical and Computer Engineering
HPRF – high power RF
HT MILO – hard tube MILO
LTD – linear transformer driver
MDO – magnetron with diffraction output
MILO – magnetically insulated line oscillator
NSWCDD – Naval Surface Warfare Center
Dahlgren Division
PIC – particle-in-cell
TC – transparent cathode
TFA – time-frequency analysis
TLD – thermoluminescent dosimeter
UM – University of Michigan
UNM – University of New Mexico
VC – virtual cathode

Administrative Point of Contact

Timothy Wester – Sponsored Projects Specialist
(505) 277-1264, osp@unm.edu

4. Plans and Upcoming Events

For the ultra-high-efficiency relativistic magnetron work, the plans in FY22 are to analyze the experimental data from NSWC. In addition, UNM will begin testing of the MDO with split cathode in FY22 as well.

For the MILO, we hope to complete the transmission line build and commence experiments. In addition, spectroscopic measurements, cathode testing, and LSP simulations will continue.

5. Transitions and Impacts

As part of its collaboration with NSWCDD, UNM is transitioning its MDO with split-cathode. In addition, we are presently developing/designing a new MILO for use in irradiation of targets of interest to the Naval warfighter. This will include our novel frequency agile design. We will transfer any cathode developments for this design which will be fielded at Dahlgren Navy facilities.

6. Collaborations

Agency/Org	Performer	Project Name	Purpose of Research/ Collaboration
NSWCDD	John Kreger, Jack Chen, and Jon Cameron Pouncey	HPM collaboration	We discussed proceeding with MDO and transparent cathode testing at NSWC
AFRL/RX	Steven Fairchild	HPM cathode collaboration	We are discussing collaborative research on HPM cathodes
AFRL/RD	Brad Hoff and Sterling Beeson	HPM cathode and switch collaboration	We are discussing collaborative research on HPM cathodes and pulsed power switches/CsI coatings
Technion, Haifa, Israel	Yakov Krasik and John Leopold	Comparison of magnetic mirror vs. cathode rod and reflector	Optimize suppression of magnetron leakage current via an electron beam in a squeezed state
Weizmann Institute of Science	Yitzhak Maron	Diagnostics	Time-resolved spectroscopic diagnostics in high power, cross-field devices
Drexel University	Genevieve Dion	Cathodes	Large area cathode assembly
DexMat	Dmitri Tsentalovich	Cathodes	Providing base material for sewn cathodes
Verus Research	Sameer Hemmady	MILO	High impact outcomes
Stanford University	Ken Hara	Cathodes, MILO, MDO	Spectroscopy
Texas Tech University	Ravi Joshi	Cathodes, MILO, MDO	Effects of outgassing

7. Personnel

Principal investigator – Edl Schamiloglu (0.5 person month), National Academy Member (N)
 Co-investigator or Co-PI – Salvador Portillo (2.5 person months), National Academy Member (N)
 Business Contact – Timothy Wester, National Academy Member (N)
 Team Members – none
 Subs – none

8. Students

Artem Kuskov (Ph.D. student – 6 person months)
 Braulio Martinez-Hernandez (M.S. student – 6 person months)
 Robert Beattie Rossberg (M.S. student – 6 person months)
 Andrew Gilbert (B.S. student – 4 person months)
 Chris Rodriguez (B.S. student – 4 person months)

9. Technology Transfer

N/A – except for ongoing collaboration with NSWC DD on MDO and MILO, and joint experiments.

10. Products, Publications, Patents, License Agreements, etc.

Peer-reviewed publications acknowledging this grant:

- a. Producing a Magnetized Lower Energy, High Electron Charge Density State Using a Split Cathode
- b. Physics of Plasmas
- c. J. Leopold, Y. Krasik, Y. Bliokh, and E. Schamiloglu
- d. Keywords: high power microwaves; virtual cathode; magnetron with diffraction output; MDO; squeezed state
- e. Distribution Statement: Unlimited release
- f. Publication Status: published
- g. Publication Identifier Type: DOI
- h. Publication Identifier: 10.1063/5.0022115
- i. Publication Date: 12 October 2020
- j. Volume: 27
- k. Issue: 103102
- l. First Page Number: 103102-1
- m. Publication Location: College Park, MD
- n. Acknowledgement of Federal Support? Yes
- o. Peer Reviewed? Yes

Peer-reviewed publications acknowledging this grant:

- a. Mode Control by Rearrangement of the Slow Wave Structure in a 12-cavity Relativistic Magnetron with Diffraction Output Using Single-Stepped Cavities Driven by a Transparent Cathode
- b. AIP Advances
- c. Y. Li, M. Liu, C. Liu, J. Feng, E. Schamiloglu, M.I. Fuks, W. Jiang, F. Li, J. Han, and X. Yang
- d. Keywords: high power microwaves; magnetron with diffraction output, MDO, transparent cathode, stepped cavities
- e. Distribution Statement: Unlimited release
- f. Publication Status: published
- g. Publication Identifier Type: DOI
- h. Publication Identifier: 10.1063/5.0041527
- i. Publication Date: 02 March 2021
- j. Volume: 11
- k. Issue: 035306
- l. First Page Number: 035306-1
- m. Publication Location: College Park, MD
- n. Acknowledgement of Federal Support? Yes
- o. Peer Reviewed? Yes

Peer-reviewed publications acknowledging this grant:

- a. Experimental and Numerical Study of a Split Cathode Fed Relativistic Magnetron
- b. Journal of Applied Physics
- c. J.G. Leopold, M. Siman Tov, S. Pavlov, V. Goloborodko, Ya.E. Krasik, A. Kuskov, D. Andreev, and E. Schamiloglu
- d. Keywords: high power microwaves; virtual cathode; magnetron with diffraction output; MDO; squeezed state
- e. Distribution Statement: Unlimited release
- f. Publication Status: published
- g. Publication Identifier Type: DOI
- h. Publication Identifier: 10.1063/5.0055118
- i. Publication Date: 15 July 2021
- j. Volume: 130
- k. Issue: 034501
- l. First Page Number: 034501-1
- m. Publication Location: College Park, MD
- n. Acknowledgement of Federal Support? Yes
- o. Peer Reviewed? Yes

Conference Papers

None

Conference Presentations

A. Kuskov, D. Andreev, S. Hernandez, B. Martinez-Hernandez, E. Bartlit, E. Krammer, and E. Schamiloglu, "Recent Advances on the Magnetron With Diffraction Output," ICOPS 2020 (Virtual, December 2020).

J.G. Leopold, Y. Krasik, Y.P. Bliokh, and E. Schamiloglu, "Squeezing a Magnetized Relativistic Electron Beam Using a Split Cathode," ICOPS 2020 (Virtual, December 2020).

S. Portillo, J.M. Chen, and R. Beattie-Rossberg, "Spectroscopic Investigation of Plasmas Produced by Velvet Cathodes," ICOPS 2020 (Virtual, December 2020).

Books

None this reporting period.

Theses

None this reporting period.

Websites

MILO HPM laboratory: www.unm.edu/~sportil. MILO HPM laboratory web site showcasing some of the work being carried out on pulsed power and HPM source development.

Patents

1. S. Portillo, “Crossed-Field Frequency Tunability,” patent disclosure submitted December 2020.
2. S. Portillo, “Long Pulse MILO,” patent disclosure submitted December 2020.
3. S. Portillo, “Slatted Frequency Agile Source,” patent disclosure submitted December 2020.

Other Products:

None

11. Point of Contact in Navy

NSWCDD – John Kreger, Jack Chen, Jon Cameron Pouncey – we have periodic (at least quarterly) telecons.

12. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research (ONR), under grant number N00014 - 19-1-2155. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Electrochemical Prime Power Supply for a Repetitively Operated High- Power Marx Generator

Grant No. N00014-17-1-2847

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to August 31, 2021

Prepared by:

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Grant or Contract Number: N00014-17-1-2847

Date Prepared: November 25, 2021

Project Title: Electrochemical Prime Power Supply for a Repetitively Operated High Power Marx Generator

Annual Summary Report: FY21

Principle Investigator: PI David Wetz, 5127880848, wetz@uta.edu, University of Texas at Arlington (UTA), Arlington, Texas, 76019

Section I: Project Summary

1. Overview of Project

Overall Goals:

The overall goals of this effort have been to study electrochemical prime power sources that are viable for use in mobile pulsed power systems, to design and implement a software-based sizing tool that engineers can use to optimize their prime power source, and to design, build, and use a high voltage capacitive-inductive-capacitive (CLC) testbed that can be used to study pulsed power capacitors.

Abbreviation List:

DEW: Directed Energy Weapon, UC: Ultracapacitor, LIB: Lithium-ion Battery, COTS: Commercial-Off-the-Shelf, DE: Directed Energy, EDLC: Electric Double Layer Capacitor, UTA: University of Texas at Arlington, PPEL: Pulsed Power and Energy Laboratory, HVPPC: High Voltage Pulsed Power Capacitor, CC: Constant Current, CLC: Capacitive-Inductive-Capacitive, VI: Virtual Instrument, cDAQ: Compact Data Acquisition, and EMI: Electromagnetic Interference

Future Naval Relevance:

The future Navy will employ countless different mobile platforms that will need to either house or generate their own electrical power. Electrochemical energy storage is a viable candidate for either buffering the onboard generation or to directly drive the load. Though lithium-ion batteries are most likely, possible energy storage technologies could include batteries (VRLA, lithium-ion, NiMH, etc.), ultracapacitors, hydrogen (fuel cell), and mechanical flywheels, among others. Lithium-ion batteries, the premier battery chemistry, face countless challenges before they will be deployed widescale, but progress is being made. Research is needed to understand the viability of using these technologies and this effort is aimed at studying lithium-ion batteries and ultracapacitors for ONR. Because there are so many energy storage options, tools are required to help Naval engineers design a prime power source that is optimized for size, weight, and power. Such a tool has been designed here. Finally, many of the directed energy loads the future Navy will employ will rely on high voltage pulsed power capacitors and the operation and life of these components needs to be understood in all operational scenarios. The CLC testbed designed here provides a platform on which to study these components.

Abstract:

The US Navy has several active research projects aimed at bringing electrically powered weaponry to the fleet, typically referred to as directed energy weapon (DEW) systems. Though many technical advances are being made, most of these efforts are still in the research phase with many unanswered questions still to be answered before they will be deployed. Once deployed, the load

can only be as effective as the power supply that drives it. Though every DEW power supply is different, two common elements that many share are the prime power supply and the intermediate energy storage, respectively. Regardless of whether the DEW is deployed on a ship or on a smaller, more mobile, platform, it must have a reliable and resilient power source from which to draw its prime power. The prime power supply may directly drive the DEW load, or it may feed energy to an intermediate energy storage device that supplies high power to the load. A power supply that operates on its own or in some sort of hybrid fashion with the platform's existing power source is required. Energy storage in the form of ultracapacitors (UCs) and lithium-ion batteries (LIBs) hold a great deal of promise for use as a prime power source for DEWs. These supplies must source high power in as compact a form factor as possible so there is still a great deal of research to be performed to understand how these devices will operate, age, and fail when operated at high power so that they can be properly considered and sized. Limited references are available for pulsed power engineers to use when designing a prime power supply. In the previous FYs of this effort, time was focused on developing empirically derived sizing tools that can be used when considering LIBs and UCs, respectively. Through additional support from the U.S. Army's Combat Capabilities Development Command C5ISR Center, the tool was finished in FY20 and it is available for use by the community. In FY21, all time was devoted to toward improving the operational reliability of a high voltage testbed, as high as 80 kV, on which to study high voltage capacitors at rates of charge and discharge. Though high voltage intermediate energy storage capacitors are technologically more mature and documented, there are still research challenges to overcome. Discharging them and recharging them at high current in a repetitive manner has been found to be hard on them and the testbed developed here provides a means to study them and what could cause failure in this mode of operation. This research will be discussed in detail here.

Objective:

The research supported by this grant has had objectives of studying primary and intermediate energy storage devices used in pulsed power supplies. The first year and a half of the three-year effort was focused on studying primary energy storage devices and establishing a framework for an empirically based sizing tool. The second year and a half has focused on developing a pulsed power test stand on which to study high voltage intermediate energy storage capacitors. The progress made on both objectives will be discussed here.

Introduction:

Task 1: Electrochemical Energy Storage Sizing Tool Development

There was no effort put into this task this year as it was completed in FY20; however, it will be reviewed briefly for complete record tracking of the work done on the grant. Electrochemical energy storage is being studied across the US Navy to fulfill the electrical power requirements that have arisen in their effort to become a more electric fleet. Many different chemistries are available commercially off the shelf (COTS) and each has unique properties with respect to its voltage, power, energy, impedance, and size characteristics, among many others. This makes choosing the correct energy storage for any application difficult and unfortunately there is no one-size-fits-all approach that can be taken. Energy storage manufacturers often design cells specifically for an application when approached by a customer. Even though they are designed for a specific application, the manufacturer's often make them available commercially to other customers once fabricated, meaning that cells of countless geometries are available with very few industry standards available. This only increases the challenges faced when sizing energy storage for an

application using COTS devices. When choosing a chemistry, there are many factors that should be considered. The high-power density of lithium-ion batteries and ultracapacitors makes them attractive for use in DE applications since they demand a compact power supply that can supply high power transiently. UCs are also referred to as electric double layer capacitors (EDLCs) for reference. UCs make sense in applications that require a power supply with high power, long life, and high safety but not high energy store. When higher energy stored is required, a LIB is likely a better choice, but they come with many tradeoffs that must be considered. Within the LIB category, there are many different chemistries to choose from, most of which have not been studied significantly under high power operation. These vast choices make the design of a prime power supply for DE applications a non-trivial task. During the first year of this effort, UCs and LIBs were studied to assess their operation and usable capacity at high power. Because these technologies are rarely used at the power levels required by DE applications, little is understood about how they perform, age, fail, and how to properly size them for a high-power applications. In the second year of this three-year effort, a framework was developed to advance the development of a MATLAB/SIMULINK® based sizing tool that can be used to assist pulsed power engineers with the design of compact prime power supplies; however, towards the end of the second year, the focus of the research changed towards studying high voltage intermediate storage capacitors and development of the sizing tool was stopped. In FY20, we were asked by US Army's Combat Capabilities Development Command C5ISR Center to expand the development of the sizing tool and with their additional funding, we were able to do so. The tool was completed at the end of FY20 and is available for use by the community using the database of cells it currently has.

Task 2: Study of High Voltage Pulsed Power Capacitors (HVPPCs) at High Charge and Discharge Rates

All effort performed in FY21 was focused on this task. In many DE power supplies, the prime power supply referenced in Task 1 is used to transfer energy into an intermediate energy storage element that is used to supply high peak power to the load. In many cases, HVPPCs are used as the intermediate energy storage. Electrostatic dielectric film capacitors with self-healing electrodes have proven to be the most reliable for pulsed power applications where short pulse discharges are required. Problems have been observed in high voltage capacitors when attempting to recharge them quickly between repetitive discharges. The capacitors are proprietary and not a great deal is known about their construction or any special design features. It is assumed that the capacitor being studied is a polypropylene metallized film capacitor. The capacitor has a rated capacitance of just under 30 nF and voltage rating of 100 kV. The capacitor is being used as storage within a multi-staged Marx generator driving a DE load. In order to study its performance and lifetime in an emulated operational scenario that involves a high-rate discharge, high-rate recharge, and a second high-rate discharge, a testbed was designed and assembled. The stand's design and construction were started in the second fiscal year of the grant. This year was spent continuing that development and as in FY20, many challenges were faced this year, but it is close to working reliably to study high voltage capacitors.

Background:

Since 2010, the University of Texas at Arlington's (UTA's) Pulsed Power and Energy Laboratory (PPEL) has been supporting the Office of Naval Research (ONR) in its study of electrochemical energy storage devices, power systems, and pulsed power systems. LIBs and UCs have been considered as technologies with potential for use in compact pulsed power systems. A Microsoft Excel based sizing tool was started in 2014 and was incrementally improved upon for future use in

studying how different LIB and UC technologies compare with respect to power supply size and weight. That tool has been considerably expanded over the years, including with support of this grant and support from the US Army's Combat Capabilities Development Command C5ISR Center in FY20. In the middle of the second fiscal year, the effort of this grant was redirected towards designing and setting up a testbed on which HVPPCs could be studied at high rates of discharge and recharge, respectively. The testbed is needed to study the performance and eventual failure mechanisms of the types of metalized film capacitors used in repetitive rate Marx generators. During this third year, the testbed was worked on with considerable difficulty but, as of this writing, it is working reliably.

2. Activities and Accomplishments

Task 1: Sizing Tool Development

As described in the objectives section, the first year and a half of this effort was focused on studying ultracapacitors for use as a prime power supply for a pulsed power system and on studying new methods for properly sizing high rate prime power supplies. This effort has been documented in previous FY reports. In FY20, we were asked by US Army's Combat Capabilities Development Command C5ISR Center to expand the development of the sizing tool. Since the focus of this effort had shifted to studying intermediate energy storage capacitors, the Army funded an additional student to continue this work. The tool is working and is available for use by the DE community. Only a quick summary will be given here.

The tool was developed using the framework that was started last year but with significant changes. Over the years, the PPEL has tested many different lithium-ion batteries and ultracapacitors for many different customers, developing a substantial database across a host of different C-rates at different temperatures. Using a reference written by Traub [1], the constant current data is converted into constant power curves and an empirical data curve fitting tool, built into MATLAB, is used to fill in data between the C-rates tested. The user enters the constant power that the supply must supply, the time it must supply it for, a minimum voltage, a maximum voltage, a size limit, and a weight limit. The tool then produces an output table that tells the user the minimum number of series/parallel cells that are needed to match their requirements for each cell type within the database. If certain cells are not able to meet the requirements, the cell is not presented as an option. A plot is shown that estimates the battery's conduction voltage and current. The tool only considers lithium-ion batteries at this time and recharge capability has not been built into it, but that functionality is coming soon. Figure 1 shows a screen capture of the tool as well as some sample curve fits that are within the cell database used by the tool for sizing.

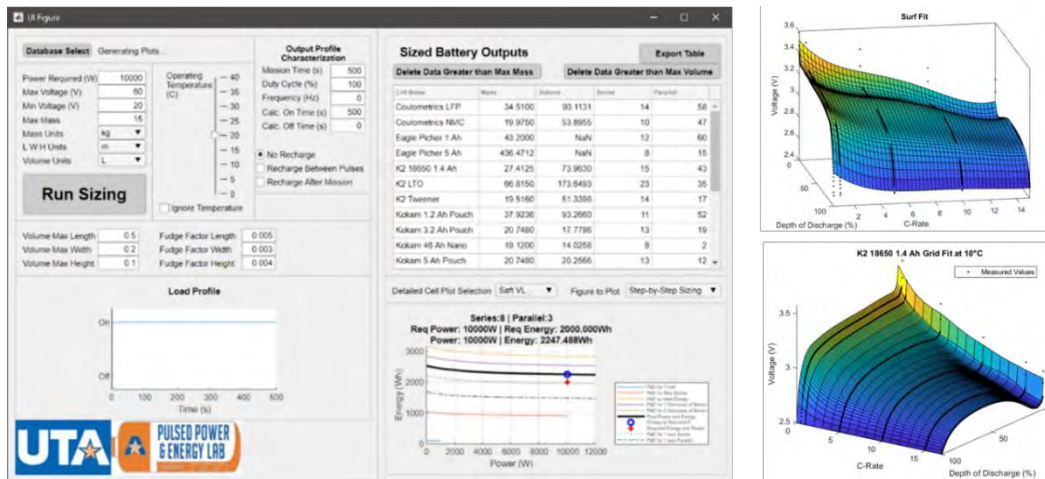


Figure 1. Screen capture of the UTA energy storage sizing tool (left) and sample curve fits (right). The black lines in the curve fits represent empirically collected data that it is fitted to.

Task 2: CLC Testbed Design, Reliability, and Testing

The work performed this FY was aimed at completing the design, construction, and operation of a CLC testbed that is used to subject HVPPCs to high current pulsed charge and discharge currents. As previously written, a team at NSWCDD has experienced problems when attempting to repetitively charge and discharge a manufacturer's HVPPCs at high pulsed currents. To better understand what is causing the failure, a capacitive-inductive-capacitive testbed has been designed, constructed, and commissioned. The design and fabrication of the testbed began in FY19 and while it works, its reliability is less than desirable. The work this year, which was only part time on a no cost extension, was focused on getting the system to be reliable. While many improvements have been made, it is still not quite where it needs to be.

A schematic diagram of the CLC testbed is shown in Figure 2. Simply described, two 40 kVDC power supplies, of opposing polarity, are used to charge two 80 nF HVPPCs, C1 and C2, that act as an intermediate energy storage. The unit under test is 30 nF capacitor labeled UUT. Initially the two 80 nF capacitors are charged to +40 kV and -40 kV, respectively, using the power supplies. The UUT is charged up differentially to 80 kV. Once charged, 'Discharge_Sparkgap' is triggered, causing the UUT to discharge its current into the load. A load impedance of 2 Ω is desired by the team at NSWCDD. Initially the 2 Ω load was constructed using several large water resistors connected in parallel; however, there was too much inductance in the load path, and this caused ringing during the discharge. To eliminate that easily, one 18 Ω resistor was used to critically damp the system. While that worked, the 18 Ω resistor severely reduced the output current below what is desired. This FY, the load portion of the testbed was redesigned to use a 2 Ω ceramic disk resistor located immediately next to the load. Hard bus is used to reduce the inductance to roughly 300 nH, creating a critically damped system. A photograph is shown in Figure 3.

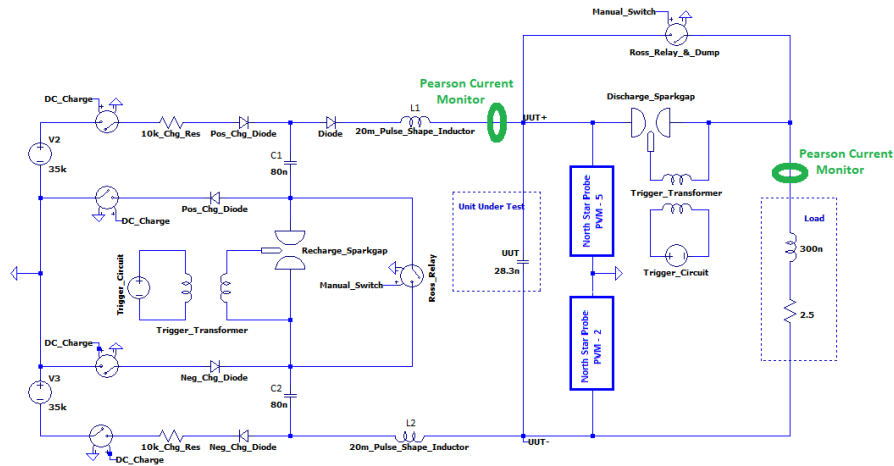
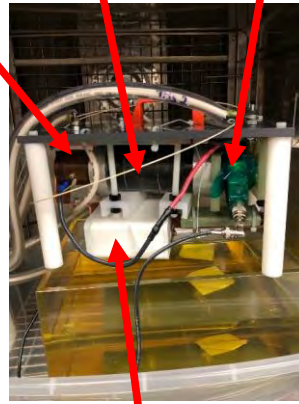


Figure 2. CLC circuit schematic describing the testbed constructed to study HVPPC operation.

Spark Gap 2 Ω Load Current Sensor



Capacitor Under Test

Figure 3. Capacitor under test and load section of the CLC circuit.

Once the discharge is complete, capacitors C1 and C2 are connected in series to bring them into the circuit. As shown in the schematic, there are two ways of connecting those capacitors in series. The first is the ‘Recharge_Sparkgap,’ while the second is to use a manually triggered 70 kV Ross Relay. Initially diodes were placed in both the positive and negative sides of the recharge path and this prevented a high voltage differential from being formed across the spark gap, preventing it from triggering. This problem was identified this FY and for the first time the spark gap was able to be used to initiate the recharge process. Though the spark gap now works, it does seem to induce a great deal of noise in the voltage measurement, discussed later, that is not seen when the manual relay is used. Occasionally, the recharge spark gap pre-triggers at the same time as the initial discharge spark gap and this causes big problems. Voltage reversal occurs due to the inductance in the recharge path that occasionally kills the expensive diodes. Identifying the ‘perfect’ settings of spark gap pressure and voltage has been difficult to nail down. Once the UUT is recharged, the ‘Discharge_Sparkgap’ is triggered to discharge the capacitor a second time. A second trigger circuit is connected in parallel with the first to trigger the spark gap and while this works much of the time, there are occasions when the second discharge does not occur and the circuit has to be quickly

discharged to try again. Figure 4 contains simulation results of the process just described. The upper plot overviews the full discharge, recharge, discharge event sequence. The middle figure zooms in on the first discharge event, which is ideally nearly identical to the second one, and the lower figure zooms in on the recharge event.

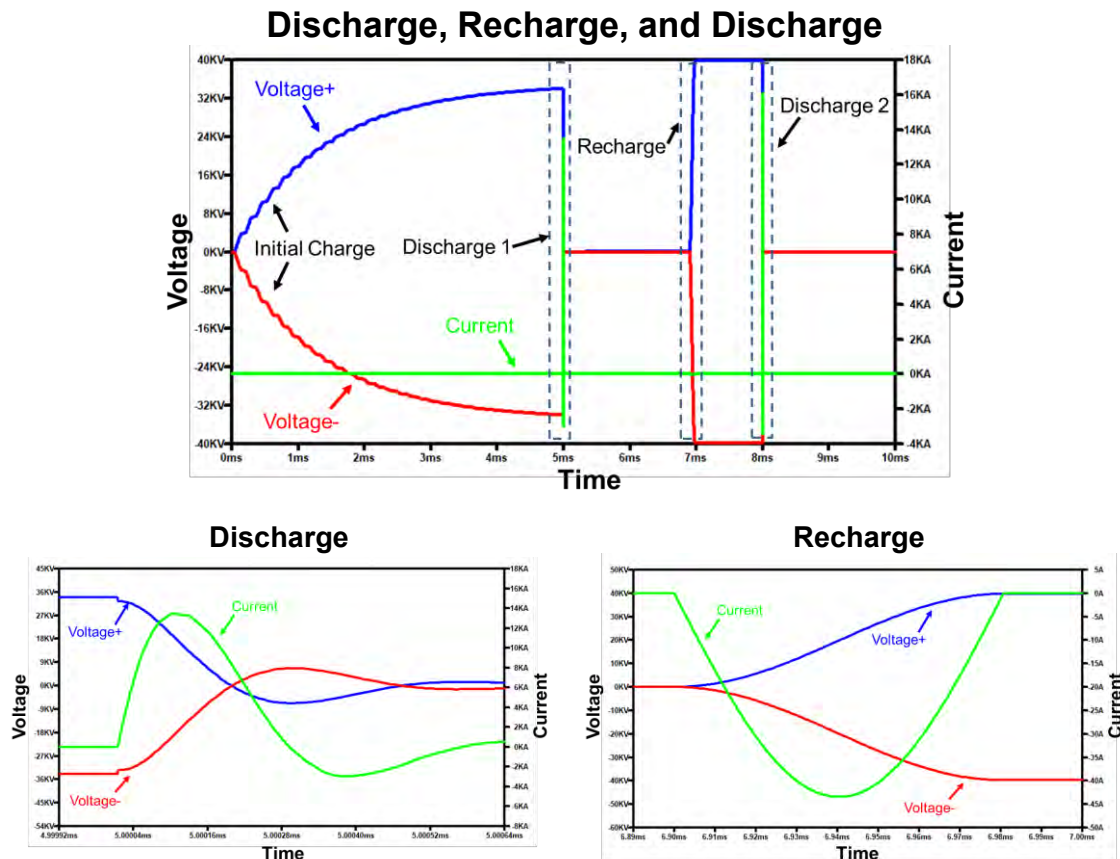


Figure 4. Simulated results of the CLC circuit demonstrating a discharge, recharge, and second discharge procedure. The first discharge is highlighted in the middle figure and the recharge is highlighted in the lower figure.

Photographs of the testbed as it currently sits are shown in Figure 5. The high voltage components are all contained within an aluminum enclosure that is lined with two pan liners and then filled with transformer oil for dielectric insulation. The testbed has been revised many times over the past two or so years, each time becoming cleaner and more organized. This year, another major revision took place to reduce wire length and clean up the organization of parts within the oil tank. The 80 nF capacitors, the capacitor under test, and the spark gaps were all provided by the sponsors. The charging inductors were contracted out for assembly. This year, time was also spent building a better shielded cabinet for the diagnostics and controller, seen in the lower right side of Figure 5. It is far from perfect, but it is better than the open cart it was on previously. The setup has been working for a little over a year now, but the reliability is just not quite there to make it ready to start testing capacitors of interest. This year has been a battle trying to improve that reliability and it's

disappointing to say that it is still not quite there. A few waveforms that demonstrate its operation, that were showed in last year's report, are shown in Figure 6.

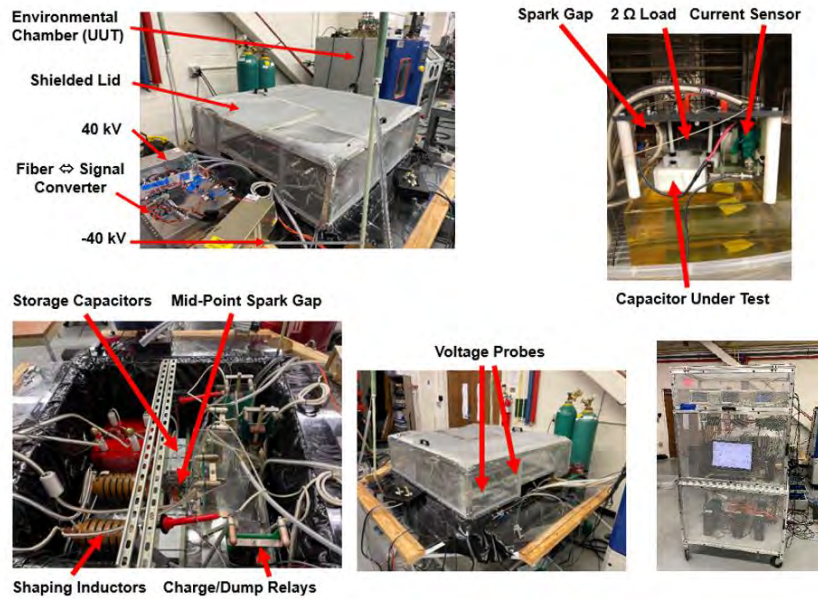


Figure 5. CLC testbed as it sits in June 2021. An photograph of the full testbed is shown in the upper left. A zoomed in view of the UUT and load portion is seen in the upper right. A view of the high voltage components in the oil tank is seen in the lower left. A photograph showing the voltage probes is seen in the lower middle figure. A photo of the shielded data acquisition cart is seen in the lower right.

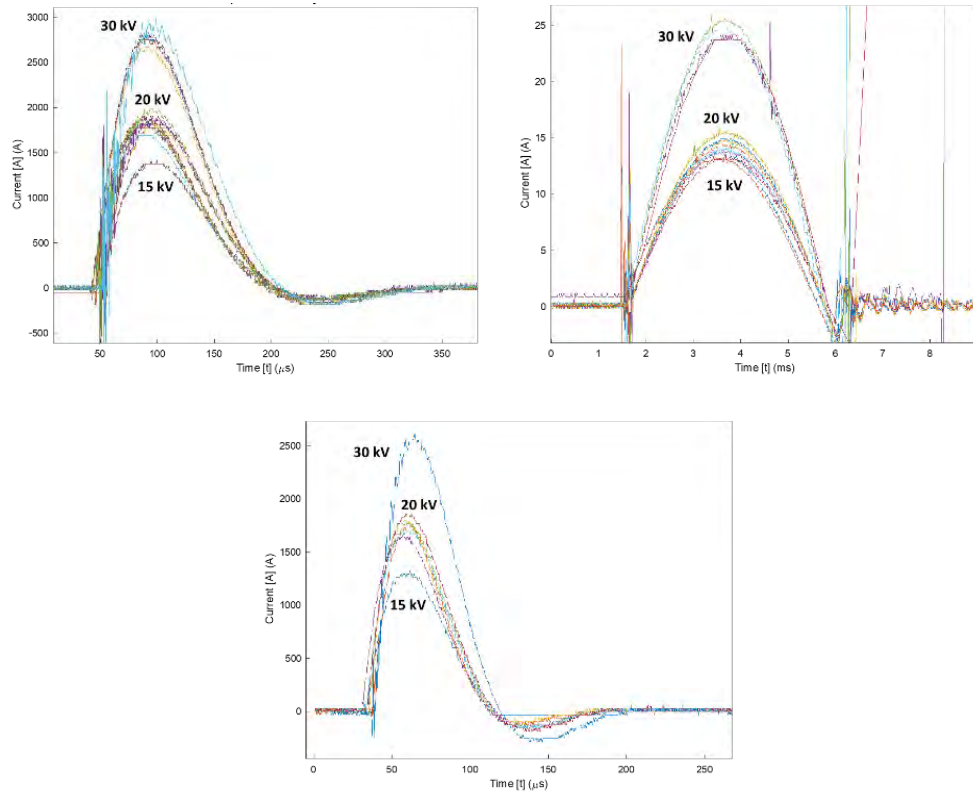


Figure 6. Data collected at 15 kV (30 kV diff), 20 kV (40 kV diff.), and 30 kV (60 kV diff) charge voltages, during the 30 nF capacitor discharge 1 (upper left), recharge (upper right), and discharge 2 (bottom).

The spark gap trigger circuit has also been revised this year. Initially they were triggered using a custom circuit, seen schematically in Figure 7 and photographically in Figure 8. They work by discharging a primary storage capacitor into the primary of a HV isolation transformer whose secondary is connected to the spark gap. Three driver circuits are seen in the lower portion of Figure 7. Two driver circuits are connected to one transformer connected to the discharge spark gap, while the other is connected to its own transformer and the recharge spark gap. When the project began, we tried using cost effective spark gaps procured from MSD, but as we previously reported, the secondaries were not isolated and did not work. We struggled to find other cost-effective transformers until we stumbled on the ones sold by Zeonics that we reported on last year, with 140 kV DC isolation. Those transformers have worked well but they are very large. They have a primary inductance 34.7 μH and a secondary inductance of 5.2 H. When coupled with the 330 μF capacitors connected in parallel on the driver circuit boards, this creates a pulse that is much longer than the 100 ns breakdown. In a discussion with the team at NSWCDD, they mentioned that MSD makes another transformer with isolated grounds, MSD PN 8230. They have a primary inductance of 189 μH and secondary inductance of 1.25 H and are much smaller and easier to work with than the larger Zeonics transformers. We are using a 2 μF storage capacitor to speed up the rise time of the trigger pulse and it appears to be working much better.

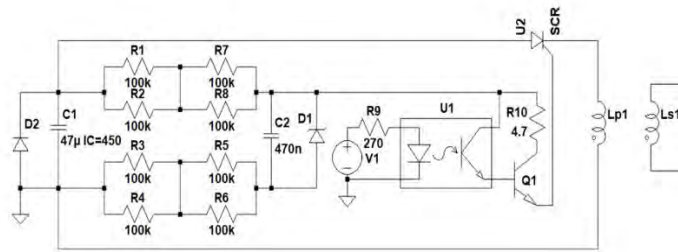


Figure 7. Photograph of the new SCR based spark gap trigger boards.

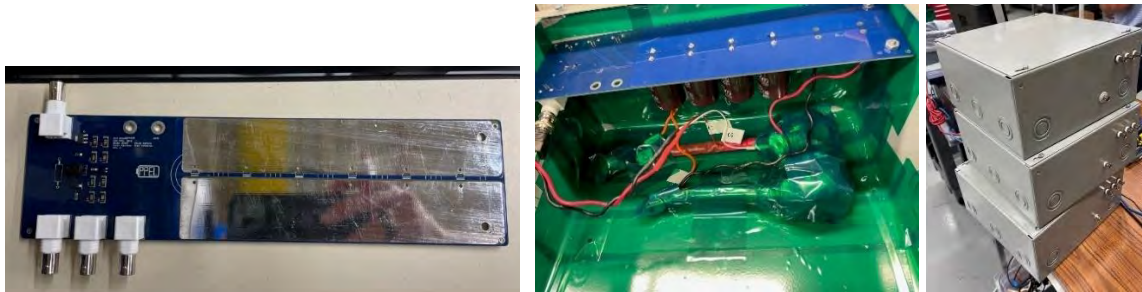


Figure 8. Photograph of the new SCR based spark gap trigger boards.

Early in the year, a separate, multi-channel TTL/Fiber ⇔ Fiber/TTL board was used to isolate each circuit's SCR gate signal from the host controller. It is still unclear why, but these boards were a very large problem this FY. Somehow a high enough voltage to fail optical isolator chips and the 15 V regulators would get induced and they would repeatedly fail as seen in Figure 9. Many attempts were made to diagnose the source of the high voltage, but it was never pin pointed. Though the parts that would break were cheap and not difficult to replace, it would take time away from collecting data and became a problem. Eventually the problem became frequent enough to consider a change. After some searching, a commercial SCR driver board made by Applied Power Systems (APS) was found and procured, seen in Figure 10.

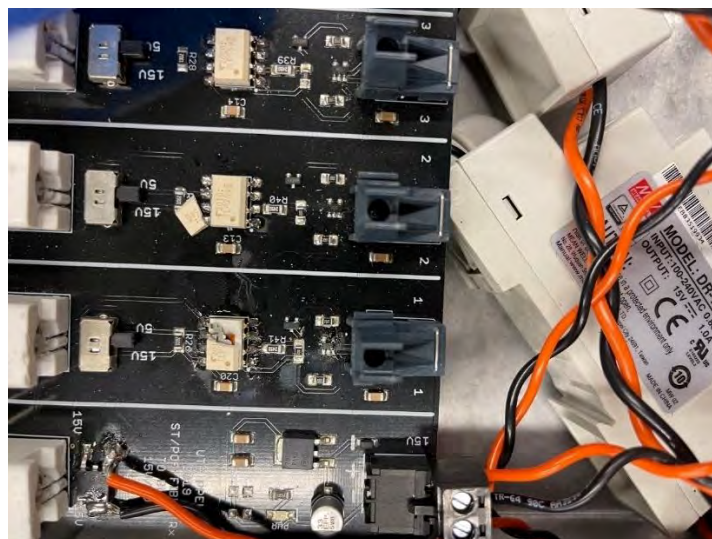


Figure 9. Photograph of the blown fiber to 5 V logic board.



Figure 10. APS SCR trigger boards we bought to replace our custom-made ones.

Even though the new driver boards are creating a much sharper rise time and the high voltage optical isolation built into the boards is preventing them from failing, another problem that has not gone away concerns the unexpected triggering of the gaps. Often, when the first discharge gap is triggered, that breakdown event self-breaks the recharge gap and sometimes even the second discharge. When the discharge and recharge capacitors trigger at roughly the same time, it can cause voltage reversal that kills the high voltage diodes in the recharge path. We believe the only way to fix this is to find the right switch gas pressure and to have some good luck.

Though the testbed has worked for over a year now, the gap breakdown problem just described has prevented us from using it to perform a lifetime test on the capacitors of interest at elevated temperatures. Problems with measuring the capacitor voltage has also been a problem that has prevented us from collecting too much data. As shown in Figure 2, two Pearson current monitors are used to measure the current in the discharge and recharge paths, respectively. There has never been any problem with these diagnostics. To fully understand what may be happening inside the capacitor during a failure event, we would like to measure the capacitor voltage. The 80 kV charge

voltage, and especially the fact that it is a differential charge of ± 40 kV, makes it difficult to make this measurement. This year we tried a few different things. First and most simply, we made our own voltage dividers using two high voltage 1 G Ω resistors and two 1 M Ω potentiometers. They were setup as two dividers in series across the capacitor under test, seen in Figure 11. What is seen are the 1 G Ω resistors floating in the oil. The inner conductor of the BNC brings the voltage up to the trim potentiometers up in the metal box where voltage is measured using two differential voltage probes. Measuring them into an oscilloscope, the signals had a great deal of noise and they did not match the expected results, seen in Figure 12.

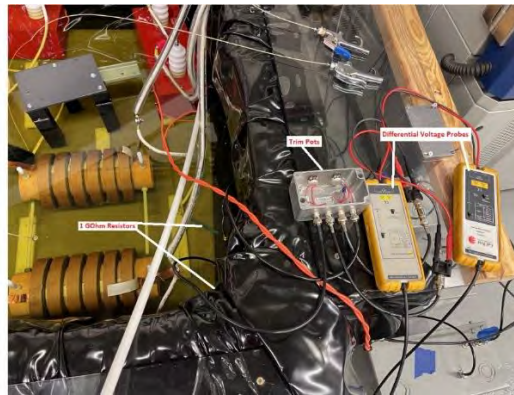


Figure 11. Photograph of the original voltage divider setup



Figure 12. Sample scope data measured during a discharge (left) and recharge (right). Notice how the voltage waveforms (purple and dark blue) do not match the expected results from simulations above at all.

Concerned that we were a bit too quick in throwing something together, we took a bit more time to enclose the divider in a shielded box, shown in Figure 13. The results were better but still do not match the expected results. Of concern especially was the way the polarity bounces when the spark gap is initially triggered, seen in Figure 14. A photo of the data collected during a recharge is shown in Figure 15. This data is what convinced us that the rise time of our spark gap trigger circuit was far too long, and it was after this that we shortened that with the shorter rise time pulse described earlier. The slow rise time was preventing the pulse from breaking down quickly. While this was not the cause of our voltage diagnostic problem, it was something we learned from the diagnostic.

The problem with the voltage divider sent us back to the drawing board and it was at this time that we revised all of the test setup to try and shorten/clean up all of the wires, shown in Figure 5 earlier.

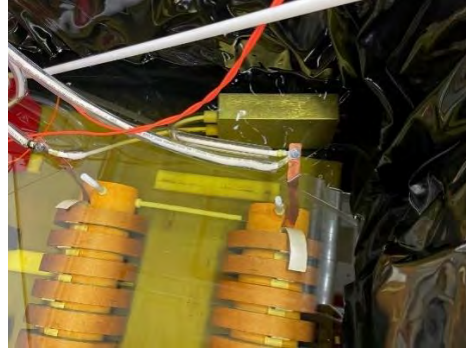


Figure 13. Voltage divider cleaned up and rehoused in a shielded enclosure.

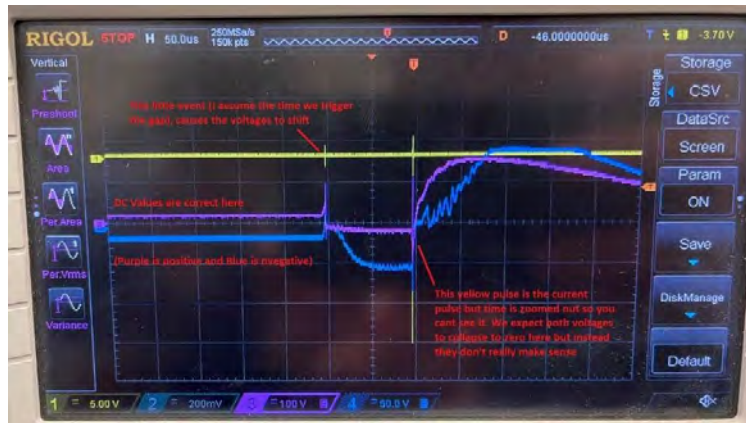


Figure 14. Data collected during a discharge showing how the voltage collapses and goes negative when the spark gap is first triggered.

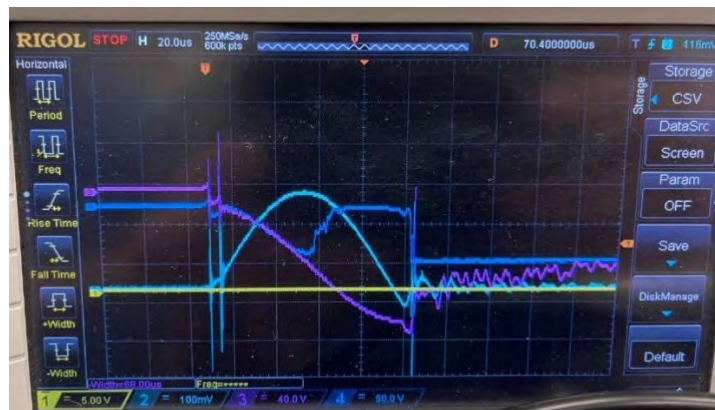


Figure 15. Data collected during a recharge using the voltage divider enclosed in a aluminum box.

In the revised testbed, we replaced the homemade voltage divider with two North Star voltage probes connected in series. We have one PVM-5 and one PVM-2. The PVM-5 is rated to 60 kVDC/100 kV pulsed while the PVM 2 is rated to 40 kVDC/ 60 kV pulsed. Each has a 1000:1 divider ratio. A photograph showing them assembled in the testbed is seen in Figure 5. Multiple plots showing data collected using the PVM probes is shown in Figure 16. The upper two photographs are of a discharge (upper left) and a recharge (upper right). In the upper right photo, the light blue capacitor current waveform is ringing which means the diodes have failed. The data shown in the upper left discharge photograph is also plotted using Microsoft Excel and that plot is shown below the two photographs in Figure 16. In that plot, the voltage waveforms seen in dark blue and purple, have a great deal of ringing in them that makes it very hard to discern the expected waveforms. Trendlines are added in the Excel plot but as shown they don't both end up at 0 V as they should. It should be mentioned that the PVM probes are designed to be terminated into 1 M Ω and in these plots, the probes are terminated into three oscilloscopes in parallel meaning they are terminated into 333 k Ω . This is a problem but since we only have one set of probes and we want to measure three single shot events quickly, it was the only option.

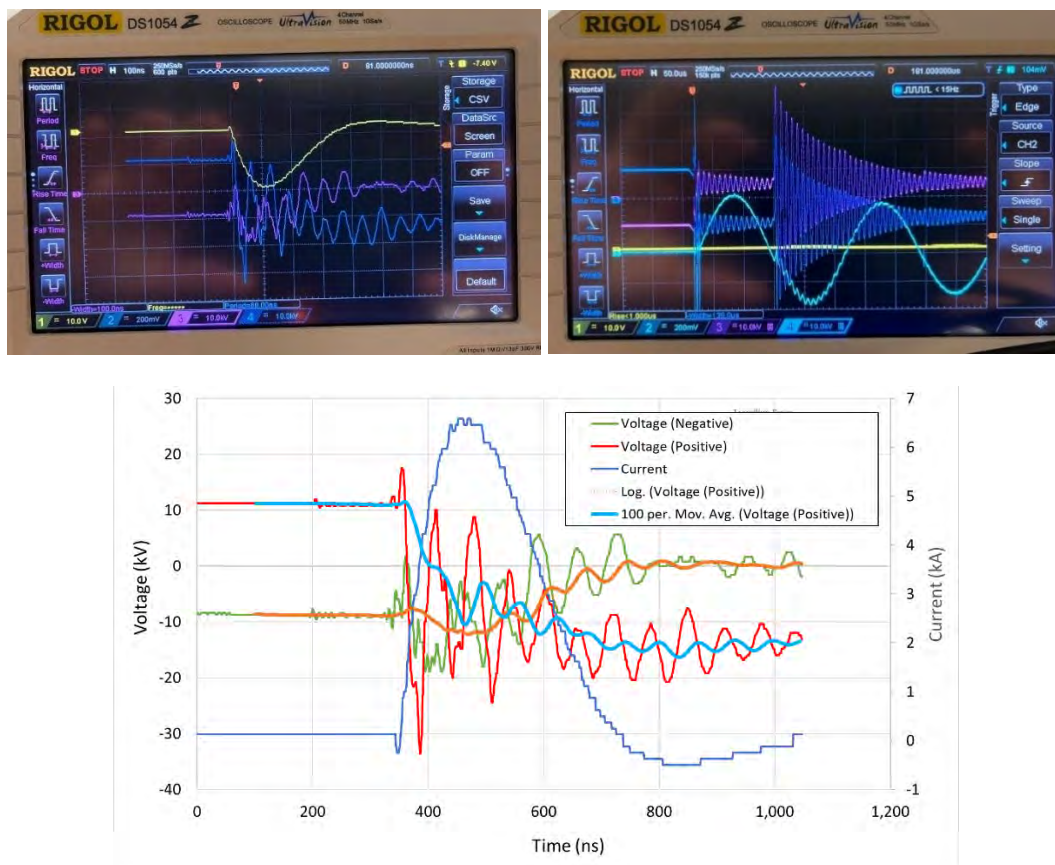


Figure 16. Data collected during a discharge (upper left and below) and recharge (upper right) experiment. Notice the ringing in the voltage waveforms that makes the expected trend difficult to discern.

We believed at the time that the termination impedance could be throwing off the RC time constant of the probes enough to cause problems, so we started to evaluate alternatives and what we came up with is interesting. We needed a way to get 1 M Ω impedance and a way to quickly switch which scopes the probes are terminated into. We don't have time to save the data, reset the trigger, and collect data before the voltages sag too much due to parallel impedances. A solution we are trying involves using a BNC selector box, seen in Figure 17. The box is a 50 Ω box that takes in a BNC measurement and the user can select which one of four output BNCs the input is passed to. The selector knob breaks both positive and negative contacts, so we can connect the output to one scope at a time but quickly select which one it's going to. We have bought two of these and installed them on the testbed only this week so we will report soon on how they work.



Figure 17. One to four BNC splitter boxes installed on the testbed.

While we were waiting for the BNC boxes to arrive, we continued to experiment with the probes. Figure 18 presents some discharge data we got terminating the probes into only one scope during the discharge event. Both probes properly measure the DC voltage of the capacitor before the event and both settle correctly to near 0 V after the discharge is over. This indicates that the termination is crucial and is a step in the right direction.

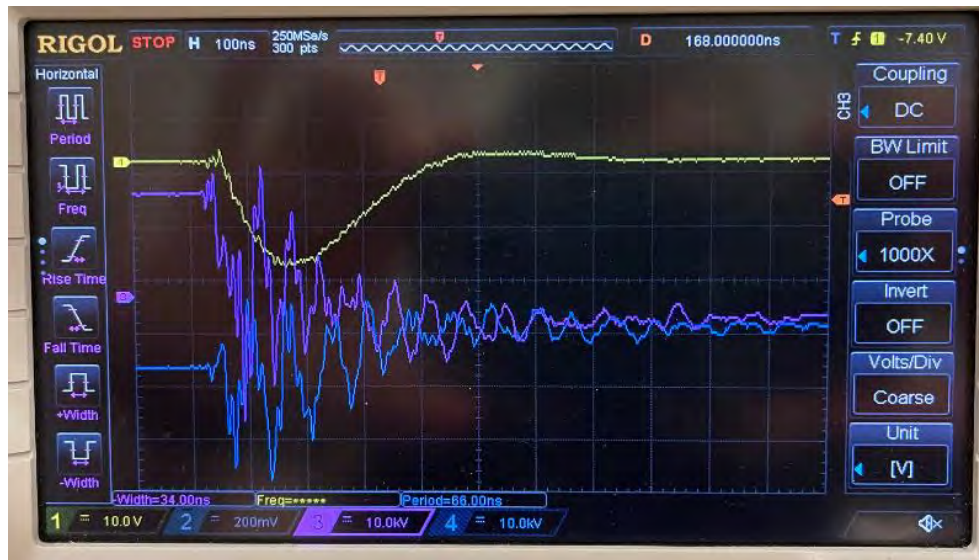


Figure 18. Data collected during a discharge with both PVM probes terminated into only one oscilloscope (1 M Ω) impedance.

During that time, we also collected some recharge data, using the probes paralleled into the three scopes, and learned something interesting. When we use a spark gap to trigger the recharge process, the recharge voltage waveforms look horrible and make no real sense but when we use the Ross relay, they look good. The only explanation is that the noise induced by the spark gap is too significant to overcome. Figure 19 presents recharge data collected when the Ross relay was used to connect the two capacitor mid-points and carry charge into the capacitor under test. Notice the shape is as we expect but the voltage values are off as they were before due to improper termination impedance. Around that time, we started to have some problems with our gaps that caused us to have to send them off for cleaning. We only recently got those back and now that we have those and the BNC selector boxes, we hope that we can start to obtain some good results soon.

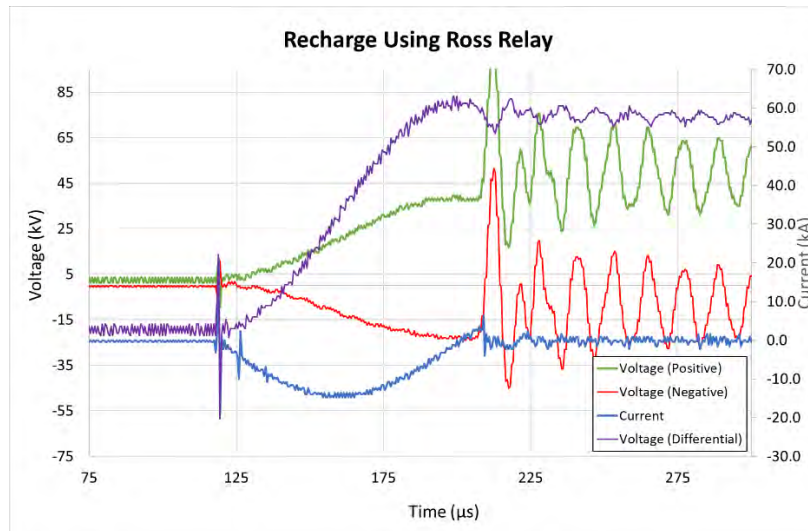


Figure 19. Data collected during a recharge experiment with the probes terminated into three parallel scopes and the Ross relay used to trigger the recharge current.

This brings us to where we are today. As of this writing the testbed works well except for the reliability. We can perform multiple charge/discharge/recharge/discharge events at charge voltages as high as ± 30 kV, but every so often the process does not go as planned and we are still concerned what variability this brings into a full lifetime study. We believe we are at the point of having to just go with the system as it is as we don't see better ways to improve these reliability issues. Waveforms collected recently from a recent discharge/recharge/discharge sequence at ± 25 kV is shown in Figure 20.

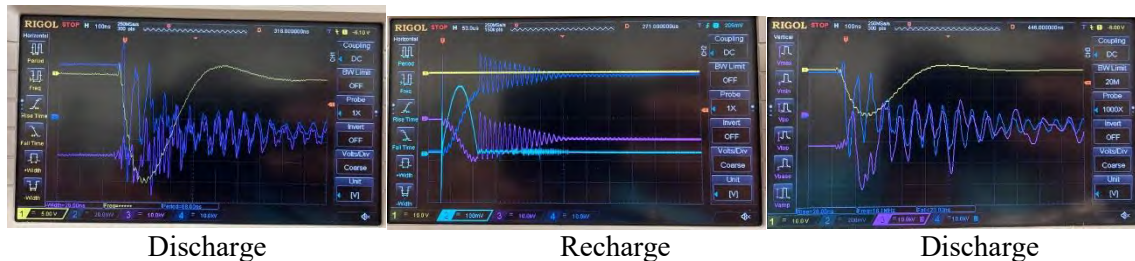


Figure 20. Data collected from a ± 25 kV discharge/recharge/discharge test sequence demonstrating a full sequence of intended operation.

3. Findings and Conclusions

At the end of this four year effort we are happy with the progress we made. With additional support from US ARMY C5ISR we were able to develop and release a fully functioning energy storage sizing tool that is available for use by the DoD and its contractors. We studied ultracapacitors at ambient temperature conditions and showed our sponsors that they have viability for the applications they were being considered for. We designed, built, commissioned, and started to use a high voltage CLC testbed that is used to study the operation of high voltage pulsed power

capacitors. We wish that we had gotten the reliability issue of the testbed to be less of a concern, but it does work and is something we hope to continue to use to support our sponsors.

4. Plans and Upcoming Events

The period of performance on this grant ended on August 31, 2021. Without additional funding, we will be continuing to work on this till we get the CLC to be reliable and useful for our sponsors.

5. Transitions and Impacts

The Excel and Matlab/Simulink based sizing tools have been transitioned out to the US Army C5ISR, NSWC-DD, NSWC-PD, and other DoD contractors when requested.

To date, the knowledge gained has been transitioned to many organizations working in the directed energy (DE) area through several monthly, FY end, and final reports.

6. Collaborations

Mathew McQuage: NSWCDD

Jordan Chaparro: NSWCDD

Jon Cameron Pouncey: NSWCDD

John Heinzl: NSWCPD

Frank Hegeler: Naval Research Laboratories (NRL)

Brett Huhman: Naval Research Laboratories (NRL)

Emily Schrock: Sandia National Laboratories (SNL)

Christopher Mullen: C5ISR Center, Command, Power and Integration Directorate U.S. Army Combat Capabilities – Financially supported much of the development of the sizing tool

Julianne Douglas: C5ISR Center, Command, Power and Integration Directorate U.S. Army Combat Capabilities – Financially supported much of the development of the sizing tool

7. Personnel

Principal investigator: Dr. David Wetz – 3 months (approx. 400 hours were spent working on the project though 0 hours of principal investigator salary was charged to the grant),

National Academy Member (N)

Business Contact: Jeremy Forsberg, ogcs@uta.edu

Team Members: Listed as students below

Subs: None

8. Students

Multiple students were funded to work on this effort. Though only one MS degree was earned directly on the work performed in 2019, many students gained valuable experience in the field of pulsed power that will be leveraged towards completion of their degrees and hopefully as they enter the field upon graduation. The students involved are listed below

1. Alex Johnston: PhD EE Student (est. graduation in May 2022). He has run the CLC testbed since Chris graduated
2. Cole Tschritter: EE undergraduate student who is now working on his PhD EE degree (est. graduation in May 2024). While he was an undergraduate, he helped Alex as needed
3. Hayden Atchison: PhD EE student (est. graduation May 2023) who led the sizing tool development both in this effort and for the Army
4. Cameron Johnston: EE Undergraduate Student (est. graduation in May 2022) who has assisted part time as needed

9. Technology Transfer

None

10. Products, Publications, Patents, License Agreements, etc.

There were no publications during this reporting period other than one conference presentation that has been put together for the 2021 IEEE International Pulsed Power Conference in December 2021. Monthly reports were compiled and delivered to ONR. A status brief was submitted for the 2021 DE Program Review and a Final Project Report was submitted to ONR in December 2021.

11. Point of Contact in Navy

Mr. Ryan Hoffman, ryan.hoffman@navy.mil, ONR Directed Energy Weapons: High Power Microwaves Program Manager (Code 351), Last Contacted on November 20, 2021

Mr. Matthew McQuage, matthew.mcquage@navy.mil, NSWC-DD, Last Contacted on November 20, 2021

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Scaleup of Materials for Optimizing High Power RF Systems

Grant No. N00014-21-1-2019

Annual Report for Fiscal Year 2021

Period of Performance: December 7, 2020 to September 30, 2021

Prepared by:

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Better Lives through Science and Technology



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Project Title: Scaleup of materials for optimizing High Power RF Systems

Annual Summary Report: FY2021

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Section I: Project Summary

1. Overview of Project

Based on our accomplishments in the previous phase for investigating the feasibility of tunable dielectric materials for high power microwave applications, this annual report describes the objective for the current phase of the work performed in the period of December 7, 2020 through September 30, 2021. The current contract completion date is April 30, 2022.

The **goals** of the current phase of work include (a) investigation of scalability of the novel tunable dielectric materials, (b) assessment of the materials at a 100W per tone power level for intermodulation distortion measurements, (c) development of thick films of the tunable materials for planar devices, (d) investigation of a novel class of magnetodielectric materials for high power microwave applications, and (e) development of models for forecasting formulations of these low loss materials for future applications. The period of performance of the project is for 18 months.

The **approach** included the fabrication and then collection of the material's response functions (ϵ' , ϵ'' , tunability, intermodulation products (IP3), and breakdown voltages). Tunability is defined as the percent change in dielectric constant of the material with applied electric field. The same approach was followed for the fabrication and characterization of magnetodielectric materials. As for the development of models, we followed the many regression models used in the field of material discovery. The thick film approach included the screen printing of the thick films followed by material characterization.

The key **technology advancement/payoff** is the ability to provide tunable delays for ultrawide band generators of high-power microwave beams. The ability to fine-tune delays allows the creation of different waveforms on target due to pre-designed constructive and destructive interference. As for the magnetodielectric materials, it is hypothesized that the dielectric materials within the ferromagnetic material matrix provide the high breakdown and lower impedance.

2. Activities and Accomplishments

There were overall five iterative tasks for the program. The activities and accomplishments for each task are described below.

Task 1. Fabrication and assessment of large size tunable dielectric material and its material characterization.

Activities- The objective of this task was to fabricate up to 6"x6" pieces of tunable dielectric ceramics and characterize those pieces.

Accomplishments- This task has been completed successfully by fabricating ~3"x3" pieces (Figure 1). Powerhouse believes that larger pieces are constrained only by the size of the available molding dies.



Figure 1. As sintered ceramic pieces of Barium Strontium Titanate (~2.9 inches square)

Task 2. Development of thick film processes for large area deposition of tunable dielectric activities.

The objective of this task was to optimize the inexpensive screen-printing process for depositing 6 square inch films with metal electrodes to study the variability of composition during preparation of samples.

Accomplishments- Fabricated thick films using an EXAKT 50i three roll mill in collaboration with Dr. Matthew Laskoski of NRL. As the first step we developed the binder for the thick film slurry. For that we utilized Ethyl cellulose of three different viscosities. 50 grams each 4 cP, 22 cP, and 46 cP of Ethyl Cellulose purchased from Millipore Sigma were prepared in three different amounts in combination with 200 proof ethanol (Table 1 below).

Table 1. Various binder mixes used for producing the thick film paste of BST

Bottle #	cP of Ethyl Cellulose	mL of 200 proof Ethanol
1	4cP	180 mL
2	22 cP	380 mL
3	46 cP	330 mL

They all produced viscous liquids that were mixed in a rolling mill overnight. The binders were then stored in a cool cabinet. For our first set of experiments, we prepared undoped $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ ceramic material that was calcined at 1100C and then ground to get rid of any lumps. The material was then sieved through a set of sieves to assure a mix of particle sizes. The third component for a thick film slurry is a dispersant; a chemical that helps disperse the solid into the binder volume while it is being sheared in a 3-roll mill. We use α -terpeniol, a widely used material in the industry, as a dispersant.

Our first experiment was conducted by mixing the three constituents (22 cP binder, ceramic powder, and the dispersant). We prepared a 80 vol% of BST with 10 vol% of binder mix. The material was hand mixed with the dispersant to a consistency of a thick toothpaste. It was then fed into the feed roll of the 3-roll mill and received at the apron roll (**Figure 2**). The material was fed thrice before a consistent slurry was created.

The slurry was then screen printed onto a Magnesium Oxide single crystal (one side polished) substrate and Alumina substrate and then sintered for 3 hours. **Figure 3** shows the morphology of the thick film inspected at about 100x+ with a handheld optical microscope.

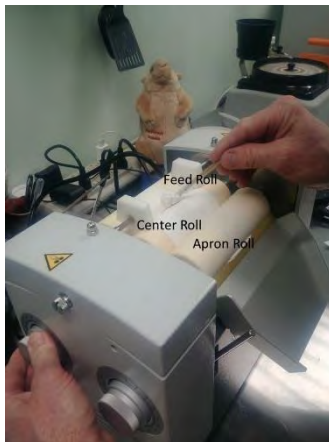


Figure 2. The operation of a 3-roll mill. Ceramic paste seen exiting at the bottom of the apron roll.



Figure 3. Thick film morphology on alumina substrate.

Figure 4 shows the x-ray diffraction pattern confirms the formation of thick films of BST on single crystal MgO substrates. Currently we are in the process of procuring larger MgO substrates for large area deposition. We will continue our effort on large area deposition for other BST compositions and magnetodielectric materials too.

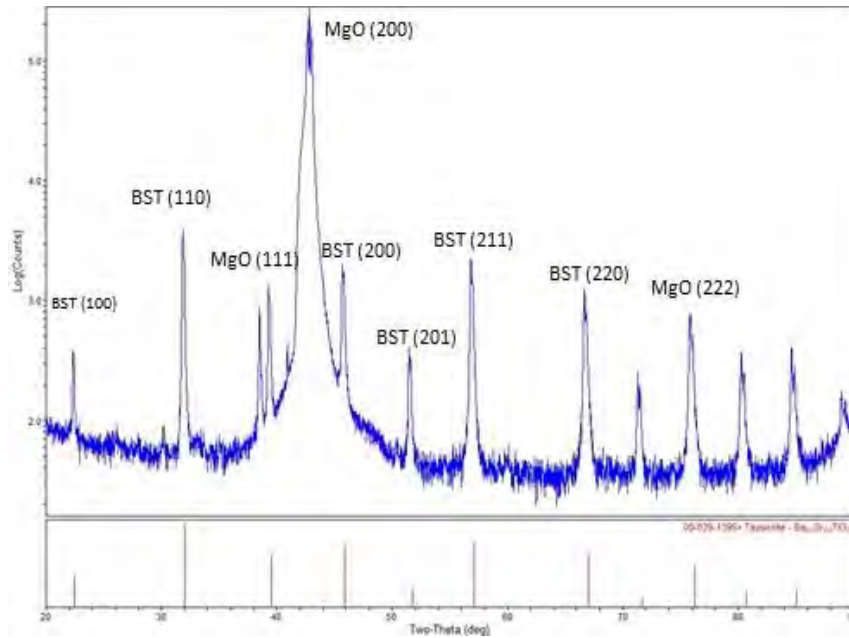


Figure 4. Xray diffraction pattern of $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ thick film on (001) MgO crystal.

Task 3: RF measurements of the ceramic materials.

Activities- The objective of this task was to measure the third order intermodulation products of the dielectric materials with a two-tone experiment with RF power of 100W for each tone, and to investigate the hysteretic nature of the material.

Accomplishments- Our plan is to continue the two-tone measurements for a variety of compositions. So far, we have performed one experiment with two 100W signals and a peak envelope power of 400 W. The two-tone conditions were:

- Tone 1: 300MHz
- Tone 2: 300.5MHz
- Output power (PEP): 400W
- Tone power: 100W/ea

Figure 5 compares the IMD3 measurements under two different sets of incident power. It shows that the IMD3 products for the barium strontium titanate materials are significantly superior to any active component like amplifiers. So, it suffices to state that components fabricated from these materials will not have significant contribution to the overall IMD3 values of the system.

Composition A (60/40 BST with ~9 wt% dopant)			
F1 (dBm)	F2 (dBm)	2f2-f1 (dBc)	2f2-f1 (dBc)
35	35	-33	-33
Composition B (60/40 BST with ~16 wt% dopant)			
26.4	26.4	-32	-32
Composition C (60/40 BST with ~60wt% dopant)			
24.9	24.9	-31.7	-31.8

(a)

BST			
F1 (dBm)	F2 (dBm)	2f1-f2 (dBc)	2f2-f1 (dBc)
50.6	50.6	-25.8	-30.3
Air			
50.6	50.6	-25.9 dBc	-30.5 dBc

(b)

Figure 5. Third order intermodulation distortion products for barium strontium titanate materials.

Third party verification- Samples of BST with various amounts of Oxide III and Oxide IV have been prepared for measurements to be performed at a university laboratory utilizing the Keysight E980A and an environmental chamber.⁷ Three samples were sent for the measurements: $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ and $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ with 20 wt% Oxide III. **Figure 6** shows the measurement data. At 1 kHz, the data agrees with our previous measurement with a DE5000 handheld LCR meter *within the margin of error*. Henceforth, we have confidence at the 1 MHz data point.

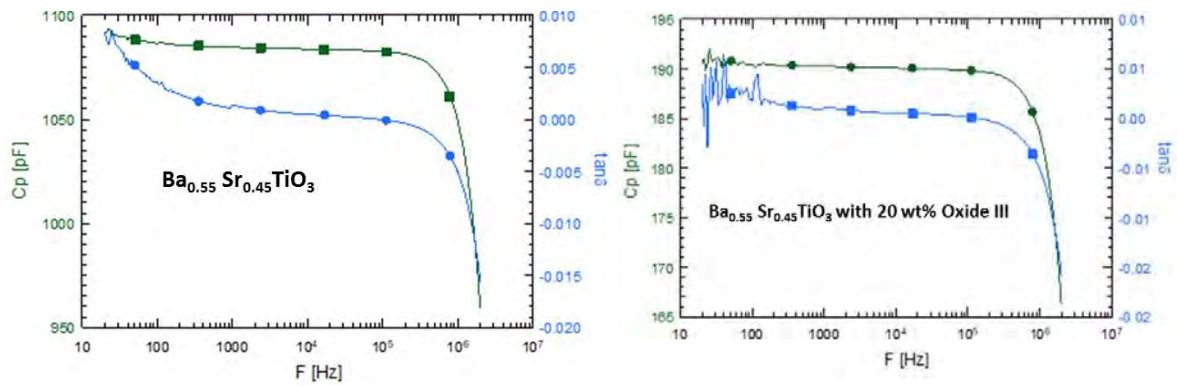


Figure 6. Third party 1 MHz data. Powerhouse 1kHz data agrees with the external data source.

Table 2 shows a voltage cycling experiment performed with a 1.3 mm thick ceramic sample of $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$. The sample was 1.3 mm thick and the electrode area was 8.5 mm x 8.5 mm. The

⁷ Professor Rick Uvic, Boise State Center for Materials Characterization , Boise State University

high voltage experiments were carried out *without any silicone guard ring around the electrodes*. The objective was to observe if we could attain sufficient tunability without the additional step of a guard ring.

Table 2. Very high change in dielectric constant can be obtained with nominal Dc bias fields.

Frequency of measurement	kV	Field (V/ μ m)	Cp(pF) (kV going up)	Cp(pF) (kV going down from 3)	Average	ϵ_r	% tunability
600kHz	0		498.8	490	494	1002	
	1	0.8	465-470	465-470	467	950	5%
	2	1.6	207	212	210	425	58%
	2.5	1.9	157	157	157	320	68%
	3	2.3	127.9	127.9	128	260	74%

A Capacitance versus Temperature study of the three material compositions were performed to determine the voltage cycling stability of the materials. Our study showed that the doped samples are more stable in voltage cycling and also show much less charge retention. **Figure 7** shows the C vs T characteristics of the three samples. The graphs show that *compositional variation can indeed reduce the hysteresis of the material over a wide temperature range*. **These results once again emphasis the application specific material compositions that can be manufactured by Powerhouse.**

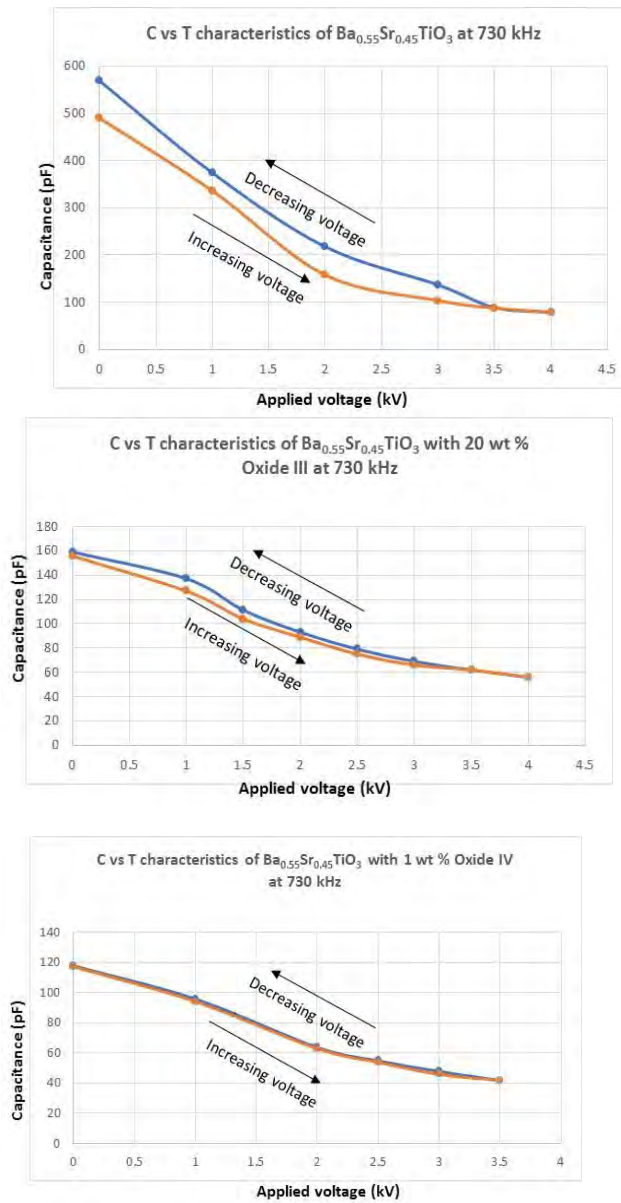


Figure 7. Powerhouse can manufacture application specific tunable dielectric materials

Task 4. Development of modeling and simulation pathways.

Activities- The objective of this task was to investigate if one could develop an algorithmic pathway for rationally designing materials through the effective use of data *without* performing too many experiments in the laboratory.

Accomplishments- A thorough literature search was performed to understand the past work in the field of material discovery and design. The work by J.Qin,Z.Liu, and M.Maetal titled “Machine Learning Approaches For Permittivity Prediction and Rational Design of Microwave Dielectric Ceramics”⁸ appeared to be very relevant. In conversation with the author, we selected seven compositions and their unique features [2]. (**Table 3**).

Table 3. Data for 7 different compositions of Barium Strontium Titanate.

	Composition	Frequency (1 MHz)		Tunability (%)
		ϵ /Dielectric Loss		Applied Fields-2V/ μm /4 V/ μm /6 V/ μm
1	$\text{Ba}_{0.00}\text{Sr}_{1.00}\text{TiO}_3$	350/0.0008		0/0/0
2	$\text{Ba}_{0.40}\text{Sr}_{0.60}\text{TiO}_3$	1132.3/0.0003		2.18/8.30/15.99
3	$\text{Ba}_{0.45}\text{Sr}_{0.55}\text{TiO}_3$	1368.1/0.0044		4.38/14.17/24.92
4	$\text{Ba}_{0.50}\text{Sr}_{0.50}\text{TiO}_3$	1813.7/0.0001		9.41/26.13/40.38
5	$\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$	2592.1/0.0004		18.72/42.32/57.01
6	$\text{Ba}_{0.60}\text{Sr}_{0.40}\text{TiO}_3$	4448.1/0.0002		41.96/66.72/76.93
7	$\text{Ba}_{1.00}\text{Sr}_{0.00}\text{TiO}_3$	2200/0.067		42.00/70.50/78.45

In order to perform any machine learning approach, we would need relevant features for these material compositions. **Table 4** below shows the relevant features. It must be emphasized that seven data points are not enough to have any learning algorithm forecast meaningful results. Nevertheless, we performed this exercise to have the models ready to be populated in the coming months. Most regression models just end up learning a function that includes all the data points, but the region between data points is just linear extrapolation.

⁸ J.Qin,Z.Liu,M.Maetal.,Machine learning approaches for permittivity prediction and rational design of microwave dielectric ceramics, Journal of Materiomics, <https://doi.org/10.1016/j.jmat.2021.02.012>

Table 4. Relevant features for developing the machine learning algorithms.

•	Ppv (polarization per unit volume) - 0.165 C/m ² (for Barium Titanate)
•	d- theoretical density - between 6.02 gm/cm ³ (for Barium Titanium Oxide) to about 4.96 gm/cm ³ (for Strontium Titanium Oxide)
•	bg- Bandgap - 1.725 eV (Barium Titanate) to 1.827 eV (for Strontium Titanate)
•	Blm- average bond length - 2 to 3 angstroms
•	fepa – Formation energy per atom (eV) - -3.477 eV (for Barium Titanate) to -3.551 eV (for Strontium Titanate)
•	Bpa- number of bonds per atom - 8 for the center Barium atom to 4 for the corner oxygen atom
•	Ord- order of symmetry - Tetragonal (for Barium Titanium Oxide) to Cubic (for (Strontium Titanium Oxide)
•	Ne- number of elements - 3 (when it is Barium Titanium Oxide) to 4 (when it is Barium Strontium Titanium Oxide)
•	na- number of atoms - 3 atoms (in Barium Titanium Oxide) to 4 atoms (in Barium Strontium Titanium Oxide)
•	cat- number of cations - 2 (in Barium Titanium Oxide) to 3 (in Barium Strontium Titanium Oxide)
•	ani- number of anions - 3 (in Barium Titanium Oxide) to 3 (in Barium Strontium Titanium Oxide)
•	Vm- primitive cell volume - 64.36 angstroms ³ (for Barium Titanate) to 61.402 angstroms ³ (for Strontium Titanium Oxide)
•	M- molecular mass - 233.192 g/mol (for Barium Titanate) to 183.49 g/mol (for Strontium Titanium Oxide)
•	Dielectric permittivity range - 7000 (for Barium Titanium Oxide) to 300 (for Strontium Titanium Oxide)
•	Insertion loss - 0.03 to 0.003

The algorithms are “learning;” however, we do not have enough data for the algorithm to learn enough to do any hard prediction. So, although the algorithms are working at this point we are not obtaining much useful information in between the data points since it is approximating in a linear fashion.

Figure 8 and **Figure 9** are just an example of a simple Gaussian processor model. As one may see, the very limited number of data points forces the algorithm to approximate linear extrapolation. So we retried the process with a larger data set of 28 data points. Also, the features in Table 3 were not used in this model development since they were not data point specific. We will also address that issue since feature data is not available for all compositions and developing those feature data *will be outside the scope of this task.*

Gaussian Processes - GaussianProcessRegressor

```
from sklearn.gaussian_process import GaussianProcessRegressor

gpr = GaussianProcessRegressor()
gpr.fit(x_train, y_train)
y_pred_gpr = gpr.predict(x)

plotGraphAndPrintError(y_pred_gpr, "GaussianProcessRegressor")
```

GaussianProcessRegressor

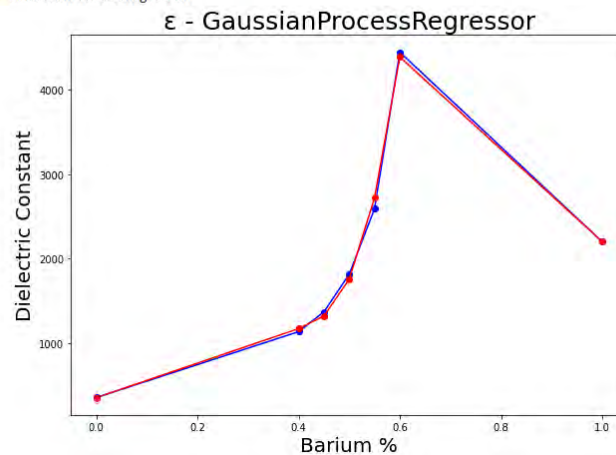


Figure 8. Example of a simple Gaussian Processor Regressor Model to forecast the dielectric constant of Barium Strontium Titanate composition.

Gaussian Processes - GaussianProcessRegressor

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GaussianProcessRegressor

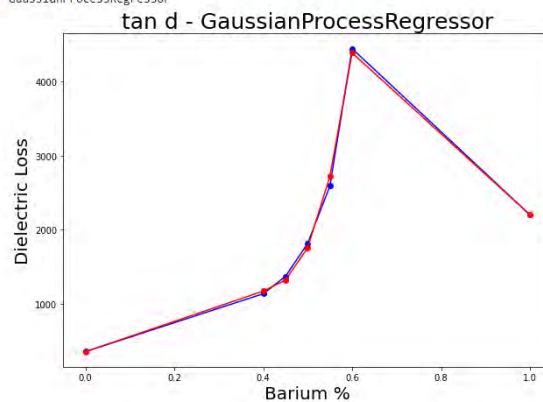


Figure 9. Example of a simple Gaussian Processor Regressor Model to forecast the dielectric loss of Barium Strontium Titanate composition.

We learned some important lessons from the first try; however, if we want to completely rely on machine learning to forecast epsilon and loss values for us, then we have to perform an elaborate study (beyond the scope of this work) and include all features (explained in the previous monthly report) as experimental values too. Since we have about two decades of data on the dielectric materials, we have high confidence in producing the right compositions for applications; *however, it might be very useful to develop a software learning based approach for magnetodielectric materials since it is a much more complicated material.* We conclude this task by showing that by using 20+ data points for epsilon and $\tan \delta$ values, the Gaussian process regressors and Multilayer perceptron regressor models are probably the most mathematically capable of learning non-linear functions. We performed an experiment by simply annotating the compositions numerically. Let's say that the composition IDs are in ascending order of barium percentage. In that case what the models learned was the target values as barium percent keeps increasing. (Numerically larger composition ID = higher barium % = different target value.) Keeping this in mind, we interpolated the composition IDs in 0.1 value increments, so if:

- '-1' = 0% barium
- '0' = 5% barium
- then '-0.9' = 0.5% barium, '-0.8' = 1% barium, etc.

With these new IDs [-1, -0.9, -0.8.... 27.8, 27.9, 28], we had the models predict the target values for each, and plot them against actual known values, to better visualize the function the models had learned from the training data (**Figures 10 and 11**).

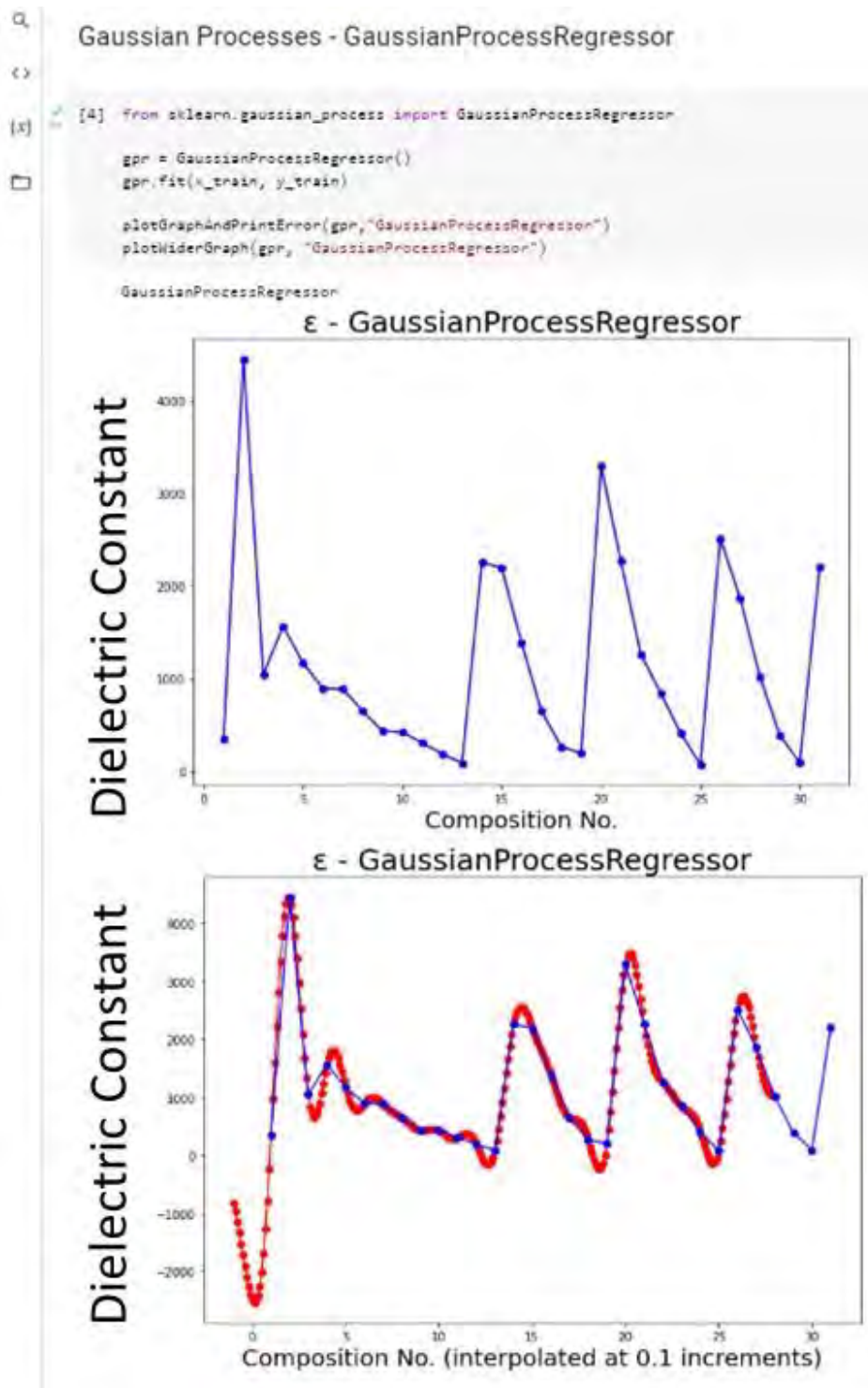


Figure 10. The Gaussian regressor model fit for the tunable dielectric material epsilon data shows a decent fit for forecasting future compositions.

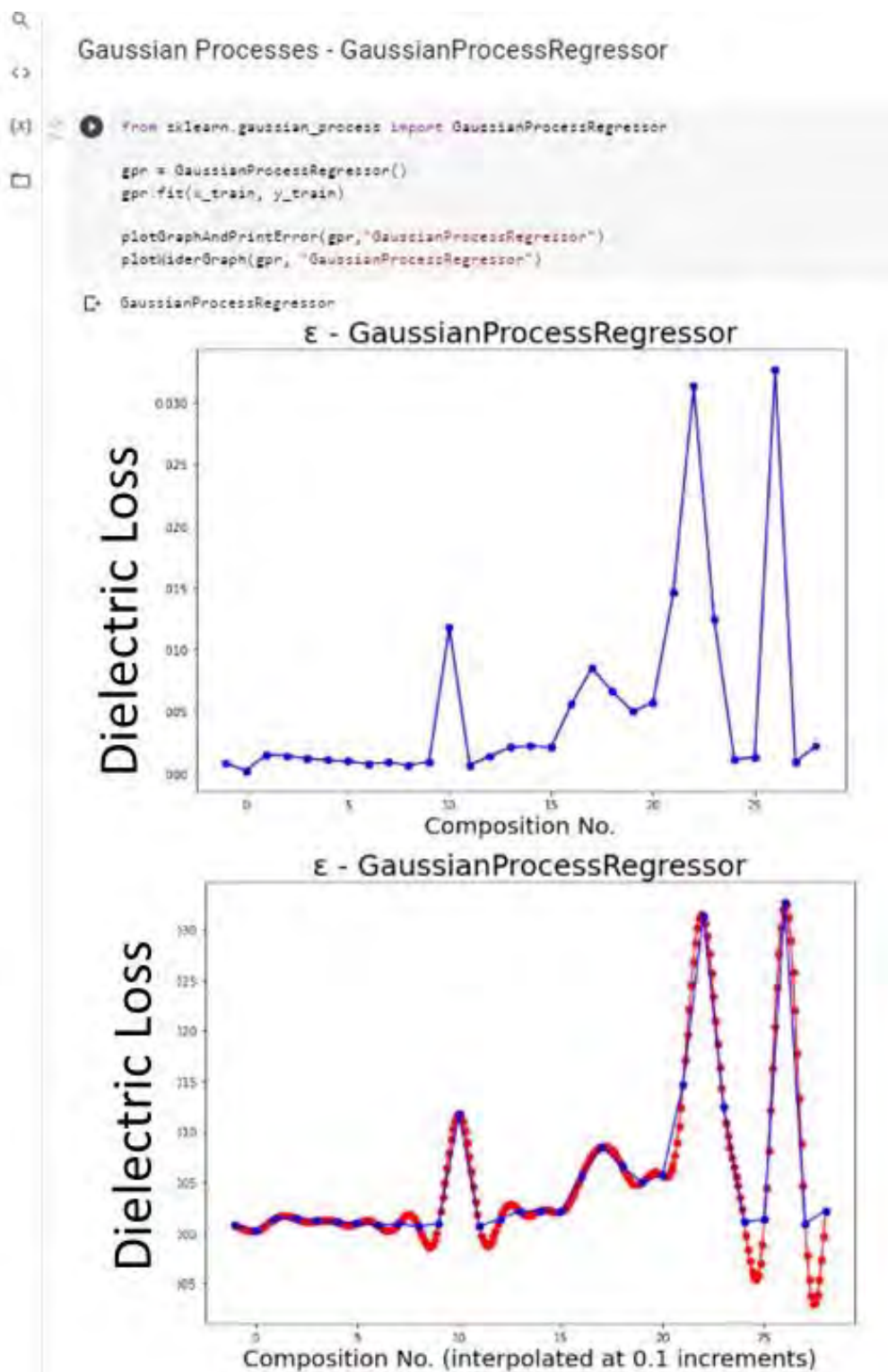


Figure 11. The Gaussian regressor model fit for the tunable dielectric material loss data shows a decent fit for forecasting future compositions.

Task 5: Assessment of magnetodielectric materials for RF applications.

Activities- The objective of this task was to fabricate a range of compositions of tunable magnetodielectric bulk ceramic materials utilizing low loss dielectric ceramic materials and low loss magnetic materials. Magnetic materials of choice are barium hexa ferrite ($\text{BaFe}_2\text{O}_{19}$), magnesium ferrite (MgFe_2O_4), and cobalt ferrite (CoFe_2O_4). X-ray diffraction techniques will be utilized to determine the phase of the materials. Once the material compositions have been down selected, we will also cast ceramic tapes of these materials for evaluating the RF properties.

Barium Ferrite ($\text{BaFe}_2\text{O}_{19}$) is a metal oxide magnetic material. One area in particular in which it has found success is long-term data storage. The material is magnetic and resistant to temperature change, corrosion and oxidization.⁹ *So, a cursory interest in choosing BaFe was to investigate the properties of the magnetodielectric materials for high permittivity data storage. To date we have not been able to identify an application partner for the Navy.*

Spinel ferrites with the general formula AFe_2O_4 ($\text{A} = \text{Mn, Co, Ni, Mg, or Zn}$) are very important magnetic materials because of their interesting magnetic and electrical properties with chemical and thermal stabilities.¹⁰

Magnesium ferrite (MgFe_2O_4) has a cubic structure of normal spinel-type.

Cobalt ferrite (CoFe_2O_4) is a semi-hard ferrite. The induced magnetic anisotropy in cobalt ferrite is also beneficial to enhance the magnetoelectric effect in composite.¹¹

Accomplishments- Barium ferrite, and Magnesium ferrite were chosen for this task since they contain atoms similar to Barium Strontium Titanate. That might create interesting phases during the sintering. *Rietveld analysis showed that intermediate phases were formed in the case of barium ferrite and not for magnesium ferrites.* We have performed a detailed study of the dielectric properties (ϵ_r and $\tan\delta$) and magnetic properties (μ_r and D factor). The samples were fabricated using standard ceramic processes. Two types of samples were prepared: ceramic cylinders for measurement of the dielectric properties and toroidal samples for the measurement for the magnetic properties (**Figure 12**). The cylinders were screen printed with silver contacts for dielectric measurements while the toroids were wound with wires to form the coils for magnetic measurements. The minimum number of turns for coils was 14. The formulae used for calculating the dielectric constant and loss were:

$$C = (\epsilon_r * \epsilon_0 * A) / d$$

where C is the measured capacitance by a LCR meter in Farads, ϵ_r is the relative permittivity to be calculated, ϵ_0 is the absolute permittivity = $8.854 * 10^{-14} \text{F/m}^2$, A is the area of the material under the electrode (m^2) and d is the thickness in meters. This renders a dimensionless value for ϵ_r . The LCR

⁹ Watson, Mark L.; Beard, Robert A.; Kientz, Steven M.; Feebeck, Timothy W. (2008). "Investigation of Thermal Demagnetization Effects in Data Recorded on Advanced Barium Ferrite Recording Media". *IEEE Trans. Magn.* 44 (11): 3568–3571

¹⁰ Valenzuela R. *Magnetic Ceramics*. Cambridge University Press, Cambridge; 1994.

¹¹ Aubert, A. (2017). "Enhancement of the Magnetoelectric Effect in Multiferroic $\text{CoFe}_2\text{O}_4/\text{PZT}$ Bilayer by Induced Uniaxial Magnetic Anisotropy". *IEEE Transactions on Magnetics*. 53 (11): 1–5

meter calculates the $\tan\delta$ value of the material by taking a ratio of the complex part of ϵ_r and the real part of ϵ_r .

The μ_r values were calculated using the formula:

$$L = \frac{\mu \cdot N^2 H \ln(b/a)}{2\pi}$$

where L= measured inductance in Henry, N is the number of turns of the coil, H is the thickness of the toroidal ceramic, b is the outside radius of the toroid, and a is the inside radius of the toroid.

The μ_r is obtained by dividing the μ value from the above equation by $\mu_0 = 4\pi \cdot 10^{-7}$

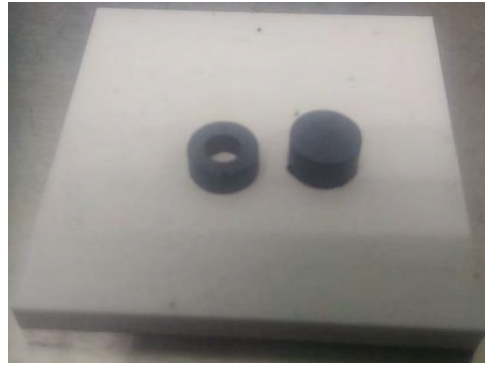


Figure 12. Ceramic cylinder and toroid fabricated for magnetodielectric measurements

A DE 5000 LCR meter was used for dielectric and magnetic measurements. In order to verify our magnetic measurements, we purchased a commercial toroid rated with a μ_r value of 900. Our measurements produced a value of 910, *a good match to proceed with confidence in measuring newly fabricated magneto dielectric materials.*

As for the compositional impact of sintering temperature, we conducted an experiment with magnetodielectric materials to determine the compositional change of the materials as a function of their sintering temperatures. The composition of 20wt% BaFe + 80 wt% Ba_{0.55}Sr_{0.45}TiO₃ with 20 wt% Oxide III was chosen to determine the effect of all dielectric inclusions. Two sets of samples were prepared, each with a disc and a toroid variation for dielectric and magnetic measurements. The samples were calcined at 1100C but were sintered at 1100C and 1350 C. **Figure 13** shows the colors of the samples sintered at different temperatures.

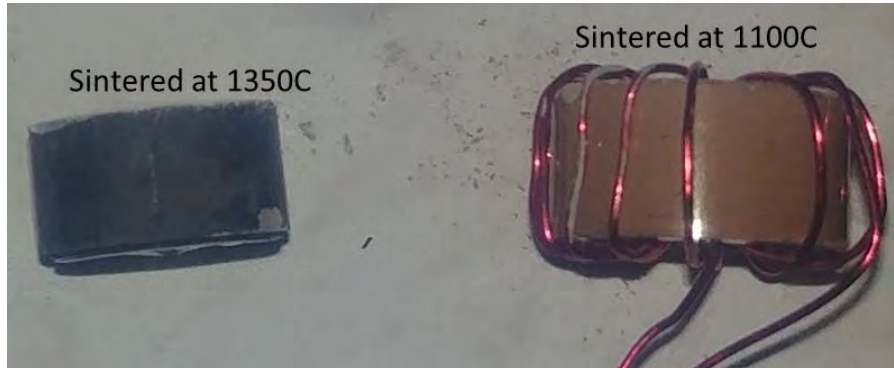


Figure 13. The final complexion of the sintered ceramics pointed to compositional variation of the ceramics.

An X-ray diffraction study including a Rietveld analysis was conducted for both samples. **Figure 14a and 14b** show the x-ray diffraction pattern of the two samples sintered at 1100C and 1350 C respectively.

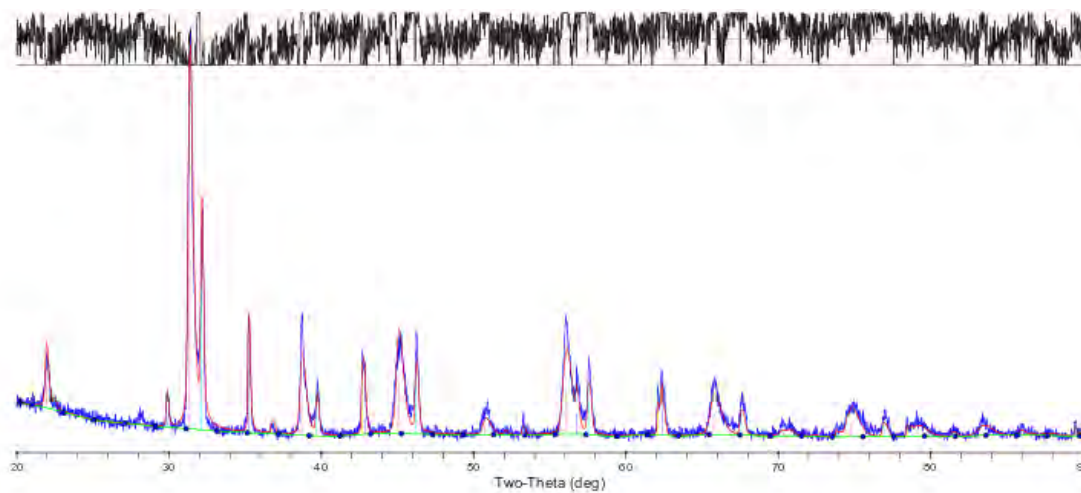


Figure 14a. XRD of 20wt% BaFe + 80 wt% $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ with 20 wt% Oxide III sintered at 1100C.

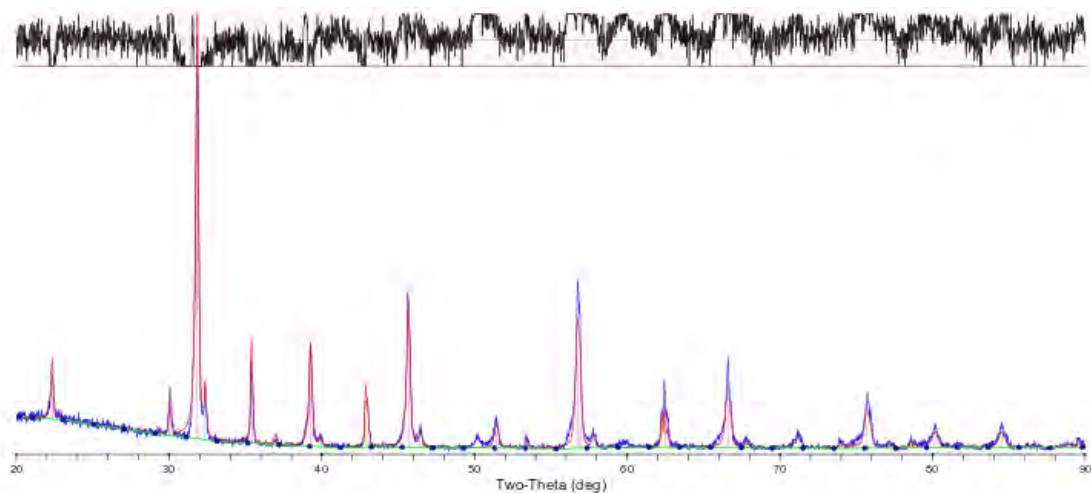


Figure 14b. XRD of 20wt% BaFe + 80 wt% $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ with 20 wt% Oxide III sintered at 1350C.

A literature search produced the XRD pattern of Barium Ferrite¹² (**Figure 15**). We compared the strong BaFe peak to the ones in Figures 14a and 14b to determine the identified phases in the material. It appears that the BaFe strong peaks might be overshadowed by the strong BST peak and requires further examination; however, it was quite clear from Figures 14a and 14b that the amount of the ferrite decreases at higher sintering temperature of 1350 C.

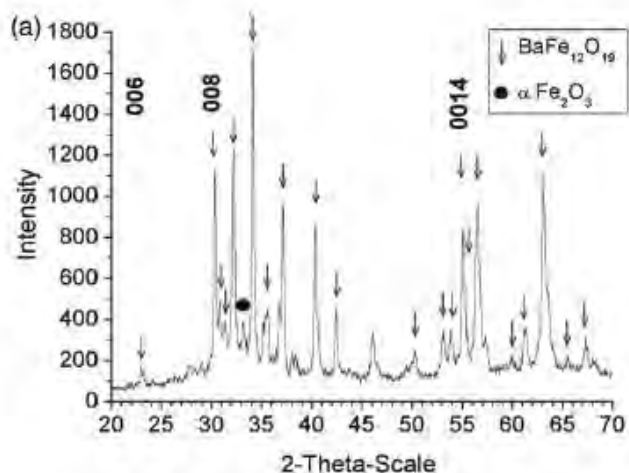


Figure 15. BaFe XRD shows strong peaks at 2q of 35 degrees [Reference 6].

Figures 16a and 16b show the Rietveld analysis of the materials sintered at 1100C and 1350 C. It confirms our findings from the XRD pattern (Figures 14a and 14b).

¹² Kolev, S. and Lisjak, D., "Preparation and characterization of magnetically ordered columnar structures of barium ferrite particles.

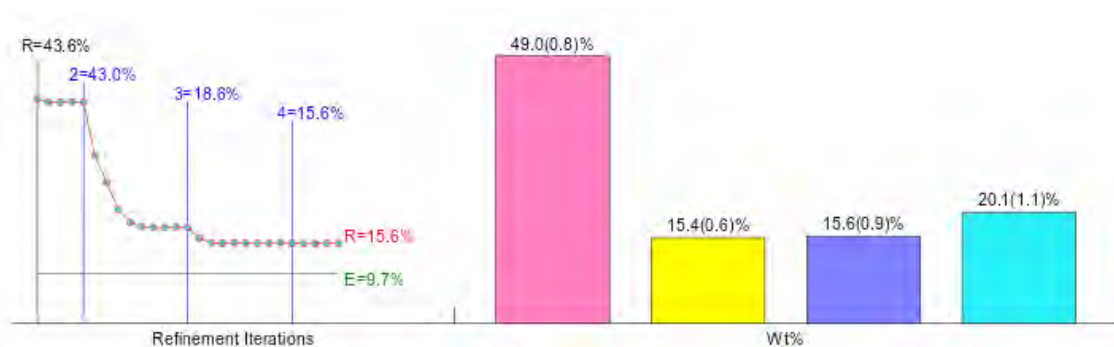


Figure 16a. Rietveld analysis of 20wt% BaFe + 80 wt% Ba_{0.55}Sr_{0.45}TiO₃ with 20 wt% Oxide III sintered at 1100C.

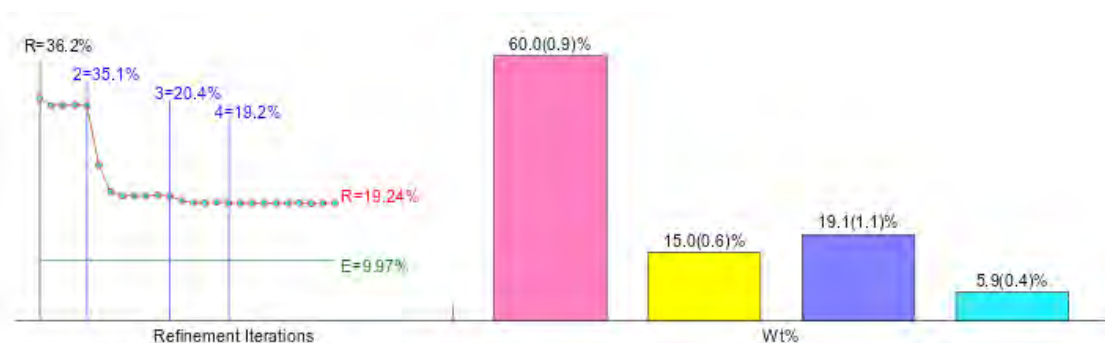


Figure 16b. Rietveld analysis of 20wt% BaFe + 80 wt% Ba_{0.55}Sr_{0.45}TiO₃ with 20 wt% Oxide III sintered at 1350C.

The two samples were also used for dielectric constant and loss measurements (ϵ & $\tan\delta$) measurements at low frequency. **Tables 5a and 5b** show the differences in the values of the parameters supporting the compositional differences.

Table 5a. ϵ and $\tan\delta$ values of 20wt% BaFe + 80 wt% Ba_{0.55}Sr_{0.45}TiO₃ with 20 wt% Oxide III sintered at 1100 C.

20wt% BaFe + 80 wt% Ba _{0.55} Sr _{0.45} TiO ₃ with 20 wt% Oxide III sintered at 1100 C									
100 Hz		120 Hz		1 kHz		10 kHz		100 kHz	
C(pF)	D	C(pF)	D	C(pF)	D	C(pF)	D	C(pF)	D
Fluctuating		21	0.672	13.5	0.333	10.62	0.121	9.92	0.046
ϵ	→	77.069		54.031		42.504		39.704	

Table 5b. ϵ and $\tan\delta$ values of 20wt% BaFe + 80 wt% $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ with 20 wt% Oxide III sintered at 1100 C.

20wt% BaFe + 80 wt% $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ with 20 wt% Oxide III sintered at 1350 C									
100 Hz		120 Hz		1 kHz		10 kHz		100 kHz	
C(pF)	D	C(pF)	D	C(pF)	D	C(pF)	D	C(pF)	D
19 pF	0.484	18	0.456	13.0	0.209	11.54	0.064	11.31	0.023
$\epsilon=168.7$		$\epsilon=186.5$		$\epsilon=119.9$		$\epsilon=94.3$		$\epsilon=88.1$	

From the above data, we surmise that:

1. The sintering temperature of the composites influence the dielectric properties of the material- *higher sintering temperature leading to the dissolution of BaFe past its melting temperature (1316 C) led to higher ϵ and lower $\tan\delta$ values.* It will therefore provide higher tunability too.
2. At the lower sintering temperature XRD confirms the presence of BaFe. Unlike the MgFe/BST composite where the MgFe and BST were in their separate phases at 1100C sintering temperature, the BaFe based compound will have the tendency of combining at the elemental level with BST and being mostly used in forming more BST by combining with the Strontium Titanate. *The solution to forming BaFe/BST could be to combine them after having fully sintered the BST at its 1350C temperature, and then mixing them to form the composite.*

Finally, we have performed comprehensive studies of dielectric/ferrite compositions to assess the variation in their dielectric and magnetic properties. As an example, we present below our data with Barium Ferrite in different combinations with $\text{Ba}_{0.55}\text{Sr}_{0.45}\text{TiO}_3$ dielectric ceramic material.

We will now compare the L vs T values of the various compositions of the BaFe based magnetodielectric materials- **Tables 6 thru 9.**

Table 6. L vs T data for 100 wt% BaFe + 0 wt% Ba_{0.55}Sr_{0.45}TiO₃ ceramics.

100 wt% BaFe										
T (°C)	L(100 Hz) μH	Q(100 Hz)	L (120 Hz) μH	Q(120 Hz)	L (1 kHz) μH	Q(1 kHz)	L(10 kHz) μH	Q (10 kHz)	L100 kHz) μH	Q (100 kHz)
25	1	0.002	1	0.002	1.4	0.023	1.36	0.226	1.320	2.57
40	1	0.002	1	0.002	1.4	0.021	1.35	0.201	1.309	2.24
50	1	0.002	1	0.002	1.3	0.021	1.34	0.212	1.308	2.29
60	1	0.002	1	0.003	1.3	0.022	1.34	0.213	1.306	2.38
70	1	0.002	1	0.002	1.3	0.021	1.34	0.211	1.306	2.36
80	1	0.002	1	0.003	1.3	0.021	1.34	0.209	1.305	2.33
90	1	0.003	1	0.002	1.3	0.020	1.34	0.206	1.305	2.30
100	1	0.002	1	0.002	1.4	0.021	1.34	0.203	1.306	2.26

Table 7. L vs T data for 80 wt% BaFe + 20 wt% Ba_{0.55}Sr_{0.45}TiO₃ ceramics.

80wt% BaFe + 20 wt% Ba0.55										
T (°C)	L (100 Hz) μH	Q(100 Hz)	L (120 Hz) μH	Q (120 Hz)	L (1 kHz) μH	Q (1 kHz)	L (10 kHz) μH	Q (10 kHz)	L (100 kHz) μH	Q (100 kHz)
25	2	0.005	1	0.004	1.6	0.035	1.60	0.347	1.559	4.41
40	2	0.004	1	0.004	1.6	0.033	1.59	0.326	1.559	4.08
50	1	0.003	1	0.002	1.5	0.032	1.59	0.318	1.560	3.96
60	1	0.005	1	0.003	1.6	0.031	1.59	0.309	1.560	3.82
70	2	0.004	1	0.004	1.6	0.030	1.59	0.302	1.559	3.69
80	2	0.004	1	0.004	1.5	0.029	1.59	0.295	1.559	3.60
90	2	0.004	1	0.004	1.5	0.028	1.59	0.288	1.558	3.50
100	2	0.004	1	0.004	1.6	0.028	1.59	0.281	1.558	3.40

Table 8. L vs T of 60wt% BaFe + 40 wt% Ba_{0.55}Sr_{0.45}TiO₃.

60wt% BaFe + 40 wt% Ba _{0.55} Sr _{0.45} TiO ₃						
T (°C)	L (1 kHz) μH	Q (1 kHz)	L (10 kHz) μH	Q (10 kHz)	L (100kHz) μH	Q (100kHz)
23.6	1.2	0.029	1.21	0.289	1.186	3.49
40	1.3	0.030	1.21	0.278	1.189	3.32
50	1.2	0.027	1.21	0.271	1.190	3.23
60	1.2	0.026	1.21	0.265	1.191	3.14
70	1.2	0.026	1.21	0.259	1.192	3.06
80	1.2	0.025	1.21	0.254	1.193	3.00
90	1.2	0.025	1.22	0.249	1.195	2.93
100	1.2	0.024	1.22	0.244	1.196	2.85

Table 9. L vs T of 20wt% BaFe + 80 wt% Ba_{0.55}Sr_{0.45}TiO₃.

20 wt% BaFe + 80 wt% Ba _{0.55} Sr _{0.45} TiO ₃						
T (°C)	L (1 kHz) μH	Q (1 kHz)	L (10 kHz) μH	Q (10 kHz)	L (100kHz) μH	Q (100kHz)
25	1.3	0.017	1.29	0.173	1.255	1.893
40	1.3	0.017	1.29	0.170	1.257	1.851
50	1.3	0.017	1.29	0.165	1.259	1.792
60	1.3	0.016	1.29	0.161	1.261	1.738
70	1.3	0.016	1.29	0.158	1.262	1.712
80	1.3	0.016	1.29	0.157	1.262	1.696
90	1.3	0.016	1.30	0.146	1.269	1.578
100	1.3	0.015	1.30	0.148	1.270	1.589

If we compare **Tables 6 thru 9**, we observe that:

1. For **all compositions and for each frequency**, the L value is very stable.
2. Within margin of error, the L values at 100 Hz are very similar across all compositions, whereas the Q value seems to decrease even at 100 Hz with the addition of the dielectric materials. *It must be emphasized that the Q value does not decrease significantly at the 20 wt% Ba_{0.55}Sr_{0.45}TiO₃ level leaving the opportunity open for high epsilon magnetic materials at lower frequencies.*
3. **Between 1 kHz and 100 kHz and for all compositions, the Q value seems to decrease** by a factor of 10 as the frequency increases by a factor of 10. *The anomaly in the low(er) Q value @ 100 kHz in Table 3 is yet to be explained.*
4. **Neither the Q nor the L seems to be significantly dependent** on the temperature between 25C and 100C.

The same comparison was performed for BaFe combined with Ba_{0.55}Sr_{0.45}TiO₃ with various amounts of Oxide III (**Tables 10 thru 13**).

Table 10. L vs T data for 100 wt% BaFe + 0 wt% Ba_{0.55}Sr_{0.45}TiO₃ ceramics.

100 wt% BaFe										
T (°C)	L(100 Hz) μH	Q(100 Hz)	L (120 Hz) μH	Q(120 Hz)	L (1 kHz) μH	Q(1 kHz)	L(10 kHz) μH	Q (10 kHz)	L100 kHz) μH	Q (100 kHz)
25	1	0.002	1	0.002	1.4	0.023	1.36	0.226	1.320	2.57
40	1	0.002	1	0.002	1.4	0.021	1.35	0.201	1.309	2.24
50	1	0.002	1	0.002	1.3	0.021	1.34	0.212	1.308	2.29
60	1	0.002	1	0.003	1.3	0.022	1.34	0.213	1.306	2.38
70	1	0.002	1	0.002	1.3	0.021	1.34	0.211	1.306	2.36
80	1	0.002	1	0.003	1.3	0.021	1.34	0.209	1.305	2.33
90	1	0.003	1	0.002	1.3	0.020	1.34	0.206	1.305	2.30
100	1	0.002	1	0.002	1.4	0.021	1.34	0.203	1.306	2.26

Table 11. L vs T values of 80wt% BaFe + 20 wt% Ba_{0.55}Sr_{0.45}TiO₃ with 20 wt% Oxide III.

80wt% BaFe + 20 wt% Ba _{0.55} Sr _{0.45} TiO ₃ with 20 wt% Oxide III						
T (°C)	L (1kHz) μH	Q (1kHz)	L (10kHz) μH	Q (10kHz)	L (100kHz) μH	Q (100kHz)
44	1.5	0.019	1.45	0.180	1.43	2.07
50	1.4	0.021	1.43	0.202	1.41	2.35
60	1.5	0.023	1.43	0.212	1.41	2.45
70	1.4	0.024	1.43	0.221	1.404	2.51
80	1.4	0.023	1.44	0.215	1.409	2.28
90	1.4	0.022	1.43	0.208	1.406	2.41
100	1.4	0.020	1.44	0.194	1.408	2.26

Table 12. L vs T values of 60wt% BaFe + 40 wt% Ba_{0.55}Sr_{0.45}TiO₃ with 20 wt% Oxide III.

60wt% BaFe + 40 wt% Ba _{0.55} Sr _{0.45} TiO ₃ with 20 wt% Oxide III						
T (°C)	L (1kHz) μH	Q (1kHz)	L (10kHz) μH	Q (10kHz)	L (100kHz) μH	Q (100kHz)
40	1.5	0.017	1.6	0.17	1.485	1.632
50	1.6	0.017	1.6	0.172	1.5	1.64
60	1.6	0.018	1.59	0.172	1.491	1.615
70	1.7	0.021	1.6	0.212	1.5	1.96
75	1.6	0.018	1.6	0.18	1.5	1.7
80	1.5	0.018	1.6	0.181	1.7	1.7
85	1.6	0.019	1.6	0.184	1.51	1.74
90	1.6	0.019	1.61	0.187	1.51	1.75
95	1.7	0.021	1.61	0.186	1.513	1.74
100	1.6	0.017	1.62	0.180	1.514	1.724

Table 13. L vs T values of 20wt% BaFe + 80 wt% Ba_{0.55}Sr_{0.45}TiO₃ with 20 wt% Oxide III.

20wt% BaFe + 80 wt% Ba _{0.55} Sr _{0.45} TiO ₃ with 20 wt% Oxide III										
T (°C)	L(100 Hz) μH	Q(100 Hz)	L (120 Hz) μH	Q(120 Hz)	L (1 kHz) μH	Q(1 kHz)	L(10 kHz) μH	Q (10 kHz)	L100 kHz) μH	Q (100 kHz)
25	1	0.002	1	0.002	1.6	0.022	1.58	0.222	1.493	2.08
40	1	0.002	1	0.002	1.6	0.022	1.58	0.216	1.485	2.03
50	2	0.002	1	0.002	1.6	0.021	1.58	0.212	1.485	1.998
60	1	0.002	1	0.002	1.6	0.021	1.58	0.209	1.475	1.950
70	1	0.002	1	0.002	1.6	0.021	1.57	0.205	1.468	1.916
80	1	0.002	1	0.002	1.6	0.020	1.57	0.201	1.469	1.903
90	1	0.002	1	0.002	1.6	0.020	1.57	0.198	1.467	1.853
100	1	0.002	1	0.002	1.5	0.019	1.57	0.194	1.466	1.829

If we now compare **Tables 10 thru 13**, we observe that:

1. For **all compositions and for each frequency**, the Q values are **better** for those with Oxide III in the composition.
2. From 1 kHz thru 100 kHz, the L values are **stable** within margin of error.
3. **Between 1 kHz and 100 kHz and for all compositions, the Q value seems to decrease** by a factor of 10 as the frequency increases by a factor of 10.
4. **Neither the Q nor the L seems to be significantly dependent** on the temperature between 25C and 100C.

So, in summary, we have shown that high(er) epsilon magnetic materials with low inductance values can be fabricated that are stable in a wide temperature range.

3. Findings and Conclusions

Task 1(Scalability): We found that there is no physical limitation of fabricating large(r) pieces of these dielectric materials. The mixing time of larger quantities of the ceramic constituents have to be studied to assure compositional uniformity of the larger pieces. Furthermore, high temperature ovens with larger areas of stable thermal profile will be needed. Therefore, we conclude that there are no scientific reasons inhibiting scalability of these novel tunable dielectric ceramic materials.

Task 2 (Thick Films): The thick film task is not complete yet. Our initial experiments have found that thick films of desired compositions can be screen printed onto single crystal substrates.

Task 3 (RF measurements): We have conducted high power RF measurements of the dielectric materials and found that they have excellent distortion properties. Also, one can choose the compositions based on the amount of hysteresis required for the application. Furthermore, very high tunability can be obtained in these materials. We conclude that we can present a library of materials for a variety of high-power microwave applications.

Task 4 (Development of modeling and simulation pathways): Although there are many elaborate machine learning models of influencing the discovery of these materials, we found that simple regression techniques might suffice. We conclude that a detailed table of features will be necessary to apply the entirety of the algorithmic approach *and might be more beneficial for the magnetodielectric compounds.*

Task 5 (Magnetodielectric materials): We found that we can design magnetodielectric materials with a variety of L and C values for different applications. Although this task was a mere assessment of the capability, we feel confident to conclude that further work towards applications must be carried out to realize the full potential of these materials for high power microwave applications.

4. Plans and Upcoming Events

For the ONR Grant #— N00014-20-1-2019, we have completed about 60% of the work. Tasks 2 and 5 will be completed by April, 2022. The plan for the rest of the program consists of:

1. Task 2- Development of thick film processes for large area tunable dielectric films. Under this task, we will develop thick films of the tunable dielectric materials and for the magnetodielectric materials. We will optimize the thick film printing processes for these materials on large substrates and deposit coplanar electrodes to measure the material properties of the thick films. The purpose of this task is to develop planar devices for high power RF applications.
2. Task 5- Assessment of magnetodielectric materials for RF applications. Under this task we have investigated several compositions of the magnetodielectric materials. Our assessment shows that they are a good candidate for high power delay line applications; however, we need to understand the impact on the saturation magnetization of the magnetic phase of the material when they exist in the same material with dielectric materials. This phase will conclude in April 2022 with the measurement of the saturation magnetization of the magnetodielectric materials.

We have demonstrated the scalability of the low loss tunable material along with their intermodulation distortion properties at 400W peak envelope power. These unique properties have led to discussions with the Naval Research Laboratory for an application where tunable delay lines fabricated from these materials can be placed between the high-power microwave generators and antenna elements. The ability to fine-tune delays allows the creation of different waveforms on target due to pre-designed constructive and destructive interference.

As for the magnetodielectric materials, we have discussed an application for tunable delay lines too, where both the magnetic and dielectric phases can be tuned for their system applications.

Therefore, we believe that our progress justifies the consideration for Phase 3 continuation work for demonstrating these materials for the US Navy's applications.

5. Transitions and Impacts

Not Applicable.

6. Collaborations

Powerhouse has collaborated with government laboratories at all levels- from material characterization to determining system applications. The following is a summary of the interactions:

1. NRL High Power Microwave Section, Code 5745 (Drikas). The Code 5745 HPM team will be submitting a proposal to ONR for evaluating Powerhouse's tunable dielectric materials for tunable delay line applications for their ultra wide band high power microwave generator.
2. NRL Advanced Materials Section, Code 6127 (Laskoski). Powerhouse performs the RF material characterization in collaboration with Dr. Laskoski's team. The thick film capability is also being developed in collaboration with Dr. Laskoski.
3. NSWCDD E13, HPM Technology Development Branch (Fairbanks). Dr. Fairbanks will utilize the magnetodielectric tunable materials for his applications in delay lines if we are awarded a follow-on contract.

7. Personnel

Principal Investigator: Somnath Sengupta
Business Contact: Somnath Sengupta

8. Students

This program was utilized to train adults with autism on sustainable high technology laboratory skills. It is our hope that we will continue to develop cutting edge science and technology for the Navy while impacting employment for a severely underrepresented group.

9. Technology Transfer

Not Applicable.

10. Products, Publications, Patents, License Agreements, etc.

Not Applicable.

11. Point of Contact in Navy

Dr. Tim Andreadis; Code 5745; Naval Research Laboratory. Last Contact: December,2021.
Dr. Zachary Drikas; Code 5745; Naval Research Laboratory. Last Contact: January,2022.
Dr. Andrew Fairbanks; Naval Surface Warfare Center - Dahlgren Division. Last Contact: January,2022
Dr. Matthew Laskoski, Code 6127; Naval Research Laboratory. Last Contact: January,2022.

12. Acknowledgement/Disclaimer

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High-Power Microwave Generation by Compact Linear Transformer Driver Technology

Grant No. N00014-18-1-2499

Annual Report for Fiscal Year 2021

Period of Performance: October, 1, 2020 to September 30, 2021

Prepared by:

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Grant or Contract Number: N00014-18-1-2499

Date Prepared: Dec 1, 2021

Project Title: High-Power Microwave Generation by Compact Linear Transformer Driver Technology

Annual Summary Report: FY2021

Principal Investigator: Ryan McBride, 734-763-7504, mcbriider@umich.edu

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Section I: Project Summary

1. Overview of Project

Abstract: The efficient generation of high-power microwaves (HPM) from compact generating equipment is of critical importance to the United States Navy and Department of Defense (DoD). Applications include radar, signal jamming, electronic warfare, counter IED (improvised explosive device), and vehicle stoppers. Example systems where HPM is critical include the Patriot Missile and the Aegis Combat/Weapon System. This project is exploring the use of compact linear transformer driver (LTD) technology to drive various gigawatt-class, narrow-band (~ 1 GHz), high-power microwave (HPM) sources, such as the magnetically insulated line oscillator (MILO). LTDs are low-voltage, low-impedance drivers. An LTD-driven HPM source could become one of the most compact, low-voltage, GW-class HPM sources available for ONR/DoD directed energy programs. To obtain this performance, a rich assortment of physics issues will be studied. For example, as we increase the driver power, electrode plasmas (particularly from contaminants adsorbed onto electrode surfaces) can become problematic. If plasmas form in the anode-cathode gap with densities $> 1 \times 10^{10}$ electrons/cc, then L-band microwaves (1 GHz) can become attenuated significantly. We will study these low-density plasmas by combining particle-in-cell simulations with experimental measurements from a vast array of diagnostics, including energetic particle detectors, Zeeman and Stark spectroscopy, self-emission imaging, and laser-based probing and imaging techniques. The use of LTD technology to drive an HPM source is advantageous for several reasons. First, the driver impedance and driver voltage is tunable, because LTD systems are modular. The PI's team is assembling a 4-cavity LTD facility called BLUE (Bestowed LTD from the Ursa-minor Experiment) at the University of Michigan (UM). The driver impedance of BLUE can be varied from 1 to 30 ohms. Second, the pulsed-power components in LTDs are completely encased in metal, thus minimizing stray high-voltage fields and electrical interference. Third, LTDs can be rep-rated up to (and possibly beyond) 0.1 Hz, thus increasing the average power. Additionally, rep-rating has the potential benefits of electrode conditioning and decontamination, therefore allowing us to emulate standard industry practices in the fabrication of commercial microwave tubes. This document describes the progress to date on this project, which includes the status of the BLUE facility, simulations of a MILO donated by AFRL for this project, and experimental results of MILO experiments with a single BLUE cavity. This document also describes the research products produced by this effort, including publications and presentations.

Objective: To explore the use of linear transformer driver technology for driving high-power microwave sources, including GW-class magnetically insulated line oscillators and potentially other crossed-field devices.

Introduction: This project will study GW-class, narrow-band HPM devices, operating at a frequency ~ 1 GHz. Such devices are driven by pulsed power technology. Pulsed power involves the use of high-voltage capacitors and fast switching techniques to store electrical energy over long time scales and discharge the energy over fast time scales; because power is the rate at which energy is delivered, the fast discharge time leads to power amplification. Often the peak powers obtainable in HPM can be quite large ($\sim$ GW), but this usually comes at the expense of high average input powers. This project will explore the use of LTD technology (an exciting new compact and efficient pulsed power technology) to drive various HPM sources. An important attribute of LTD technology is that it has the potential to be rep-rated up to (and possibly beyond) ~ 0.1 Hz.

In narrow-band HPM, the pulsed-power driver is used to apply a large, fast-rising voltage pulse across a vacuum-filled anode-cathode gap (A-K gap). This A-K gap then serves as the load for the pulsed-power driver, sometimes being referred to as a “diode” load. The large applied voltage (and its associated electric field) can cause electrons to be emitted from the cathode surface; this is especially true if the cathode is treated in a way that favors emission of electrons (e.g., velvet covered cathodes). If the voltage applied across the A-K gap is an appreciable fraction of the electron's rest mass energy (511 keV), then the predominantly vacuum-filled region within the A-K gap can become populated with relativistic electrons. Longer timescale electromagnetic fields [$\sim$ DC fields relative to the faster radio frequency (RF) timescales of interest] can then be applied to direct these electrons into a well-formed electron beam. The electron beam can then be modulated to amplify and/or excite RF electromagnetic waves.

In crossed-field devices (CFDs) – such as relativistic magnetrons and crossed-field amplifiers – an approximately DC electric field $\mathbf{E}$ and an approximately DC magnetic field $\mathbf{B}$ are applied at right angles to one another, so that the well-known $\mathbf{E} \times \mathbf{B}$ drift velocity ($\mathbf{v} = \mathbf{E} \times \mathbf{B} / B^2$, where B is the scalar magnitude of the magnetic field) can be used to drive and steer the electron beam. To get the beam to interact with an RF field, the beam is driven in close proximity to a slow-wave structure (i.e., an anode structure with periodically spaced metal vanes). A synchronized, modulating interaction between the beam and the RF wave can then be obtained if the magnitude of the drift velocity $v = E/B$ is well matched to the phase velocity of the RF wave propagating in the slow-wave structure. A bunching instability, called the phase-focusing mechanism, causes the beam to become modulated, enhancing the RF output.

To drive the electron beams, this project will use a pulsed-power technology called linear transformer drivers. The LTD concept was pioneered in 1995-1997 at the High Current Electronics Institute (HCEI) in Tomsk, Russia, by Kovalchuk, Vizir, Kim, and colleagues. Since then, the LTD concept has been advanced further by HCEI as well as researchers at Sandia National Laboratories

and many others worldwide. LTDs have been called the greatest advance in prime-power generation since the invention of the Marx generator in 1924.

In the late 2000s, a collaboration was developed between HCEI, Sandia National Laboratories, and the University of Michigan (UM) to bring LTD technology to the United States. In 2006--2007, five 3-m-diameter, 1-MA, 100-ns LTD cavities were tested at HCEI with resistive and electron-beam diode loads. In July of 2007, one of these HCEI cavities was shipped to UM, becoming the MAIZE facility and the first 1-MA, 100-ns LTD in the United States. In 2008, ten more 1-MA, 100-ns LTDs cavities were shipped to Sandia, becoming part of the Mykonos facility. Additionally, smaller (1.25 m in diameter), lower-current cavities were shipped to Sandia, becoming the Ursa Minor facility. The Ursa Minor facility stacked 21 of these 1.25-m-diameter cavities together to obtain a high-impedance driver for high-energy x-ray source development:

https://www.sandia.gov/Pulsed-Power/research_facilities/Ursa_Minor.html

Four of the Ursa Minor cavities were shipped to UM, where we are now assembling them into the BLUE facility (Bestowed LTD from the Ursa-minor Experiment) to drive HPM sources for this project.

Background: This project, using LTDs to drive HPM sources, is both basic and applied research, involving HPM design and optimization with particle-in-cell (PIC) simulations and experimental optimization of driver impedance using the 4-cavity BLUE LTD facility. BLUE will provide a variable drive voltage of 50–800 kV and a variable drive impedance of 1–30 Ω . Our approach will also involve the study of electrode plasmas (particularly from contaminants adsorbed onto electrode surfaces), which can become problematic. If plasmas form in the anode-cathode gap with densities $>10^{10}$ electrons/cc, then L-band microwaves (1 GHz) can become attenuated significantly. We will study these low-density power flow plasmas by combining particle-in-cell simulations with experimental measurements from a vast array of diagnostics, including energetic particle detectors, Zeeman and Stark spectroscopy, self-emission imaging, and laser-based probing and imaging techniques.

2. Activities and Accomplishments

2.1 Pulsed Power Development

The BLUE LTD facility is composed of 4 LTD cavities which were formerly part of the Ursa Minor experiment at Sandia National Laboratory. The 1.25m cavities are each composed of 10 “bricks”, or sets of two capacitors joined by a spark gap switch. These bricks can be charged to +/- 100 kV and discharged in parallel to produce a 200 kA pulse with a ~100 ns rise time. Each cavity has a generator impedance of ~0.5 Ohms, and produces 100 kV across a matched load. By stacking additional cavities, the generator impedance and load voltage can be linearly increased. The generator impedance can be further increased, at the cost of reduced current, through the removal of bricks.

At the onset of this project, BLUE consisted of merely a set of metal cavities, plastic insulators, and Metglas inductive toroids. Today, BLUE's first cavity is fully operational, having driven various resistive loads and a MILO load, while BLUE's second cavity is presently being tested with resistive loads.

Images of the first completed BLUE cavity are presented in Figure 45 and Figure 46. In Figure 45 (a) and Figure 46, a clear poly-carbonate lid was in use, which enables the interior components to be observed during operation. The plastic lid also eliminates the parasitic current path around the LTD case [8], and thus all of the current is driven through the load at the center of the machine. Because the parasitic current path is eliminated, ferromagnetic cores were not required nor installed in Figure 45 (a) and Figure 46 (i.e., the cavity was in a bipolar Marx generator configuration). As our testing evolved, the clear plastic lid was eventually replaced with a metal lid, and thus pre-magnetized ferromagnetic cores became a requirement.

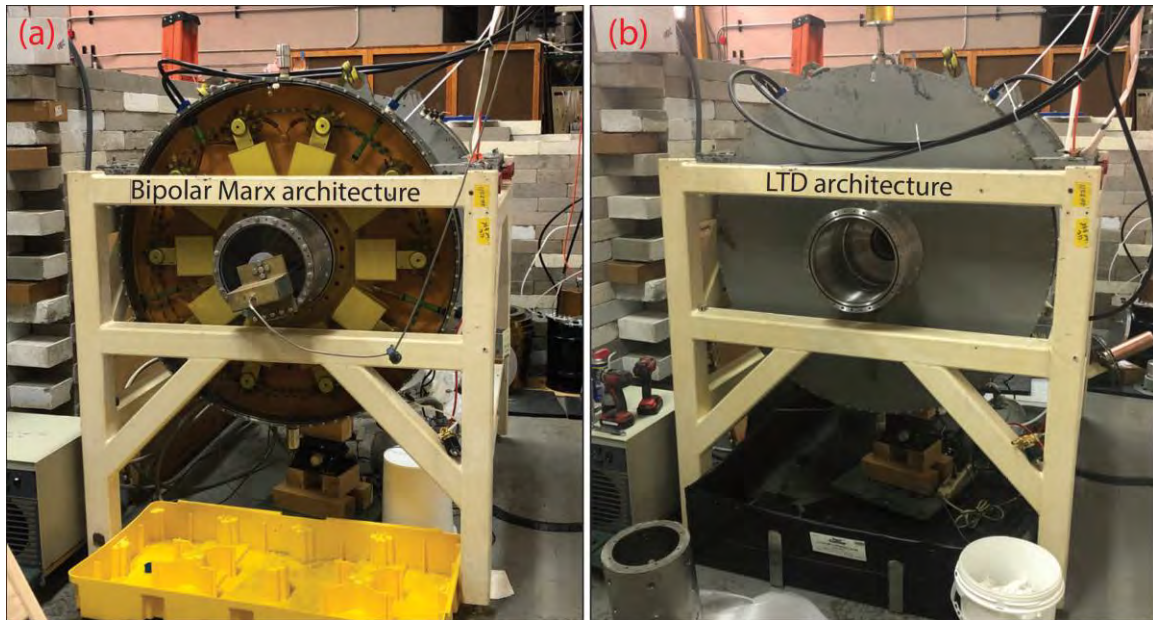


Figure 45: The BLUE experimental bay in the Plasma, Pulsed Power, and Microwave Lab (PPML) at the University of Michigan, with the prototype BLUE cavity configured as: (a) a bipolar Marx generator with a clear plastic lid; and (b) as a linear transformer driver with a steel lid.

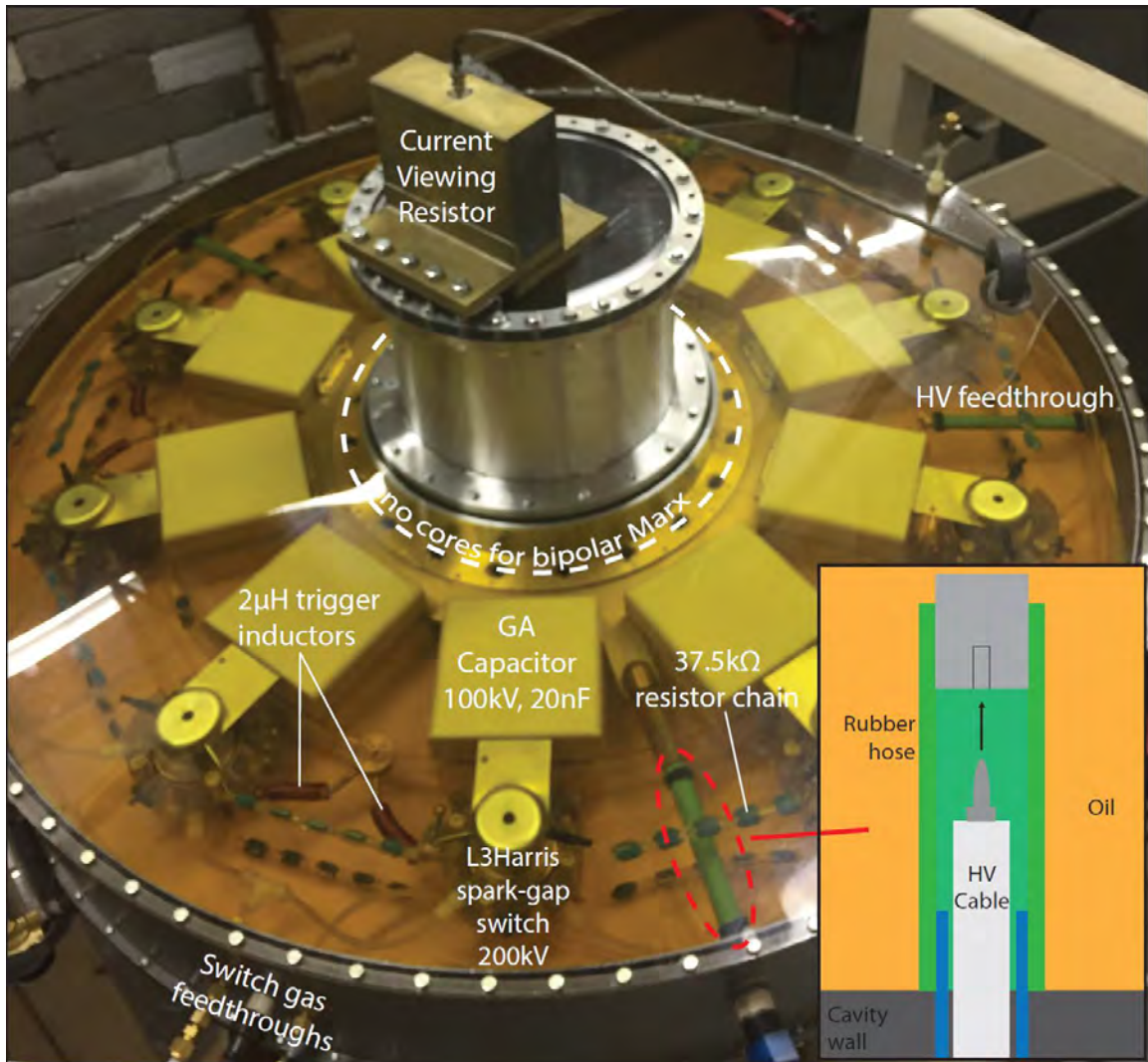


Figure 46: The first assembled BLUE cavity, shown here with a clear polycarbonate lid and no ferromagnetic cores (i.e., the cavity is in a single-stage bipolar Marx generator configuration). The cavity is filled with transformer oil. The small vacuum chamber on top of the cavity houses the resistive load. The brass structure on top of the chamber is the current viewing resistor (CVR). Plug-in feedthroughs with 3D-printed parts allow high-voltage cables to be easily disconnected from the cavity without removing the lid or draining the transformer oil.

Referring to Figure 46, each BLUE cavity is comprised of 10 “bricks,” where each brick consists of two 100-kV, 20-nF capacitors (General Atomics Part # 35467) and a single 200-kV (100-kV) spark-gap switch (L3Harris Model # 40264-200kV). A photograph of an L3Harris spark-gap switch is presented in Figure 47. Each switch was refurbished and tested with ten nominal discharges in the PPML “brick-tester” before installation in the BLUE cavity. Switch pre-fires were rarely observed in either the brick tester or in BLUE—only one definite pre-fire event was confirmed in the 100 shots performed thus far on the first cavity.



Figure 47: An L3Harris spark-gap switch with brass electrodes, capable of operation at 200 kV (± 100 kV) and up to 200 psi gas fill. These switches are used in the MAIZE and BLUE LTD systems at the University of Michigan. In this image, the switch is shown with a shorting wire between the UV-pin and mid-plane. In the BLUE cavity, the shorting wires are replaced with 3-M Ω resistor chains for proper operation of the UV-pin.

Each BLUE cavity also consists of a transmission line framework for mounting the bricks in the cavities, large plastic insulator disks for separating the anode and cathode sides of the cavity, charging and triggering circuitry (such as HV resistors, inductors, and cable feedthroughs), switch gas lines, and diagnostics.

The trigger inductors (each 2 μ H) were installed between the main trigger bus line and the UV-pins/mid-planes of the L3Harris switches. Due to the finite capacitance of a switch mid-plane (7 pF), the trigger inductors serve to amplify the trigger pulse and reduce the jitter of the switch. They also provide some isolation between switches during the breakdown process. The bronze-colored trigger inductors can be seen attached to the switches in Figure 46.

Bipolar LTD cavities like BLUE require both a positive and negative high-voltage charging supply. The open-circuit output voltage of the cavity is equal to the difference between the positive and negative values. Since these values usually have the same magnitude, the open-circuit output voltage is usually twice the “charge voltage.” For example, a 100-kV charge voltage results in a 200-kV open-circuit output voltage. The spark-gap switches are bipolar as well, holding off both charge polarities from each other, until a trigger pulse on the grounded mid-plane electrode breaks down the switch. Each L3Harris switch also includes a “UV- pin.” Upon triggering, the pin creates a small spark at the switch mid-plane. The spark floods the switch gas with photo-ionizing UV light, thus reducing the breakdown jitter [9,10]. In a typical bipolar LTD cavity, the switch electrodes (and charging side of the capacitors) are chained together around the cavity through charging resistors or charging inductors (see Figure 46).

A high “rep-rate” (rate of repetitively charging and firing) is desired for various experimental platforms on BLUE (e.g., HPM experiments). Thus, dual Spellman 12-kW power supplies were acquired. They allow a theoretical rep-rate >1 Hz, as long as the charging impedance is kept low. However, having a small charging impedance between each brick may lead to degradation of the L3Harris spark-gaps during pre-fire events, due to excessive current draw from neighboring bricks. HVR resistor chains were assembled to serve as the charging impedance between each brick. Ultimately, a 37.5-k Ω total resistance for each chain was chosen as a compromise between brick isolation and fast charging time. These HVR chains limit undesired pre-fire currents through adjacent bricks to <2.7 A. Considering the 20-nF capacitors used in BLUE, the RC time-constant of this charging impedance is 750 μ s.

Five high-voltage cables are fed into each BLUE cavity: one for each charge polarity, one for a trigger pulse, and one for each pre-magnetization pulse polarity. Since the BLUE cavities must be moved back and forth between the servicing test stand and the side-mounting stacking rack, it was desired for the HV cables to be able to be unplugged from the cavity without the need to open the cavity or drain the transformer oil. To this end, a novel plug-in connection was developed utilizing SLA 3D-printed parts. This HV feedthrough connection is depicted in Figure 46. The cavity dimensions limited the length of the feedthroughs, making the DC charge cables especially prone to arcing. Luckily, it was found that the arcing could be eliminated by partially filling the feedthroughs with a dielectric grease.

Control Panel

To streamline the firing sequence of the BLUE system, a consolidated and intuitive control interface was desired. The firing sequence includes monitoring safety interlocks, operating the Spellman high-voltage power supplies, operating high-voltage Ross relays for isolation/grounding, and generating the fire command logic pulse. Semi-autonomous control of the firing sequence and other system functions minimizes manual input and allows for faster rep-rating of the facility.

Figure 48 shows the control panel assembled for BLUE. The panel is semi-autonomous, using the programmable Arduino Uno board (which is based on the ATmega328P 8-bit microcontroller). The best electrical resilience was obtained with the Ruggeduino-SE, a ruggedized version of the Uno manufactured by Rugged Circuits.

The panel is capable of rep-rating BLUE by automatically controlling the charging sequence as fast as possible. The only user input required is pressing the button to fire the machine. The panel also monitors for pre-fire events, automatically purges the switch gas after each shot, and controls the pre-magnetization pulse generator.



Figure 48: Arduino Uno (ATmega328P-based) control panel for semi-autonomous control of the BLUE charging and firing sequence, as well as other system functions.

HV Relay Barrel

Three high-voltage relays (produced by Ross Engineering Corporation) are used to connect/disconnect the cavity capacitors from the charging supplies. They also provide passive grounding in the event of an emergency abort or unexpected power loss. Operation of the three relays is handled by the Arduino-based control panel.

The relays must be submerged in transformer oil to prevent arcing, so a 20-gallon steel drum was used to house the three relays, as shown in Fig. 6. The drum also contains two 50-k Ω ceramic dump resistors, which absorb the energy stored in the cavity(s) upon abort. High-voltage feedthroughs similar to those developed for the prototype BLUE cavity allow up to five positive and five negative cables to plug into the barrel.



Figure 49: A 20-gallon oil drum contains the three Ross HV relays used in the charging circuit. The relays are operated by the control panel during the charging sequence. The large copper-sulfate dump resistors in this photograph were ultimately replaced with 50-k Ω ceramic resistors to minimize maintenance.

200 kV Trigger Pulse Generator

The L3Harris spark-gap switches require a high voltage pulse as a trigger. The pulse is applied to the mid-plane, distorting the field in the switch enough to break down the pressurized “zero” air in the switch. A very fast dV/dt on the rising edge of the pulse is desired to minimize jitter. The pulse should also have sufficient energy (> 1 J) to ensure consistent triggering of many switches in parallel (up to 40 switches with all 4 cavities in operation).

To achieve a large dV/dt , a single brick, charged in parallel with the LTD cavities, is used as a trigger. This gives a trigger voltage equal to twice the charge voltage. The trigger brick is housed in a 10- gallon steel drum with high-voltage plug-in feedthroughs similar to those used on the prototype BLUE cavity and Ross relay barrel. Positive or negative trigger output may be chosen by grounding the opposite polarity. The trigger pulse generator barrel is shown in Figure 50.

The brick used in the trigger generator is identical to those used in the BLUE cavities, consisting of two 20-nF capacitors and a L3Harris spark-gap switch. The single spark-gap switch in the trigger generator is itself triggered by a PT55 pulse generator, which is mounted to the top of the barrel, as shown in Figure 50.



Figure 50: The 10-gallon oil drum containing the trigger pulse generating brick, which is charged in parallel with the BLUE LTD cavities and triggered by the PT55 pulse generator mounted to the top of the drum.

300 V Pulse Generator (PT003 Replacement)

The Pacific Atlantic Electronics (PAE) PT55 module, which is no longer in production, uses a rare krytron switch to produce a +50 kV output pulse with a risetime of less than 2 ns. The module requires a low power +7 kV DC charge voltage and a positive 250–300 V trigger pulse. PT55s are compact, low-jitter, and very useful in a pulsed-power laboratory, namely for triggering spark-gap switches. The single L3Harris spark-gap switch used in the BLUE trigger pulse generator (and also used in the BLUE LTD cavities) can be reliably triggered by a PT55 pulse, even when the switch is being operated at full voltage (200 kV). Several PT55s of varying condition are stockpiled in the PPML.

The PT55 draws <1 mA from its +7 kV DC power supply, so the charge voltage can be provided by a small 12 V DC-DC module. By contrast, the PT55's positive 250–300 V input trigger pulse is not as trivial to produce. Thus, the defunct PAE company also offered the PT003, a small solid-state device that, when given a +100 VDC charge voltage and a logic-level (+5 V) trigger pulse, produces a positive 250–300 V output pulse suitable for triggering the PT55. For minimal jitter, the PT003 had a <10 -ns risetime, as shown in Figure 51.

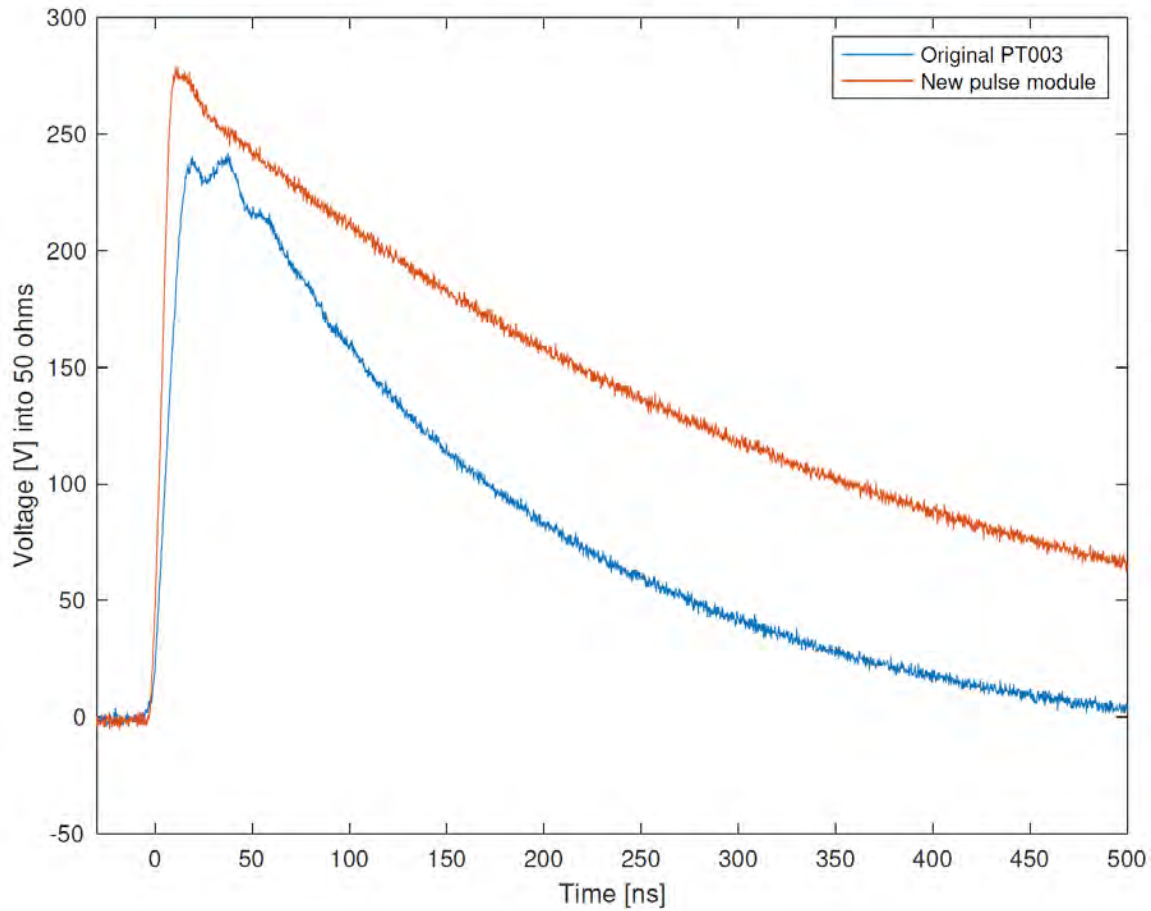


Figure 51: Output pulses from an original PAE PT003 (blue) and the new +300 V pulse generator (orange) into 50 Ω , when given a +5 V TTL trigger signal.

Unfortunately, the PPML supply of PT003s has dwindled much faster than the supply of PT55s. Since PT55s continue to be used around the lab, including for the BLUE trigger pulse generator, a suitable replacement for the PT003 had to be procured. With no inexpensive (<\$10k) commercial options, the new/replacement module was developed, with inspiration from the 200-V spark-gap trigger circuit developed by Simon Bland at Imperial College [11].

The circuit of the new +300 V pulse generator is shown in Figure 52. Six small film capacitors in parallel, totaling 6 nF, are charged to -300 V with a small, commercially available 12-V DC-DC module. Five enhancement-type, P-channel MOSFETs (PMOS) in parallel (Nexperia BSP230,135) are used as a low-side switch to rapidly connect the -300 V to ground when triggered. Multiple capacitors and PMOS elements are used in parallel to minimize the inductance and resistance of the circuit. Triggering the PMOS elements produces a +300 V pulse into 50 Ω on the opposite side of the capacitors. The

over-damped pulse has an approximately 200-ns e-folding decay time, similar to the original PT003 (see Figure 51).

To trigger the PMOS elements in this configuration, a negative voltage pulse must be applied to the gates. It was found in testing that a positive 10–20 V pulse, produced by a commercial BNC pulse generator, could be inverted with a low-leakage-inductance pulse transformer, and thus trigger the PMOS elements; however, the gate input capacitance of the PMOS elements, with several in parallel, is significant. The inverted pulse from the BNC pulse generator, even at the maximum +20 V amplitude, was unable to draw enough instantaneous current from the gates to achieve the desired risetime and amplitude.

To trigger the PMOS elements more strongly with only a logic-level (+5 V) pulse, an NPN transistor (Diodes Inc. ZXTN25020DGTA) was added to the circuit. A 10-nF capacitor is charged to +20 V from an additional DC-DC converter. This capacitor is discharged to ground via the transistor upon receipt of a positive logic-level pulse. Closure of the transistor switch produces a -20 V pulse on the output of the capacitor, which is fed to the PMOS gates. The addition of the NPN transistor to the circuit produced the desired amplitude and risetime to reliably trigger the PT55 with jitter <10 ns (see Figure 51).

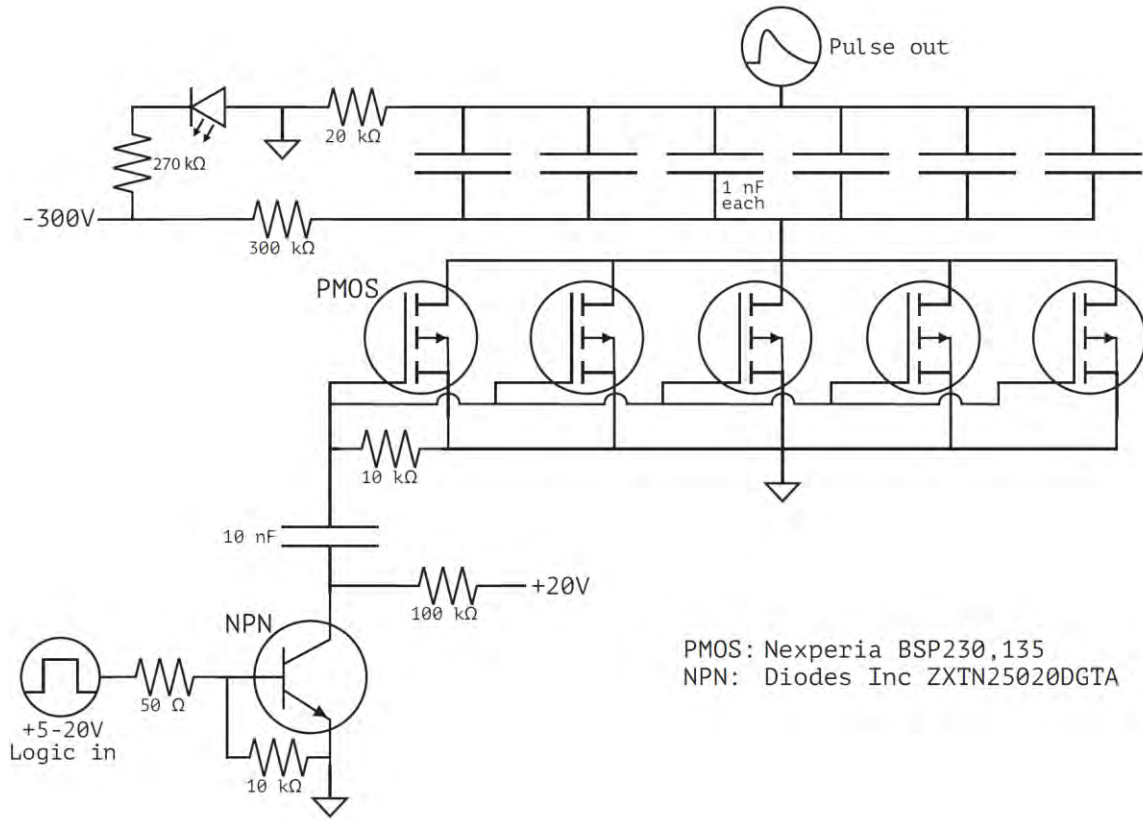


Figure 52: Circuit diagram of the +300 V pulse generator designed to trigger the PT55 mounted to the BLUE trigger pulse generator. The +20 V and 300 V are provided with small 12 V DC-DC converters. This generator replaces the defunct PT003 module.

Pre-magnetization Pulse Generator

In an LTD cavity, there is a parasitic path that the discharge current can take along the inner surface of the LTD's metallic case [8]. This parasitic path is in parallel with the load. To limit the current that takes this parasitic path (and thus force the current through the load as desired), LTD cavities usually include two ferromagnetic cores (an upper core and a lower core) within the loop formed by the parasitic current path.

The ferromagnetic cores typically consist of thin iron or Metglas tape, which is laminated with a dielectric film, wound into large rings, and potted in epoxy resin. Since the parasitic current path encloses the cores, generation of a parasitic current drives magnetization of the cores. Since the cores are made of thin strips of semi-resistive material with high magnetic permeability $\mu \gg \mu_0$, there is a high inductance associated with the parasitic path, which minimizes the fraction of current taking this path. In addition, there is a resistive effect due to eddy currents generated during magnetization of the cores, which appears at high-frequency [26]. Energy losses in the cores during an LTD discharge are often modeled with a static (and many times empirically determined)

resistance in parallel with the load. To model lower-frequency pulses around the cores, such as the core resetting/pre-magnetization discharge, an initial resistance that reduces rapidly after several microseconds is appropriate.

Due to magnetic hysteresis in the cores, the parasitic current from repeated cavity discharges eventually saturates the magnetic domains in the cores in a direction that reduces the effective permeability of the cores and thus reduces the impedance of the parasitic current path. To recover the maximum effective impedance for the parasitic current path, the alignment of the magnetic domains must be reset (reversed) back into their ideal direction for an LTD discharge. This can be done by applying a pre-magnetization pulse to the cavity. This “pre-mag” pulse drives a current in the LTD's metallic case that runs in a direction opposite to that of the parasitic current generated during an LTD discharge. The pre-mag pulse can be applied using a much lower voltage and generating a much lower peak current than that of an LTD discharge, but the pre-mag pulse must then be applied over a proportionally longer timescale. The pre-mag pulse can be applied anytime between LTD discharges, but it is typically done before installation of the experimental load, since the pre-mag pulse can ruin sensitive loads by driving modest currents through the load over long timescales.

The “volt-second product” of the cores is the parameter that defines the magnetic saturation properties of the cores. It can be roughly calculated from the material properties and geometry of the cores. From previous literature on the cavities (during the development of Ursa Minor) [12], the volt-second product of the cores used in the BLUE cavities is estimated to be around 20 mV*s. This figure makes intuitive sense: one can think about the volt-second product as if each core must “hold-off” the 100-kV pulse from half of the cavity for at least 200 ns (the typical experimental time). It also gives an estimate of the required pre-mag pulse duration for saturation. For example, if the pre-mag pulse voltage is 600 V, then saturation can be expected after a pulse duration of 33 μ s. Reference 12 also recommends a pre-magnetizing current of at least 1.5 kA to reach saturation in the Ursa Minor/BLUE cores.

After exploratory modeling in LTspice, a relatively simple RC discharge was chosen to generate the required pulse while minimizing cost and complexity of the pre-mag system. As shown in Figure 53, eight resistor-capacitor combinations are needed to provide a positive and negative channel for each of the four cavities. The capacitors (which can be individually disconnected from the circuit via screw-in breakers) are charged by a double-rectified 450-VAC transformer to (theoretically) 636 V. In reality, the capacitors charge to about 610 V due to leakage through the passive dump resistors. After charging is complete, a high-power, push-pull thyristor (Behlke HTS 40-1000-SCR) discharges the positive and negative channels to each other in a low-side bipolar fashion, similar to the operation of a bipolar LTD brick. In each channel, the resulting output pulse of the 1-mF capacitor is sent through a short length of nichrome wire acting as a high-power 250-m Ω resistor, over-damping the pulse, before it is sent to the cavity. An internal photograph of the pre-magnetization pulse generator constructed for BLUE is shown in Figure 54.

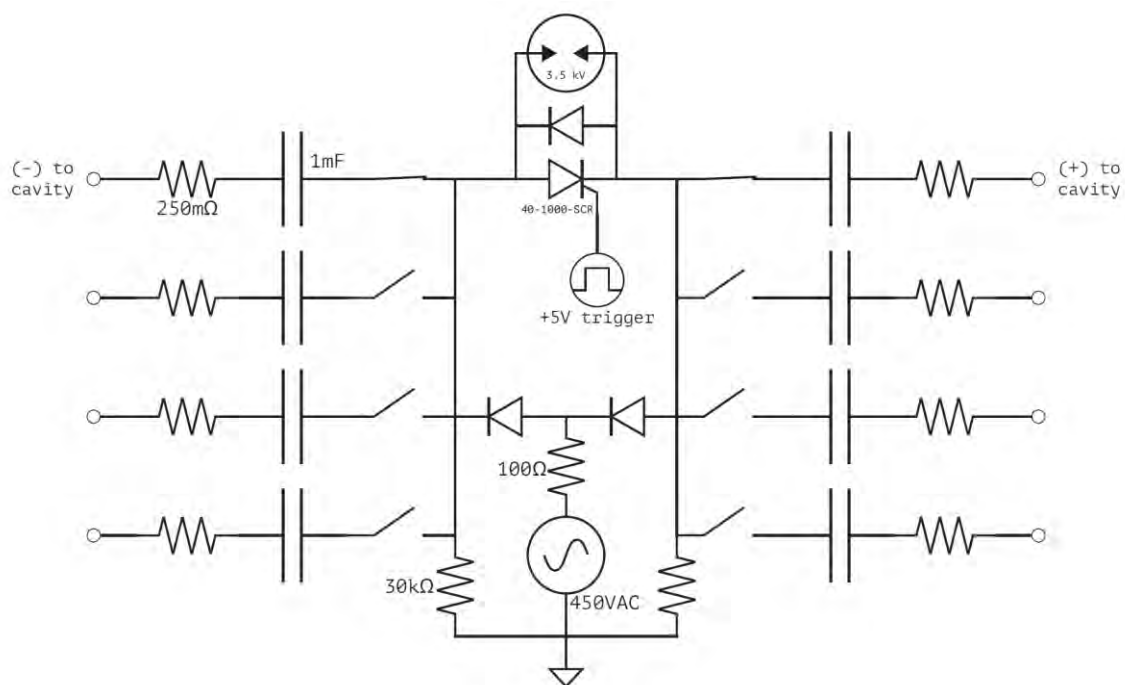


Figure 53: Circuit diagram of the pre-magnetization pulse generator for resetting the ferromagnetic cores on BLUE. In this diagram, only the output to the first cavity is enabled.

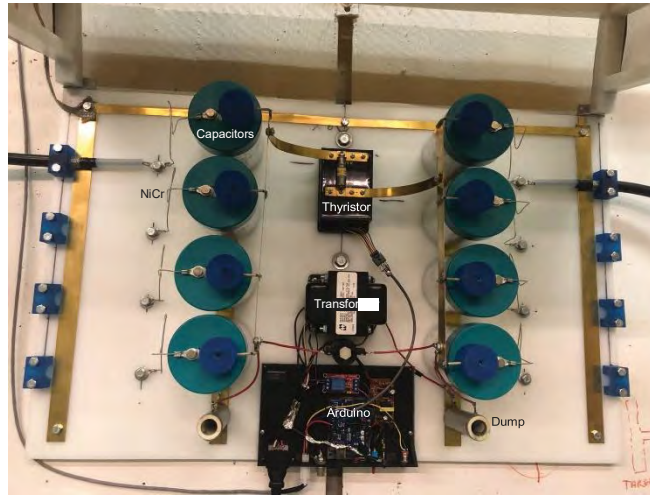


Figure 54: Photograph of the internal components of the pre-magnetization pulse generator constructed for resetting the ferromagnetic cores on BLUE. This photograph shows the generator's four positive and four negative output channels. The dark blue 3D-printed plastic structures on top of the capacitors are the screw-in breakers for connecting individual channels. In this photograph, only the output to the first cavity is enabled.

Output current pulses from a single channel of the pre-magnetization pulse generator were measured with a Pearson coil (see Figure 55). When the cores have already been saturated in the desired direction (i.e., the pre-mag generator has already been successfully fired in preparation for an LTD discharge), the pre-mag current pulse into the cavity is nearly identical to the pulse into a short-circuit load, indicating that the cavity has a very low impedance for the direction of the pre-mag current pulse (and thus a high impedance for the direction of the parasitic current pulse during an LTD discharge). When the cores are saturated in the undesired direction (i.e., the cores are in need of a resetting pre-mag pulse), a notch in the waveform of the pre-mag current is observed (see Figure 55). This notch is the result of the initially high impedance of the cavity (for the direction of the pre-mag current) dropping rapidly in the first $25\ \mu\text{s}$ of the pulse. Note that $25\ \mu\text{s}$ is consistent with the rough estimate of $33\ \mu\text{s}$ from the volt-second product of the cores. This notch was predicted via LTspice modeling prior to the first experimental tests of the system. The LTspice pre-mag model was then fine-tuned to nearly replicate the experimental results, as shown in Figure 55. The dynamic impedance seen by the pre-mag generator is both inductive and resistive, with the resistive component being due to the eddy current effect mentioned previously; however, only the resistive component was tuned (modulated in time) to nearly replicate the experimental results with LTspice. Note that a tuned inductance (modulated in time) could also have been used to obtain results that agree well with experiments, so this tuning method does not necessarily provide the exact temporal behavior of the cores' effective inductance or resistance values.

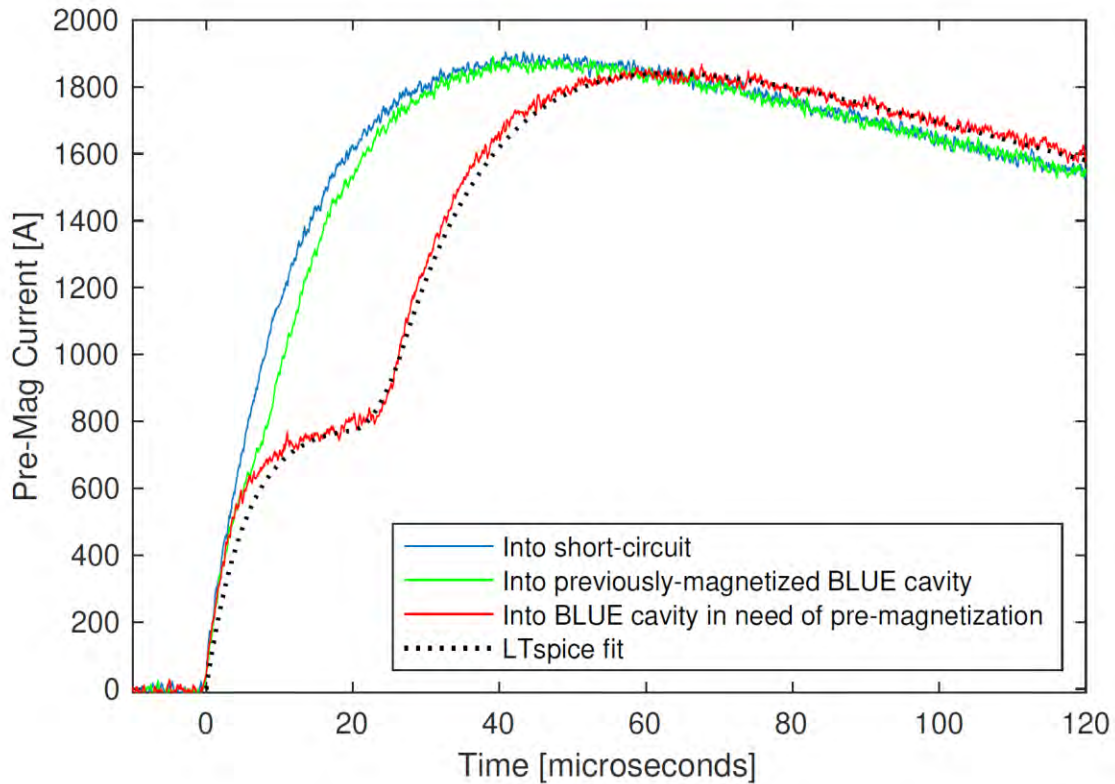


Figure 55: Output current waveforms from a single channel of the pre-magnetization pulse generator into three load scenarios: (1) into a short-circuit load (blue); (2) into the cavity for the case where the cores have already been reset/pre-magnetized (green); and (3) into the cavity for the case where the cores need to be reset/pre-magnetized (red). Also shown is a waveform produced by an LTspice model fine-tuned to closely match the experimental results.

The effects of successful pre-magnetization on the main LTD cavity discharge can be seen in load current measurements taken when the cavity is fired into a resistive load. In general, pre-magnetization of the cavity increases the amplitude of the LTD's main discharge current by 10-20% and extends the duration of positive current into the load.

There is a large issue to be aware of in designing a pre-magnetization pulse generator for LTDs. Since (ideally) the pre-mag cables remain attached to the cavity during an LTD discharge, the high-voltage, high-frequency pulse from the main discharge can travel back to the pre-mag generator, potentially damaging medium-voltage electronics such as the charging diodes or, more importantly, the thyristor. Two thyristors on BLUE's pre-mag system were damaged during LTD discharges, despite attempts to protect them with metal-oxide varistors (MOVs) and an over-voltage spark-gap placed directly across the thyristor terminals (see Figure 53). Transient-voltage-suppression (TVS) diodes and/or better spark-gaps may provide more effective protection from the fast transients, but this has yet to be demonstrated experimentally. For now, triggered spark-gaps are recommended as a more robust alternative to thyristors for a pre-mag system switch.

Resistive Load Testing of the First BLUE Cavity

Bipolar Marx Generator Configuration

The prototype cavity was first tested with a polycarbonate lid. This allows for internal visual access during testin It also eliminates the parasitic current path and thus the need for ferromagnetic cores. This effectively puts the cavity into a bipolar Marx generator architecture, rather than a LTD architecture. This coreless configuration is closely related to an LTD spinoff concept known as the impedance-matched Marx generator (IMG) [13].

A dummy resistive load for the cavity was fabricated using an arrangement of spare ceramic resistors. The resistance of the load was approximately $1\ \Omega$, while the inductance was estimated to be greater than 100 nH (based on the experimental current traces). An image of the cavity mounted on its side (i.e., mounted in the white, cavity-stacking support rack) and firing into the resistive load is shown in Figure 56.

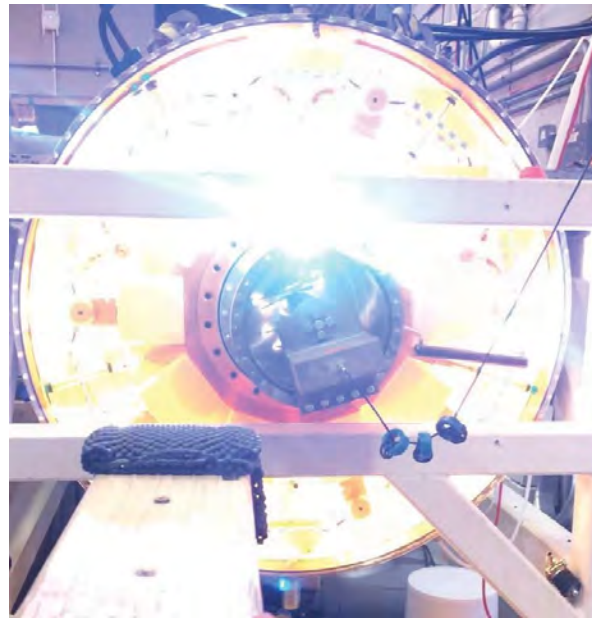


Figure 56: The prototype BLUE cavity mounted on its side and firing into a resistive load in the bipolar Marx generator configuration (i.e., using the clear plastic lid and thus not using ferromagnetic cores). The bright flash is an undesirable arc to the white support frame.

A current-viewing resistor (CVR) was installed in series with the resistive load to obtain inherently calibrated load current data; however, the anode of the cavity must be grounded for the CVR to be properly monitored by an oscilloscope. This became an issue with the polycarbonate lid, as technically the cathode is grounded when the cavity is mounted on the grounded steel frame. Thus, useful calibration data was not obtained. Additionally, operating the cavity in this configuration

resulted in troublesome arcing to the steel frame (see Figure 56). These issues likely could have been remedied by placing the polycarbonate lid on the opposite side of the cavity and isolating the cathode from the vacuum pump systems with a ceramic break; however, to avoid delays in commissioning the BLUE facility, the decision was made to move on to testing the cavity in its original LTD configuration -i.e., replacing the clear plastic lid with the cavity's steel lid, installing the ferromagnetic cores, and implementing the core reset/pre-mag system described above.

Linear Transformer Driver Configuration

Replacing the polycarbonate lid with the original steel lid and inserting the ferromagnetic cores transforms the cavity back into the traditional LTD configuration (see Figure 45b). The pre-mag pulse generator is now desired to magnetize the cores in the proper direction prior to an LTD shot, thus minimizing the current taking the parasitic path.

A new, higher-quality resistive load (using new HVR APC ceramic disk resistors) was fabricated for BLUE in the LTD architecture. One of the motivations for doing this was that the simple cylindrical geometry of these disk resistors allows the load inductance to be more precisely estimated. The new load was also designed to have a variable resistance of 0.5-4 Ω by stacking multiple disk resistors in series. For the experiments reported herein, the load resistance was 1.5 Ω , and the load inductance was estimated to be ~ 110 nH.

Figure 57 and Figure 58 show experimental current traces from the prototype BLUE cavity in the LTD configuration. These traces were acquired by the CVR. Figure 58 shows the current traces at varying charge voltages: 50 kV, 60 kV, and 70 kV. Figure 58 also shows the effects of pre-magnetization on the load current. Without pre-magnetization, the load current is smaller in amplitude and shorter in duration, as significant current begins to leak into the parasitic current path around the time of peak current.

Figure 57 shows good agreement between an experimentally measured current trace and the current trace generated by an LTspice simulation of the discharge. In this case, the charge voltage was 70 kV. The larger amplitude of the experimental trace before ~ 80 ns is likely due to imperfect modeling of the core behavior and thus current losses to the parasitic current path.

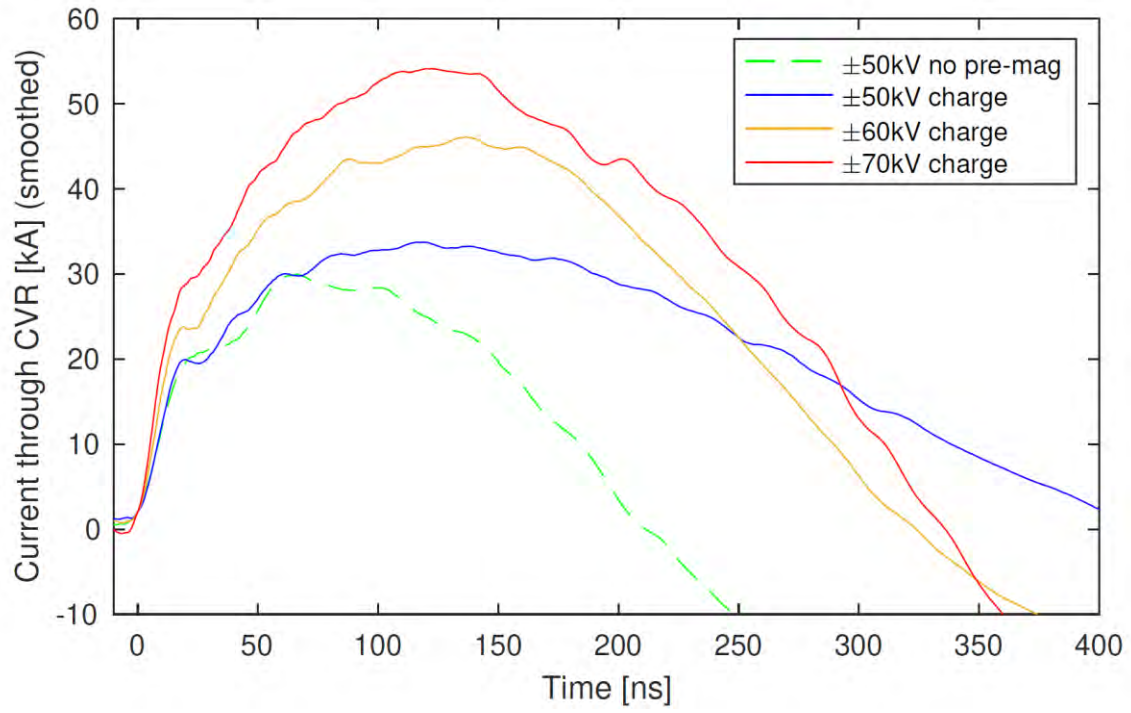


Figure 57: Nominal experimental current traces from the prototype BLUE cavity configured as an LTD at different charge voltages, acquired using a current-viewing resistor (CVR). The data have been smoothed to reduce high-frequency noise. The resistive load has resistance and inductance values of approximately $1.5 \, \Omega$ and $110 \, \text{nH}$, respectively.

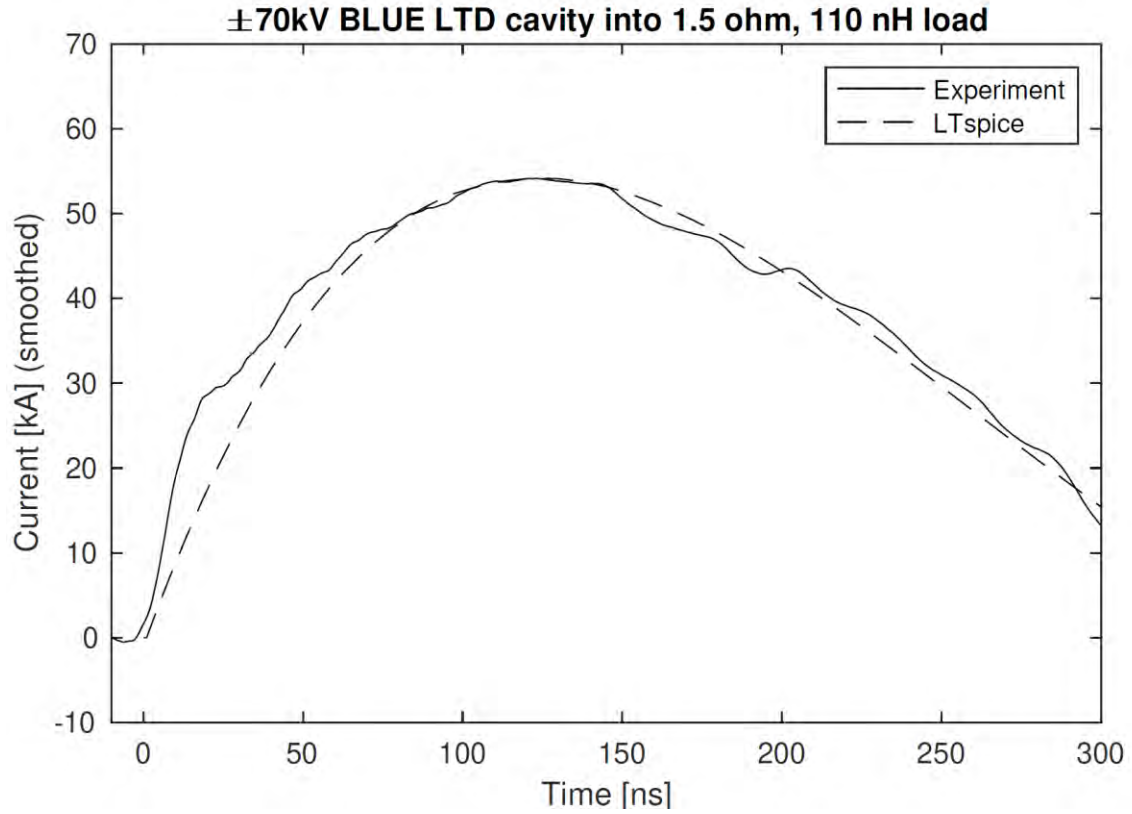


Figure 58: Experimental current trace from the prototype BLUE cavity configured as an LTD at ± 70 kV charge voltage. Also plotted for comparison is the current trace from an LTspice simulation of the discharge. The experimental curve has been smoothed to remove high-frequency noise. In the simulation, the load resistance was 1.5Ω and the load inductance was 110 nH, which is in good agreement with the estimated load inductance based on geometry.

From these initial calibration and pre-magnetization experiments, a simple circuit model was semi-empirically developed for BLUE. The model is illustrated schematically in Figure 59. The values to be used in the circuit model are provided in Table 1. In the central column of Table 1, formulas are provided for calculating the circuit element values as a function of the number of cavities, N_{cav} . In the rightmost column of Table 1, approximate values are given for a single cavity, i.e., with $N_{\text{cav}} = 1$.

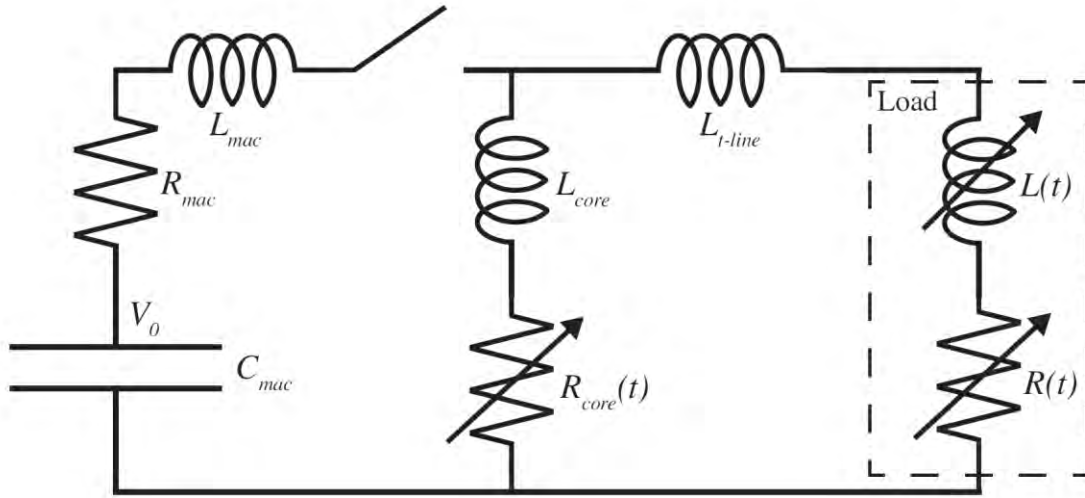


Figure 59: A simple circuit model of the BLUE LTD facility. Formulas for the circuit elements, along with approximate values for a single cavity, are provided in Table I.

Table 4: Formulas for the simple circuit elements shown in Fig. 17. The approximate values provided in the rightmost column are for a single cavity—i.e., with $N_{\text{cav}} = 1$. $L_{\text{t-line}}$ is the inductance of the transmission line to the load, which can vary depending on the installed hardware. A transmission line to the chamber procured for Z-pinch experiments has an inductance of ~ 16 nH. Z_{mac} is the machine impedance.

Circuit Variable	Formula	Approximate Value for $N_{\text{cav}} = 1$
C_{mac}	$5 C_{\text{cap}} / N_{\text{cav}}$	100 nF
V_0	$2 V_{\text{charge}} \cdot N_{\text{cav}}$	200 kV max.
R_{mac}	$R_{\text{brick}} N_{\text{cav}} / 10$	4–60 m Ω
L_{mac}	$L_{\text{brick}} N_{\text{cav}} / 10$	22 nH
L_{core}	$L_{0,\text{core}} N_{\text{cav}}$	950 nH
$R_{\text{core}}(t)$	$R_{0,\text{core}}(t) \cdot N_{\text{cav}}$	0.50 Ω (for $t \ll 10\mu\text{s}$)
$L_{\text{t-line}}$	$L_{\text{t-line}}$	≈ 16 nH for chamber loads
Z_{mac}	$\sqrt{L_{\text{mac}} / C_{\text{mac}}}$	0.47 Ω

Development of the Second Cavity

After working through the issues that arose during the assembly of the first cavity, we applied those lessons to quickly assemble the second cavity. The cavity is now assembled and being tested horizontally (as shown in Figure 60), with the cores removed and the polycarbonate top lid installed.

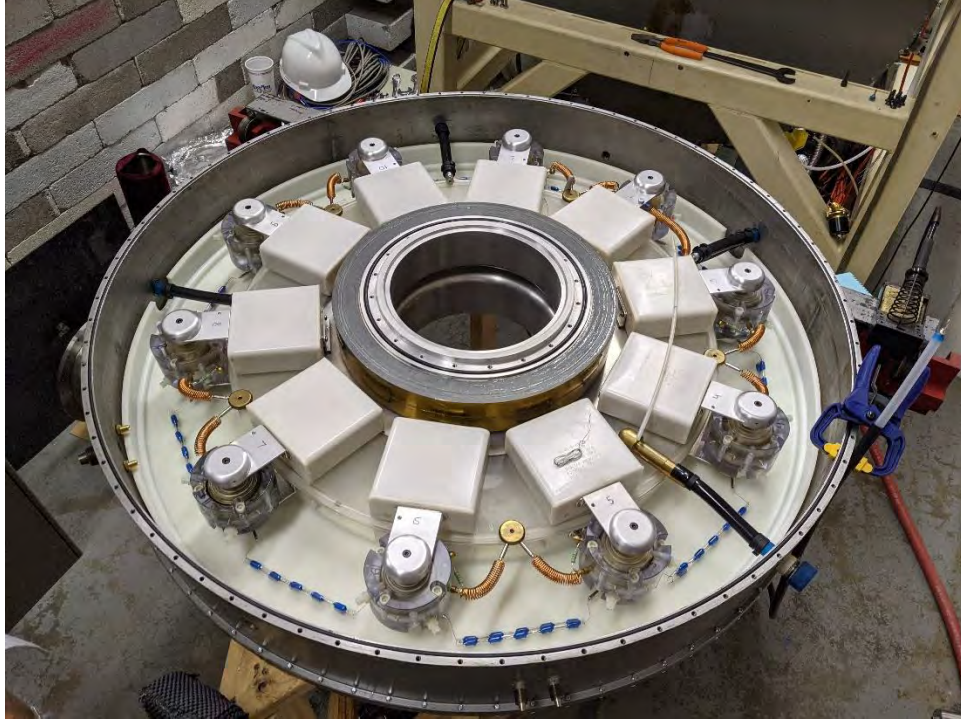


Figure 60: Second cavity ready for gas lines and top insulator.

A cathode extension for BLUE has also been fabricated, to account for the additional thickness of the second cavity and maintain the original cathode position within the MILO and other loads.

2.2 HPM Generation

The first physics load to be mounted on the prototype BLUE cavity was a magnetically insulated line oscillator (MILO) [4]. The MILO is a crossed-field HPM device that, in this case, operates in a coaxial, axisymmetric geometry. In a MILO, the drive current produces a magnetic field that insulates the anode from electrons emitted at the cathode. Thus, external magnetic field coils are not required to operate a MILO, as they are in the case of other crossed-field devices (e.g., magnetrons). For the cylindrical MILO shown in

Figure 61, the insulating magnetic field is azimuthal, $\mathbf{B} = B_\theta \hat{\theta}$, and the driving electric field is radial, $\mathbf{E} = E_r \hat{r}$. Electrons emitted radially outward from the velvet-covered central cathode are turned by the magnetic field and begin to drift axially through the periodic slow wave structure (SWS) at a velocity of $\mathbf{v}_{\text{drift}} = \mathbf{E} \times \mathbf{B}/B^2$ (see

Figure 61(b)).

The MILO mounted to BLUE is shown in

Figure 61(c). This MILO was previously tested by the Air Force Research Laboratory (AFRL) [4, 15-17]. In these tests, the MILO was driven by the Sandia National Laboratories 500-kV, 5- Ω , 300-

600 ns IMP pulser [16-17]. The IMP pulser has remarkably similar drive characteristics to the full 4-cavity BLUE facility. Using CST Microwave Studio, we simulated the performance of this MILO with applied voltages ranging from 100 to 500 kV, encompassing the expected test range of the BLUE driver. The details of those simulations can be found in Ref 14.

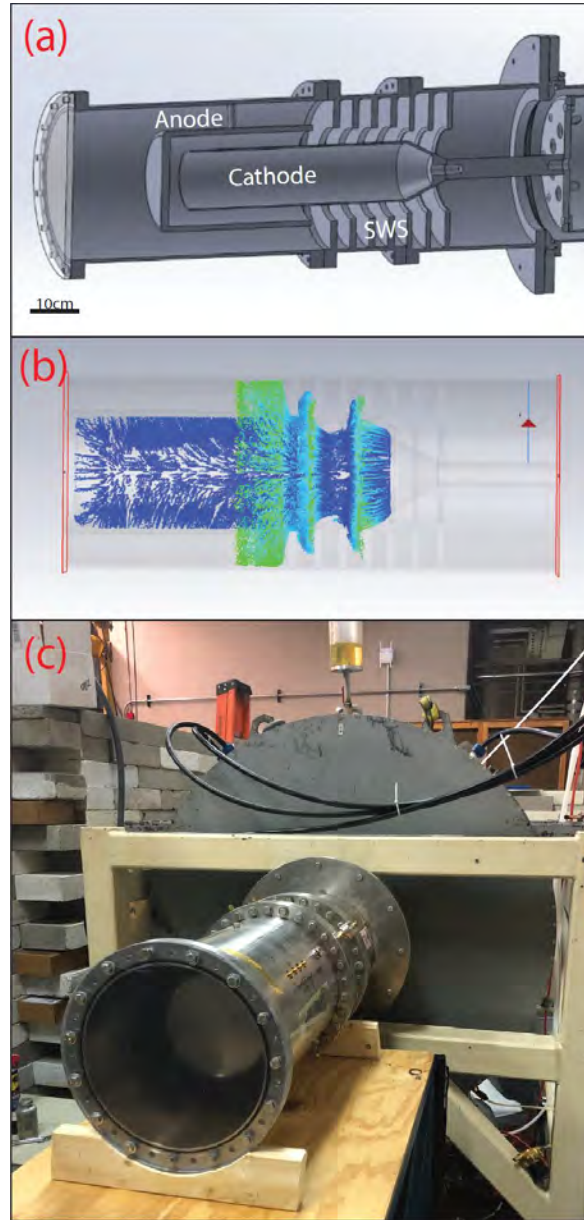


Figure 61: (a) Cross-section of the MILO HPM device. (b) CST particle-in-cell simulation of the MILO in pi-mode operation, with the simulated electrons (blue/green) bunching into well-formed spoke-like structures in the SWS [14]. (c) The MILO mounted to the prototype BLUE cavity.

In Figure 62, voltage signals are presented from three B-dot probes located in the SWS of the MILO. Also shown is a Rogowski coil signal, integrated and calibrated to give the total current entering the MILO. The charge voltage for the shot was 70 kV. Microwave oscillations at a frequency of 1.187-GHz are observed for approximately 80 ns (during the period of 65-145 ns). The oscillations are well-sampled for Fourier analysis and are distinct from background noise. The frequency of 1.187 GHz is consistent with beam-loaded pi-mode operation in particle-in-cell simulations [14]. The excitation of these oscillations for approximately 80 ns is remarkable given the relatively low drive voltage applied ($V_0 = 2 * V_{\text{charge}} = 140$ kV) and the 0.5Ω impedance of just a single BLUE LTD cavity.

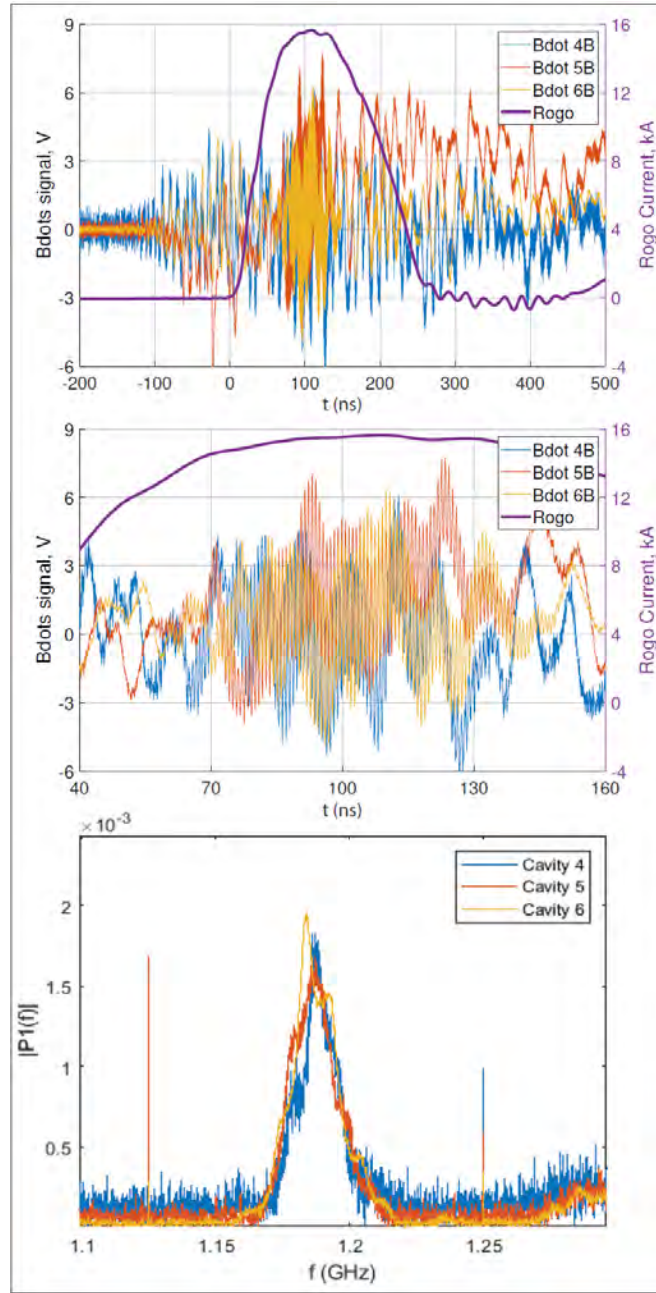


Figure 62: (top and middle) Voltage signals from three B-dot probes in the slow-wave structure of the MILO during a discharge of the BLUE prototype cavity with a charge voltage of 70 kV. Also plotted is the load current into the MILO, which was measured using a calibrated Rogowski coil. Microwave oscillations at a frequency of 1.187 GHz are observed for approximately 80 ns (during the period of 65-145 ns). The oscillations are well-sampled for Fourier analysis (bottom).

2.3 Circuit Modeling in SCREAMER

Roman Shapovalov, a post-doctoral researcher working on this project, has modeled BLUE using SCREAMER, a pulsed-power circuit modeling code developed by Dr. Mark Kiefer at Sandia National Labs. While we had previously modeled BLUE in LTSpice, Roman was able to implement a Martin spark-gap switch model in SCREAMER, rather than assuming a constant resistance for the spark-gap switches. As shown in Figure , this results in differences in the pulse shapes near the pulse take-off point at 0 ns. With this Braginskii-Martin formalism, the switch resistance is inverse to the time-integral of the 2/3 power of the switch current (the current action integral). From 10 to 100 ns the switch resistance drops from 200-300 Ω down to 2-3 Ω . The final switch resistance varies from 20 m Ω to 540 m Ω , depending on the load.

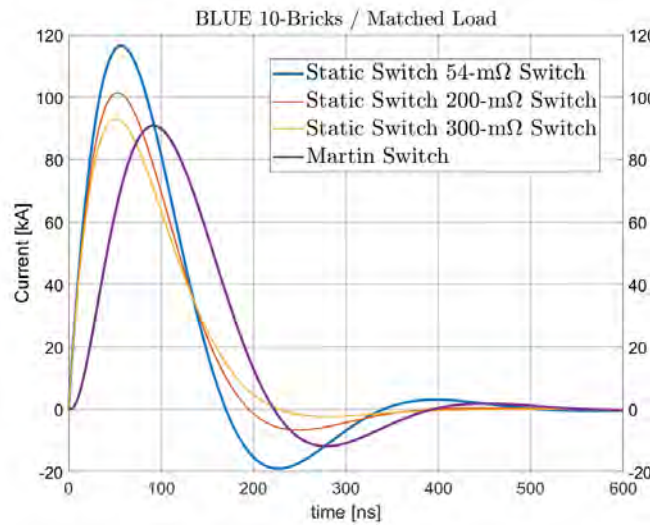


Figure 19. Improved modeling of BLUE by using the Martin spark-gap switch model in SCREAMER, rather than assuming a constant resistance for the spark-gap switches. A static switch over-predicts the peak current and under-predicts the risetime.

3. Findings and Conclusions

The first prototype cavity of the BLUE LTD facility at the University of Michigan is now operational. The components to make three more identical cavities have been procured, and the second cavity has been assembled and is currently being tested with a resistive load. Particle-in-cell simulations of a GW-class MILO on BLUE have been conducted, and predict high power operation with an applied voltage of ~ 150 kV, within the range achievable on BLUE with two cavities in operation. Preliminary test of a MILO have been conducted on BLUE, with demonstrated operation at 1.19 GHz, the predicted pi-mode frequency in simulation.

4. Plans and Upcoming Events

Additional current diagnostics have been implemented within the MILO, and will provide a time-resolved map of current flow within the device, revealing the fraction of the current which flows to the slow wave structure, to the axial beam dump, and to the chamber walls around the beam dump. Development of a cathode voltage monitor is underway, and a calibrated microwave power extractor could be created based on a design developed by D. Packard for other MILO experiments at UM [18]. Future experiments could characterize the RF output power as a function of the applied drive voltage by increasing the number of BLUE cavities stacked together in series.

5. Transitions and Impacts

This research project required substantial build-up of a new pulsed power capability at UM, thus many of the transitions and impacts have been in the direction from Sandia and AFRL to the University of Michigan. As we continue building out BLUE to become a multi-cavity system, we will transition research outputs, technology products, and trained students/PhDs back to these labs.

Prof. McBride has developed and taught a brand new course on pulsed power (UM-NERS 590) based on “primer” paper in IEEE TPS: <https://doi.org/10.1109/TPS.2018.2870099>. This course will be offered remotely to other universities in the fall of 2022, and every 2 years thereafter.

6. Collaborations

As part of this program/project, we are collaborating with Dr. Brad Hoff of the AFRL, who is providing guidance on what is important to directed energy programs in the Navy and Air Force and who has also sent us a mini-LTD pulser for HPM device testing. Similarly, we are collaborating with Dr. Kyle Hendricks of the AFRL, who has sent us a working crossed-field HPM device (along with its CAD models) for testing on BLUE.

We have also been collaborating with Dr. Jon Douglass, Mr. Tommy Mulville, Mr. Matt Sceiford, Dr. Josh Leckbee, and (previously) Dr. Matt Wisher, all of Sandia National Laboratories, who have been working to help us with the transition of the four Ursa Minor cavities to the University of Michigan, where they are part of the BLUE LTD facility. It is of strategic importance to Sandia’s pulsed-power development labs that students are being trained in new LTD technology.

Additionally, we have been working with Dr. Patrick Corcoran and Dr. David Phipps (both of L3Harris) to work through the issues with our L3 switches on both MAIZE and BLUE.

This program is also allowing us to collaborate with Prof. Allen Garner of Purdue University, who has his own ONR HPM funding to test out a non-linear transmission line (NLTL) HPM source on an LTD. We will be providing the LTD and Prof. Garner's group will be providing the NLTL source. Prof. McBride recently gave a guest lecture on pulsed power and LTDs at Purdue University as part of Prof. Allen Garner's NUCL 697 course on Pulsed Power and Vacuum Electronics.

Recently, we have collaborated with Prof. Simon Bland of Imperial College London on the development of fast, solid-state pulse generators for LTD triggers. They are a much-needed replacement for discontinued PT-55 and PT-003 trigger generators.

7. Personnel

PI - Prof. Ryan McBride ~1 person months - National Academy Member: No
Co-PI - Dr. Nicholas Jordan ~1.5 person months - National Academy Member: No
PhD Student - Mr. Brendan Sporer ~5 person months - National Academy Member: No
Post-Doctoral Fellow - Dr. Roman Shapovalov ~5 person months - National Academy Member: No

8. Students

1 graduate student:

Mr. Brendan Sporer: PhD student

Primarily supported by this ONR YIP MILO project (construction of BLUE)

Mr. Drew Packard: PhD student

MILO simulation for this ONR YIP MILO project (supported by other ONR HPM projects: Multi-Frequency RPM and MILO projects)

9. Technology Transfer

We planned laboratory visits for Yeong-Jer "Jack" Chen, John Kreger and Matt McQuage from NSWC Dahlgren as well as Walter Sessions at Georgia Tech Research Institute (GTRI), but COVID travel restrictions have prevented those visits to date. We will work to accommodate a visit when possible.

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Archival Publications

1. B. J. Sporer, A. P. Shah, G. V. Dowhan, R. V. Shapovalov, D. A. Packard, M. Wisher, J. J. Leckbee, K. J. Hendricks, B. W. Hoff, Y. Y. Lau, R. M. Gilgenbach, N. M. Jordan, and R. D. McBride, "[Multicavity linear transformer driver facility for Z-pinch and high-power microwave research](#)," *Phys. Rev. Accel. Beams*, vol. 24, no. 10, p. 100402, Oct. 2021, doi: [10.1103/PhysRevAccelBeams.24.100402](#).
2. Y. Y. Lau, D. A. Packard, C. J. Swenson, J. W. Luginsland, D. Li, A. Jassem, N. M. Jordan, R. D. McBride, and R. M. Gilgenbach, "[Explicit Brillouin flow solutions in magnetrons, magnetically insulated line oscillators, and radial magnetically insulated transmission lines](#)", vol. 49, no. 11, pp. 3418–3437, Nov. 2021, doi: [10.1109/TPS.2021.3092606](#).
3. D.A. Packard, Y. Y. Lau, E.N. Guerin, C.J. Swenson, S.V. Langellotti, A. Jassem, D. Li, N.M. Jordan, J.W. Luginsland, R.D. McBride, and R.M. Gilgenbach, "Theory, Simulation, and Experiments on a Magnetically Insulated Line Oscillator (MILO) at 10 kA, 240 kV Near Hull Cutoff Condition", *Physics of Plasmas*, [accepted, Dec 2021 issue]. **[Editor's Pick]**

Conference Papers

1. R.V. Shapovalov, B.J. Sporer, N.M. Jordan, R.D. McBride, "Progress on multicavity BLUE LTD System at the University of Michigan", PPC/SOFE, Denver, CO, Dec 2021. [accepted]
2. R.V. Shapovalov, B.J. Sporer, N.M. Jordan, R.D. McBride, "Progress on the 4-cavity BLUE LTD System at the University of Michigan", ICOPS 2021, Sept 2021.
3. N. Jordan, B. Sporer, D. Packard, R. Shapovalov, R. Gilgenbach, R. McBride, "Driving a Magnetically Insulated Line Oscillator with a Linear Transformer Driver", IVEC, Apr 2021.
4. R.V. Shapovalov, N.M. Jordan, B. Sporer, R.D. McBride, "BLUE MILO axial diode gap optimization using the pulsed-power circuit code Screamer", ICOPS 2020, Dec 2020.
5. B. Sporer, N.M. Jordan, R.D. McBride, "Testing of the Prototype BLUE Linear Transformer Driver (LTD) Cavity at University of Michigan", ICOPS 2020, Dec 2020.
6. B. Sporer, N. Jordan, R. Shapovalov, D. Packard, R. Gilgenbach, R. McBride, "Testing of the First BLUE Linear Transformer Driver (LTD) Cavity at the University of Michigan", 62nd APS-DPP, Nov 2020.

Books: None

Book Chapter: None

Theses: None

Websites: None

Patents: None

Other Products: Identify any other significant products that were developed under this project. Describe the product and how it is being shared.

- a. Description: Developed models and simulations of crossed-field devices for use on the BLUE LTD facility. Developed SCREAMER models of BLUE to optimize power delivery. Also developed a SolidWorks CAD model of the BLUE LTD facility.
- b. Product Type: models

11. Point of Contact in Navy

Dr. Joseph Schumer
Head, Pulsed Power Physics Branch
Plasma Physics Division
Naval Research Laboratory
(202) 841-2766
joe.schumer@nrl.navy.mil

Date we last discussed HPM research: June 25, 2019

12. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research (ONR), under grant (or contract) number N00014-18-1-2499. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Surface Breakdown and Plasma Formation in Cross-Field High Power Microwave Sources

Grant No. N00014-21-1-2698

Annual Report for Fiscal Year 2021

Period of Performance: July 1, 2021 to September 30, 2021

Prepared by:

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This work was sponsored by the Office of Naval Research (ONR), under grant number N00014-21-1-2698. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Grant or Contract Number: N00014-21-1-2698

Date Prepared: January 31, 2022

Project Title: Surface Breakdown and Plasma Formation in Cross-Field High Power Microwave Sources

Annual Summary Report: FY2021

Principle Investigator: Ken Hara, 650-72V, Department of Aeronautics and Astronautics, Stanford University

Section I: Project Summary

1. Overview of Project

Abstract: In this annual report, we summarize the activities on the recently awarded ONR (YIP) grant, “Surface Breakdown and Plasma Formation in Cross-Field High Power Microwave Sources,” covering the period from July 01, 2021 to September 30, 2021.

Objective: The goal of this research project is to advance the understanding of surface breakdown and plasma formation in cross-field High Power Microwave (HPM) devices. Specific research objectives include: (i) to develop and test electromagnetic plasma fluid and kinetic models; (ii) to characterize the space charge limited (SCL) sheath due to the plasma formation near explosive emission cathodes; and (iii) to investigate the anode plasma formation and radiofrequency wave-driven surface breakdown mechanisms.

Introduction: Plasma dynamics in high power microwave sources are considered detrimental to the operation of vacuum electronic devices (VED) to generate electromagnetic signals. The formation and existence of the plasma flows become more and more critical, particularly when operating the HPM sources at a high frequency range, which is of great interest to the future of U.S. naval missions. While HPMs theoretically must operate in high vacuum conditions, due to available materials and operating conditions, outgassing can occur from materials. This issue becomes more problematic for compact HPM devices because the volume-to-area ratio worsens, and the plasma-wall interactions greatly influence the electromagnetic wave properties. For instance, pulse shortening of the microwave output signal due to gap closure and lifetime of the device can highly depend on the dynamics of the charged particles.

Background: We are developing high-order moment (five- and ten-moment) fluid models and particle-based kinetic models to study plasma formation, providing an efficient model for the dense plasma formation around the anode, cathode, and window surfaces, such as the antenna. The fluid and hybrid fluid-kinetic models will be benchmarked against particle simulation results to assess whether reduced-order description can be constructed to model the beam-plasma interactions in the HPM devices.

The research outcomes can help (i) address existing issues in the HPM sources developed and deployed by the U.S. Navy, and (ii) improve the optimization and design processes of future HPM sources using the predictive modeling capabilities developed through this project. In addition, advancing the fundamental understanding of the interaction between plasma flows, electromagnetic waves, and plasma-immersed materials possesses further immense impacts to other DoD applications and missions, including space propulsion, fusion energy, space weather, aerodynamics, combustion, and material processing.

2. Activities and Accomplishments

One of the key research themes is to characterize plasma sheaths so that a high-fidelity model can be constructed to understand the time-dependent plasma behavior as well as the electron emission characteristics. The emitted electron flux, the ion flux from the plasma, the electron flux from the plasma, and neutral flux due to outgassing can contribute to the plasma formation near the electrodes. It is expected that in the presence of large electron emission (such as due to field emission, ion/electron-induced secondary electron emission, thermionic emission) the plasma sheath becomes space charge limited (SCL). The structure of the plasma sheath will likely play an important role in the plasma formation and how much electron emission occurs within the VED.

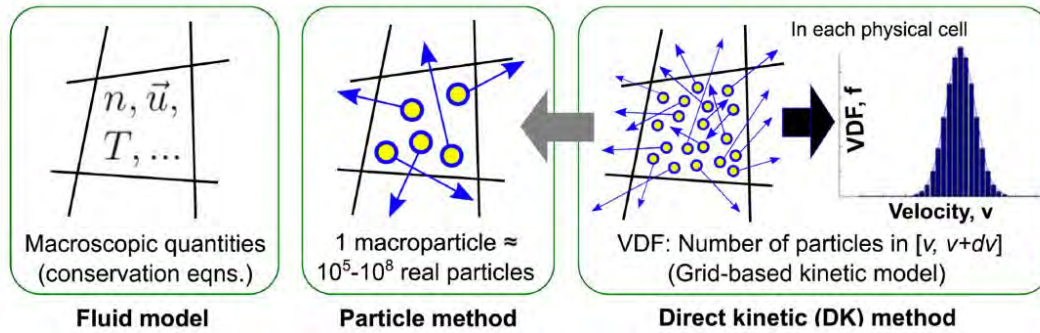


Figure 1. Computational models for plasma simulation

In our group, we have developed various plasma simulation tools including fluid, particle-based kinetic, and grid-based kinetic models, as shown in Figure 1 [Hara, Plasma Sources Sci. Technol. **28**, 044001 (2019)]. The fluid model solves for the macroscopic quantities by solving conservation equations, which are derived from taking the moments of the kinetic equation, such as the Boltzmann and Vlasov equations. The most standard approach in the low-temperature plasma community is called the drift-diffusion approximation, which assumes that the inertia term is negligible, and thus, the drift (due to the electric field) and diffusion (due to the pressure gradient) balance with the collisional drag. Inspired by the cross-field discharge plasmas such as in the Hall effect thrusters, we have recently developed a 5-moment fluid model that takes the inertia term into account. In addition to the shear gradient in the cross-field devices, we have also identified that the 5-moment fluid model captures more physics near the sheath, where the electrons can be accelerated, in comparison to the drift-diffusion approximation [Sahu, Mansour, and Hara, Phys. Plasmas **27**, 113505 (2020)].

The other approach is a kinetic approach, which can be divided into particle-based approach and grid-based approach. The kinetic method is needed and useful for plasma and rarefied fluid dynamics problems where the velocity distribution function exhibits a non-Maxwellian distribution. The former includes methods such as the direct simulation Monte Carlo (DSMC), Monte Carlo Collision (MCC), and particle-in-cell (PIC) simulations. The latter solves the kinetic equations, such as the Boltzmann equation and Vlasov equation, directly on discretized phase space. While the grid-based direct kinetic (DK) method can be used without the numerical uncertainties due to the use of macroparticles in particle-based kinetic approaches, the computational cost can be large due to the discretized phase space. Therefore, we decided to use the PIC/MCC simulation to study the plasma sheath and plasma formation for HPM devices.

During the period of performance, we have applied our 1D in-house PIC model to replicate the non-magnetized plasma sheath results performed by Schwager and Birdsall [Phys. Fluids B: Plasma Physics, **2**, 1057-1068 (1990)] and investigated magnetized plasma sheaths performed by Chodura [Phys. Fluids **25**, 1628 (1982)]. In Chodura's test case, an applied magnetic field is prescribed with various magnitudes and various angles with respect to the wall. With an adjusted setup that follows the work by Chodura, this model is applied to illustrate the presence of a magnetic pre-sheath and oscillations in the plasma potential, where the latter occurs due to the excitation of an ion acoustic mode according to Chodura.

Following Chodura's paper, the prescribed magnetic field is described using the normalized parameter, $\vec{\alpha} = \frac{eB_0}{m_e\omega_{pe}} (\cos \theta, \sin \theta, 0)$, where B_0 is the magnetic field strength and θ is the angle of the magnetic field with respect to the x-z plane. Note, the x-direction is perpendicular to the dielectric wall. Consequently, the equations of motion for the ions and electrons (in the normalized units) are now defined as:

$$\frac{d\tilde{x}_i}{d\tilde{t}} = \tilde{v}_i; \quad \frac{d\tilde{v}_i}{d\tilde{t}} = \frac{m_e}{m_i} (\tilde{E} + \tilde{v}_i \times \vec{\alpha}),$$

$$\frac{d\tilde{x}_e}{d\tilde{t}} = \tilde{v}_e; \quad \frac{d\tilde{v}_e}{d\tilde{t}} = -(\tilde{E} + \tilde{v}_e \times \vec{\alpha}).$$

To solve these equations a general Boris push algorithm is built, tested, and implemented into the plasma model.

Figures 2 and 3 show the plasma sheath calculation using the 1D in-house PIC code in comparison to the results in Chodura's paper. Ions are assumed to be cold, and an artificial ion-to-electron mass ratio ($m_i/m_e = 100$) is assumed. Here, the plasma is assumed to be partially magnetized, i.e., the electrons are magnetized but the ions are non-magnetized because the ion Larmor radius is much larger than the sheath width. Additionally, the ions are injected at $x = 0$ into the computational domain with a drift velocity equal to or greater than the Bohm velocity, $\tilde{v}_b = \sqrt{m_e/m_i}$, which consequently eliminates the source sheath. Note, this drift velocity is also directed along the magnetic field. At $x = L$, we consider an absorbing wall without any electron emission in these simulations. We have implemented two types of calculations: one where a constant flux of charged particles are injected into the domain at $x = 0$ and the other is where the injection of charged particles are done only when the charged particles are absorbed at the wall. In this report, we show the results when using constant injection flux.

Figure 2 is when the magnetic field is perpendicular to the wall, i.e., the plasma sheath is non-magnetized, recovering the plasma sheath potential that can be analytically derived. While in Chodura's results, there seems to be a non-monotonic distribution, we are showing the time-averaged results and we consistently observed a monotonic distribution. It is possible that Chodura's calculation (1982) did not have sufficient time averaging for this particular result.

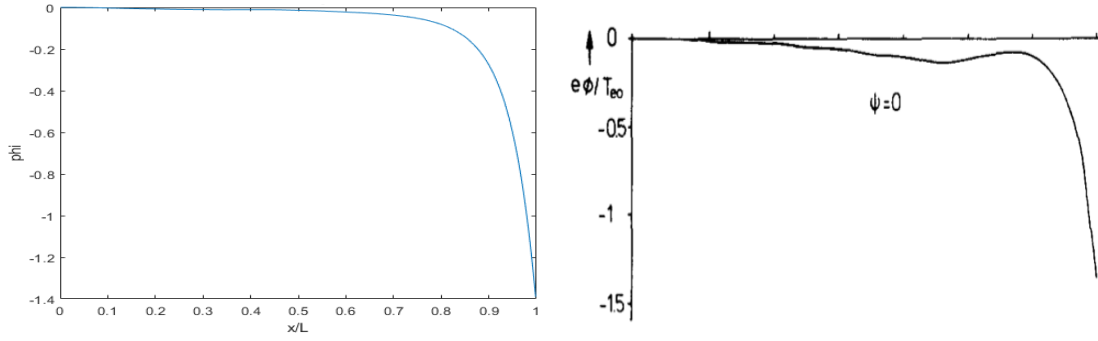


Figure 2. Normalized potential distribution, $\theta = 0^\circ$ (magnetic field is perpendicular to the wall, i.e., the plasma sheath is non-magnetized). Left: our result. Right: Chodura's result.

Figure 3 shows the results of the plasma sheath simulation when assuming the angle of the magnetic field with respect to the direction normal to the wall is 60 degrees. It is interesting to observe that there are some plasma oscillations that appear at the plasma sheath edge, while the potential drops near the wall similar to Figure 2. Chodura named this oscillatory region to be a *magnetic presheath*. However, our recent simulations and analysis show that these oscillations might be due to the fixed injection scheme. We are currently working on understanding the boundary condition for the magnetized plasma sheath simulation.

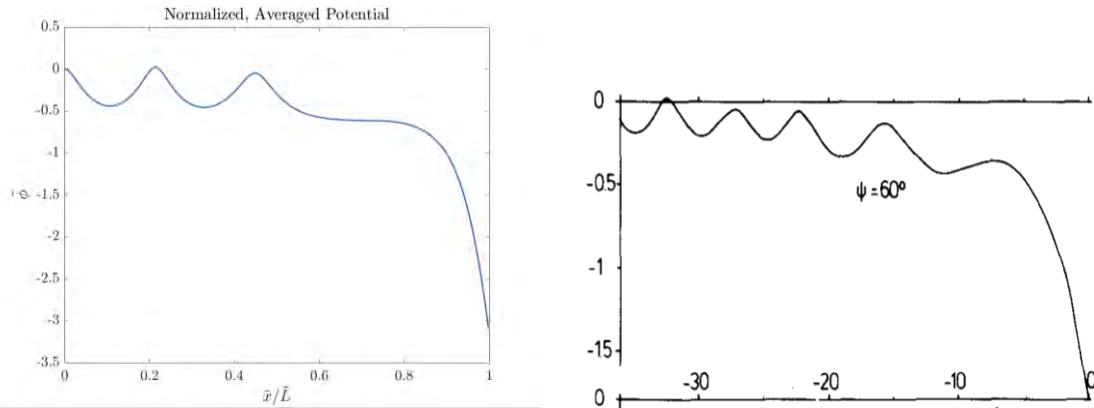


Figure 3. Normalized potential distribution, $\theta = 60^\circ$ (magnetic field is becoming parallel to the wall). Left: our result (with $m_i/m_e = 1836$). Right: Chodura's result ($m_i/m_e = 100$).

We are also developing a full fluid moment (FFM) model for low-frequency cross-field plasma discharge oscillations. The FFM model takes into account the inertia term and uses numerical methods developed in the computational fluid dynamics (CFD) community. Figure 4 shows the application of a 5-moment model that accounts for the electron inertia term, showing rotating spokes on the order of 100 kHz. The spoke propagates in the diamagnetic drift direction. This has led us to revisit the so-called modified Simon-Hoh instability that is often cited for rotating spoke studies.

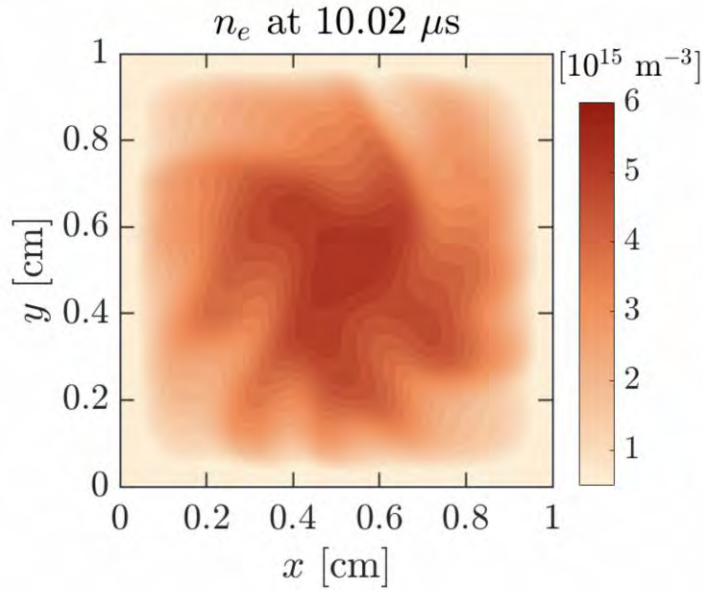


Figure 4. Plasma density of a rotating spoke. The magnetic field is into page and the boundaries are at 0V, setting up a quasineutral plasma and a rotation of the spokes in the azimuthal direction.

3. Findings and Conclusions

This research project started on July 1, 2021. So far, we have developed a PIC simulation of magnetized plasma sheath, which is a topic based on suggestions from Dr. John Luginsland during the kickoff meeting. We have reproduced results that are consistent with the results in the literature, and we have identified a few opportunities to improve the simulation.

4. Plans and Upcoming Events

We plan to complete the magnetized plasma sheath study. Improvement of the boundary condition for the plasma injection is needed to proceed with the plasma formation study, as the plasma simulation most likely will be influenced by the boundary condition. Once we have a “quiet” boundary condition, we plan to immediately apply it to a more HPM-like configuration.

We are also adding the electron emission from the material into the PIC simulation. Our preliminary calculation shows a transition of the plasma sheath from a space charge limited (SCL) sheath to an inverse sheath, which shows that the material potential is higher than the potential at the sheath edge.

One of our major activities for the FY2022 is to proceed with the benchmarking of various fluid models in the lab against the PIC/MCC simulation results. The test case used will be from Welch et al. [Welch et al., “Hybrid simulation of electrode plasmas in high-power diodes,” *Phys. Plasmas* **16**, 123102, (2009).]

In FY2022, PI Hara is invited to give a talk at the Michigan Institute of Plasma Science and Engineering in December 2021. In addition, we are planning to present a few presentations at

ICOPS in May 2022, International Electric Propulsion Conference in June 2022, and Rarefied Gas Dynamics in July 2022. PI Hara is invited to give an invited talk at Rarefied Gas Dynamics in July 2022, the EurophysicS Conference on Atomic and Molecular Physics of Ionized Gases (ESCAMPIG) in July 2022, and the American Physical Society Gaseous Electronics Conference in October 2022.

5. Transitions and Impacts

Graduate student Andy Castillo has been selected as a year-round intern at Sandia National Laboratories, where he will work on plasma global models for high-power switches.

6. Collaborations

AFRL: Peter Mardahl – we visited AFRL and had discussion about state-of-the-art HPM computational models, including ICEPIC.

Sandia National Laboratories: Amanda Lietz – collaboration regarding high power switch simulation using a plasma global model (year-long internship).

Sandia National Laboratories: Matthew Hopkins – submitted proposal for Sandia Plasma Research Facility (DOE).

UNM: Sal Portillo – we visited UNM in July and had multiple discussions regarding plasma simulation and experiment collaboration remotely. We are planning to perform the simulations of their experimental system in FY 2022.

Lam Research: Saravanapriyan Sriraman – we are collaborating with Lam research to study RF breakdown in low-pressure capacitively coupled plasma source.

CNRS: Sedina Tsikata – collaboration on cross-field plasma discharge physics, particularly focusing on the kinetic and fluid instabilities in partially magnetized plasmas.

7. Personnel

Principal investigator: Ken Hara, 0.3-person month, National Academy Member (N)

Business Contact: Thomas Merritt, Associate Research Administrator

8. Students

Two graduate students (post-quals PhD candidates) are supporting this research. Andy Castillo is developing the plasma sheath simulations. Adnan Mansour is supported by different funding but is the main developer of the full-fluid moment (FFM) model, which we plan to use for this ONR project.

One postdoc, not supported by this ONR project directly, is in charge of the RF breakdown simulations.

9. Technology Transfer

We discussed our research with Joe Schumer, Ian Rittersdorf, Alexander Vlasov, and Simon Cooke at NRL before the proposal. We plan to contact them during FY2022 and re-initiate interactions.

10. Products, Publications, Patents, License Agreements, etc.

We do not have any products generated during the period of performance: July 1, 2021 – September 30, 2021.

11. Point of Contact in Navy

Joe Schumer, Ian Rittersdorf, Alexander Vlasov, and Simon Cooke
Naval Research Laboratory

We discussed our research remotely on February 26, 2021.

12. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research (ONR), under grant (or contract) number N00014-21-1-2698. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Direct Generation of Electromagnetic Radiation with a Compact, Air-Stable, Optically Modulated Electron Emitter

Grant No. N00014-21-1-2634

Annual Report for Fiscal Year 2021

Period of Performance: July 1, 2021 – September 30, 2021

Prepared by:

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This work was sponsored by the Office of Naval Research (ONR), under grant (or contract) number N00014-21-1-2634. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Grant or Contract Number: N00014-21-1-2634

Date Prepared: 1/29/2022

Project Title: Direct Generation of Electromagnetic Radiation with a Compact, Air-Stable, Optically Modulated Electron Emitter

Annual Summary Report: FY21

Principle Investigator: Rehan Kapadia, 213-821-0845, rkapadia@usc.edu, University of Southern California

Section I: Project Summary

1. Overview of Project

1.1 Abstract

In this report, we will cover the objectives, background, accomplishments, and future plans for the grant titled “Direct Generation of Electromagnetic Radiation with a Compact, Air-Stable, Optically Modulated Electron Emitter”. Through this grant we aim to demonstrate a new type of electron source that enables rapid modulation of emitted electron density but allows the use of established telecommunications photon sources to excite the electron source. In this way, an optical signal imprinted on the incident photon source can be converted into an electron density modulation. Using this density modulated electron beam, we then aim to design a vacuum electron device that can convert the density modulated electron beam into a high-power RF signal.

1.2 Objective

The first goal of this proposal is to continue to develop and demonstrate a simple *planar* silicon-insulator-graphene structure to create an air-stable, *electrically tunable*, negative electron affinity surface by applying a bias between the graphene and silicon, termed Hot Electron Light Assisted Cathode (HELAC). A continuous or pulsed photon source may then be used to excite electrons in the silicon, which will then be emitted into vacuum when a small (4-10 V) bias is applied across the device. This electron source can be compact, environmentally robust, and use low energy photons in the near-IR to visible range. Based on initial simulations, modulation frequencies of >250 GHz and 1 A/cm^2 emission currents should be achievable through device optimization. Initial experimental prototypes have already demonstrated 1 mA/cm^2 , despite a relatively unoptimized structure.

Using this electron source, we will then design and build a device similar to an Inductive Output Tube (IOT), where an electron beam is density modulated by incident light, then accelerated to a desired voltage, and finally RF power is extracted from the beam using an output cavity. We refer to this device as a Light Modulated IOT (LM-IOT). Unlike IOTs, which have frequency and total current limitations due to the grid-cathode spacing and uniformity, this approach is expected to

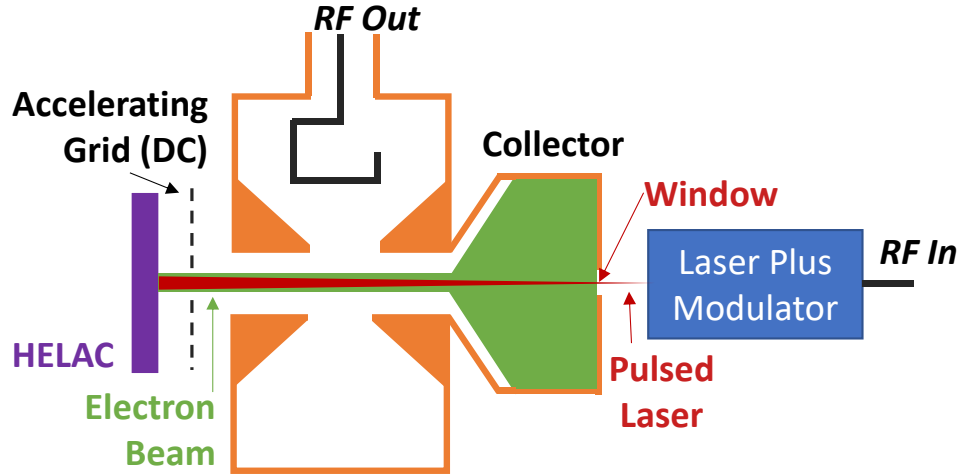


Figure 1: A schematic view of our device. In this structure, the cathode (HELAC) is excited by a modulated laser beam, generating a density modulated electron beam. This beam is accelerated by a grid held at a DC bias. The beam will then pass through an RF cavity to extract the high frequency content of the beam. The HELAC will be excited by a laser beam that travels in reverse through the electron beam tunnel. The size of the laser spot on the cathode, and therefore the area of the beam will be determined by the divergence of the spot, which can be tuned by an optical lens at the source.

overcome those issues by eliminating the need for a grid and input cavity. We will build a prototype LM-IOT, where the beam generation, confinement, and collector segments are fixed, and the output frequency will be determined by swapping output cavity. Specifically, we will carry out simulations to establish basic operation principles, design the overall device, and then fabricate and assemble the device. This will be used to establish the proof of principle operation for LM-IOTs as well as make projections about device parameters.

Finally, we aim to explore multi-frequency devices, where we simultaneously excite the electron emitter with multiple modulation frequencies, creating an electron beam with multiple frequencies, and then use multiple output cavities to extract and emit those frequencies separately. In this task, the goal is to understand interaction between multifrequency beams and multiple cavities, the limitations in power distribution between frequencies, and any non-linear effects due to the electron source itself that could take two input frequencies and generate different output frequencies. These limits would be driven by a combination of the physics of the electron source and the beam-cavity interactions.

1.3 Background

The modern day congested and contested electromagnetic spectrum has placed stringent demands on electronic systems^{1, 2}. A single electromagnetic (EM) source that change transmission bands, multiple frequencies, or even frequency bands, and be able to quickly switch frequencies when the desired communication channels becomes contested is of value in a contested environment. Additionally, directed EM sources which can temporarily or permanently deny communications are of significant value. One approach to this may be the direct generation of EM radiation from a modulated electron source. This approach could enable compact, high-frequency, high-power HPM sources which could serve the needs of directed energy systems³⁻¹⁴. An Inductive Output Tubes (IOT) is a source which utilizes a directly modulated approach, where a continuous beam of electrons is modulated by a grid, and an output cavity converts the high frequency component in the beam to electromagnetic radiation. IOTs, however, use a high voltage grid which couples to an input RF signal, this limits the frequency of operation due to electron transit time between the grid and cathode, and also limits scaling of the cathode due to grid spacing uniformity requirements. Here, we propose utilizing an optically modulated cathode technology to directly create a density modulated electron beam, and then extract the high frequency content from the beam using an output cavity. By eliminating the use of a grid to modulate the electron density, this approach would enable (i) higher frequency operation, (ii) larger cathodes for increased drive current, (iii) higher beam voltages, (iv) a reduction in size and weight, and (v) multi-frequency operation from a single device.

Electron emission cathodes are used in a wide variety of applications, including but not limited to, electron microscopes^{15, 16}, electron beam lithography¹⁷, space propulsion¹⁸, high power microwave (HPM) devices¹⁹⁻²¹, free electron lasers²², and displays²³. HPM sources for millimeter-wave and terahertz radiation are of great interest for military and defense applications such as radar, electronic counter measures, and communications^{20, 24}. While photo-assisted field emission devices have been explored in the past^{25,26,27,28,29}, as promising high frequency emitter, these are generally studied utilizing free-space optics to directly focus a laser on a tip or tip array, and use p-type silicon to enable photogating of field emission. Recently, simulation and experimental results have shown that optically driven emitters³⁰⁻³⁷ could play a valuable role in cathodes for high power microwave and vacuum electron devices in general.

2. Activities and Accomplishments

2.1 HELAC Electron Gun Fabrication and Testing

Over the course of this reporting period, we have carried out a number of experiments focusing on the following three areas.

- a) Modification of the insulator component of the silicon/insulator/graphene devices
- b) Modification of the overall structure of the silicon/insulator/graphene devices
- c) Growth of InGaAs on InP to serve as a telecom sensitive semiconductor for the HELAC

While studying the modification of the insulator component of the silicon/insulator/graphene devices, we have identified a new fundamental mechanism that modifies the emitted current from the HELAC. Specifically, we have found that charge trapping in the oxide can either enhance or depress the local field inside the oxide, which will in turn suppress or enhance the emitted current. We have also found that this can be tuned by choice of the insulator stack, as well as the applied voltage during the operation of the HELAC.

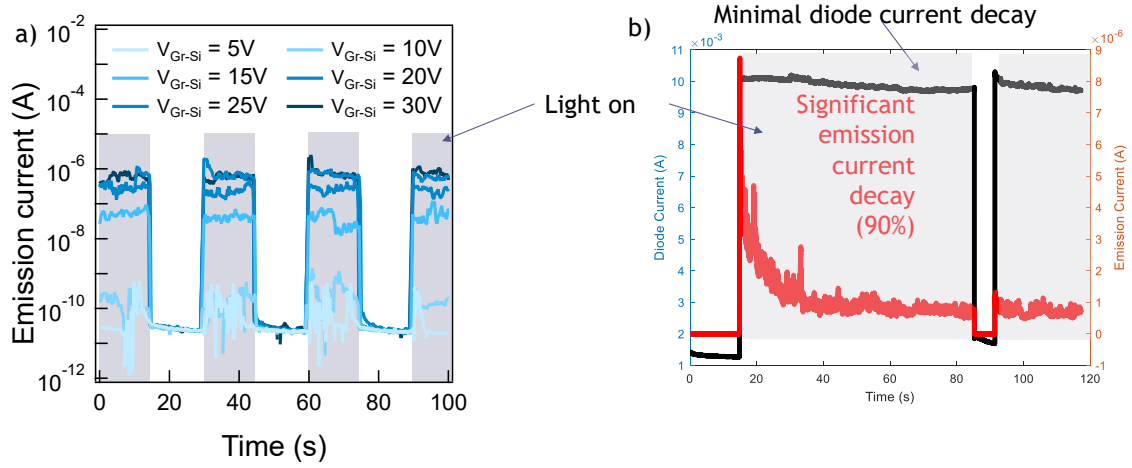


Figure 2: a) Previous device behavior observed (across ~10 devices all fabricated at separate times). b) Current device behavior.

Additionally, we faced an issue where we observed emitted current decay from our devices. We have been systematically studying this to understand what could be causing this. Our primary hypothesis is that additional trapping in the oxide layer causes a modulation of the electric field, which in turn reduces the energy at which carriers are injected into the graphene. The key issue is shown in figure 2. Based on this hypothesis we have tested a number of potential causes. Presently, we have identified a key potential source which we are working to eliminate: leakage through the field oxide. This path that exists even when no graphene is present in the device. This

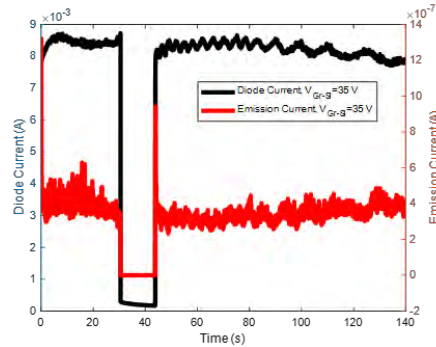


Figure 3: Thicker oxide enables stable emission current (red curve) over ~100 seconds. Dip in currents from ~30-45 seconds due to light being turned off.

should not occur, and was minimized in our previous device iterations. However, due to conditions in the oxide deposition tool changing over time, we have found that a considerable amount of current flows even when no graphene is transferred to the device. This essentially tells us that our field oxide, which is supposed to be a complete insulator, is breaking down during operation. We are presently working on eliminating this issue by (i) using a higher quality field oxide, and (ii) increasing the thickness of the field oxide. We anticipate that this approach will eliminate the issue previously seen and also improve the performance of the devices, as it will increase the voltage across the graphene/oxide.

Initial results of the experiments with thicker field oxides are shown in Figure 3. By using a thicker oxide, we see that recovery of the stable current vs time behavior is observed. Specifically, a 3 micron thick field oxide was used, which is $\sim 10\times$ thicker than the previously used 300 nm field oxide. The curve shown in figure 4 is for a silicon/oxide/semiconductor device which is biased so that the voltage across the graphene-silicon junction is 35 volts. Then, the current vs time characteristics are measured. For this graph, the initial segment, from 0~30 seconds is with exposure to light, the next segment, from ~ 30 -45 seconds is with no light, and finally the rest of the time period is under light exposure. Critically we see that the emission current is only present when exposed to light, which is a key indicator of the functionality of this device.

Finally, as shown schematically in figure 4, we have developed a new approach for integrating the extraction grid with the HELAC. As shown in the figure below, we use the difference in thickness between the HELAC semiconductor wafer and a silicon wafer to control the grid-HELAC spacing. Since semiconductor wafers have tight tolerances, this approach will enable us to create a compact HELAC gun which shields the sensitive semiconductor components from any external high fields.

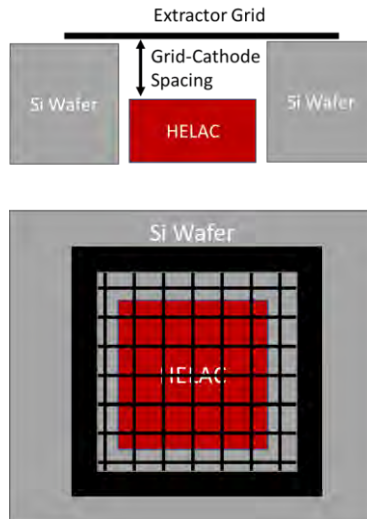


Figure 4: HELAC gun assembly approach

2.2 LM-IOT Component Design

The LM-IOT design stage requires us to design the gun holder, the accelerating grid, the magnetic focusing solenoid, the collector, and the output cavities. Initially, we are designing the solenoid, so that we can develop and test the emission/collection segments of the LM-IOT.

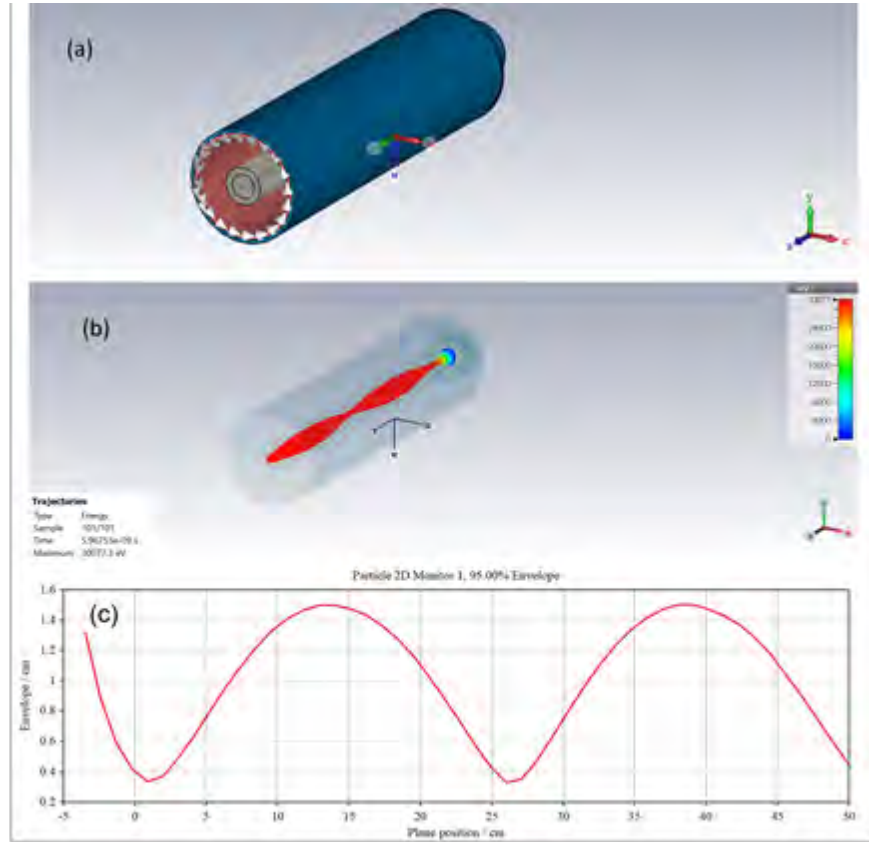


Figure 5: (a) Schematic of the simulated electron gun. (b) Electron beam trajectory. (c) Transverse modulation of the beam cross section

2.2.1 Solenoid Design

Particle tracking simulation has been performed via CST Particle Studio in order to design the solenoid for preventing the transversal expansion of the electron beam at the Inductive Output Tube (IOT). Figure 5a illustrates the simulated structure consisting of a cathode, an anode, a drift tube and a highly permeable hollow cylinder. Here, the cathode acts as the source of electrons with a fixed current of 100 mA. For acceleration, 30 kV and 0 V potentials have been applied to the anode and cathode, respectively. In addition, a large current-driven coil has been used in the system to generate the required magnetic field which has been guided by the hollow cylinder. The magnetostatic field generated by the coil was tuned via the coil current and number of turns to

control the focus of the trajectories inside the drift-tube. By varying these two parameters, it seemed reasonable to design a 52 cm solenoid with 2000 turns which can withstand at least 3 A of continuous current. If the solenoid is driven by 3 A, it will generate a magnetic field of 0.0145 T with 3.15 Wb flux linkage at the cathode. The generated magnetic field will keep the electron beam in focus of the drift tube as shown in Figure 5b. The transverse modulation of the beam cross-section is shown in figure 5c.

2.2.2 Output Cavity Design

The particle-in-cell (PIC) solver of CST studio was used to design an output cavity which will amplify radio frequency signals. The amplified signal was extracted using waveguide ports. As only the output cavity was simulated, a Gaussian emission model was used to define an already bunched electron beam. The material inside the cavity was considered to be vacuum and the

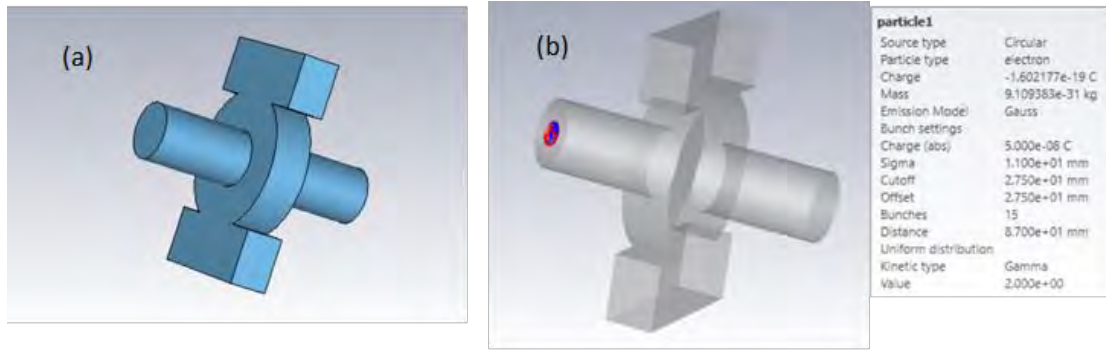


Figure 6: (a) Schematic of the simulated beam tube/cavity. (b) Gaussian electron beam source.

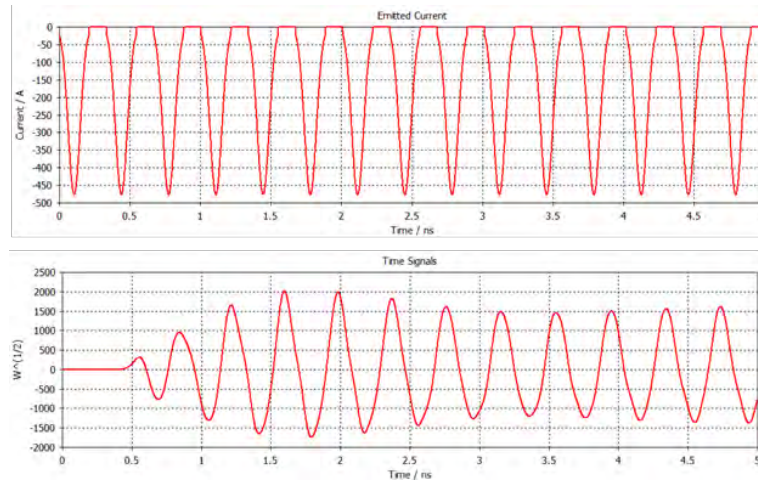


Figure 7: (a) Emitted current by the particle source. (b) Extracted output power. The output signal corresponds to the square root of the peak power, which means that the average output power extracted from the beam

perfect electrical conductor (PEC) was chosen as the background material (surrounding the output cavity volume). Figure 6a illustrates the structure of the output cavity that was simulated which consisted of a tube, a cavity and two waveguide ports for extracting the output. Figure 6b shows the Gaussian source for electron beam. The specifications of the Gaussian source were chosen to be suitable for this simulation. The simulation was done for two different tube lengths (12 cm and 16 cm). Figure 7a shows the charged particle motion through the 12 cm tube. Figure 7b illustrates the emitted current by the source for this simulation and Figure 8c shows the output power extracted from the beam.

2 Findings and Conclusions

Presently, we have identified and overcome key barriers to HELAC device performance. These findings enable us to continue improving the performance of these devices, and bring them up to the level of performance desired for use in the LM-IOT system. Furthermore, we have been successfully carrying out both gun and tube/cavity design for the LM-IOT systems. Thus, we are well positioned to execute on our originally planned scope for this proposal.

3 Plans and Upcoming Events

Our next steps include: (i) Modification of the substrate from silicon to a telecom wavelength sensitive semiconductor, either InGaAs or Ge, (ii) Construction of an initial proof-of-concept LM-IOT beam line, (iii) Fabrication and testing of the output cavities for LM-IOTs, and (iv) Continued optimization of our HELAC device performance.

Our milestones are as follows: (i) Demonstration of $>1\text{mA/cm}^2$ HELACs with InGaAs or Ge substrates, (ii) Test of the LM-IOT beam-line, (iii) Test of the output cavities.

4 Transitions and Impacts

We presently do not have any transitions since this program has only started in the second half of 2021.

5 Collaborations

Due to this work, we have begun a collaboration with Prof. Peng Zhang at MSU where his team is theoretically exploring material combinations and structures that may be used to improve our device performance.

We also have an on-going collaboration with Prof. John Booske and Prof. Nader Behdad that is where we will be sending them HELAC devices for use in x-ray generation devices for the purposes of communications.

6 Personnel

Principal investigator: Rehan Kapadia, 1 person month, NA Member: N
Business Contact: Janet Ng

7 Students

A total of 4 Graduate students have assisted with this work: Subrata Das, Hyun Uk Chae, Ragib Ahsan, and Anika Tabassum.

8 Technology Transfer

Currently, we do not have commercialization or technology transfer efforts. We expect that once we can consistently achieve the desired baseline level of performance, we will be able to send working cathode/gun fixtures to interested parties.

9 Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project: 0

References

1. Spezio, A. E. *IEEE Trans. Microwave Theory Tech.* **2002**, 50, (3), 633-644.
2. Schleher, D. C. *Dedham* **1986**.
3. Beunas, A.; Bel, C.; Robert, C.; Racamier, J. C.; Bussiere, D.; Bariou, D.; Khelifa, K. H.; Hermann, V.; Yates, C.; Halatsis, N. In *Manufacturing and performance results of a 1.2 MW peak, 704 MHz multi-beam inductive output tube*, 2017 Eighteenth International Vacuum Electronics Conference (IVEC), 2017; IEEE: pp 1-2.
4. Freund, H.; Miner, W.; Verboncoeur, J.; Li, Y.; Wright, E. *IEEE transactions on plasma science* **2007**, 35, (4), 1081-1088.
5. Jensen, M. **2004**.
6. Heppinstall, R.; Clayworth, G. *EBU Technical Review* **1997**, 43-52.
7. Lau, Y.; Chernin, D. P.; Wilsen, C.; Gilgenbach, R. M. *IEEE transactions on plasma science* **2000**, 28, (3), 959-970.
8. Caryotakis, G. *Physics of Plasmas* **1998**, 5, (5), 1590-1598.
9. Lau, Y.; Friedman, M.; Krall, J.; Serlin, V. *IEEE transactions on plasma science* **1990**, 18, (3), 553-569.
10. Sessler, A. M.; Simon, S. Y. *Physical review letters* **1987**, 58, (23), 2439.
11. Nyaiesh, A. R.; Garwin, E. L.; King, F. K.; Kirby, R. E. *Journal of Vacuum Science & Technology A* **1986**, 4, (5), 2356-2363.
12. Girard, B.; Lapierre, Y.; Ortega, J.; Bazin, C.; Billardon, M.; Elleaume, P.; Bergher, M.; Velghe, M.; Petroff, Y. *Physical review letters* **1984**, 53, (25), 2405.
13. Lau, Y.-Y. *Physical review letters* **1984**, 53, (4), 395.
14. Chodorow, M.; Wessel-Berg, T. *IRE Transactions on electron devices* **1961**, 8, (1), 44-55.
15. Goldstein, J.; Newbury, D. E.; Echlin, P.; Joy, D. C.; Romig Jr, A. D.; Lyman, C. E.; Fiori, C.; Lifshin, E., *Scanning electron microscopy and X-ray microanalysis: a text for biologists, materials scientists, and geologists*. Springer Science & Business Media: 2012.
16. Reimer, L., *Transmission electron microscopy: physics of image formation and microanalysis*. Springer: 2013; Vol. 36.
17. Vieu, C.; Carcenac, F.; Pepin, A.; Chen, Y.; Mejias, M.; Lebib, A.; Manin-Ferlazzo, L.; Couraud, L.; Launois, H. *Applied Surface Science* **2000**, 164, (1), 111-117.
18. Goebel, D. M.; Katz, I., *Fundamentals of electric propulsion: ion and Hall thrusters*. John Wiley & Sons: 2008; Vol. 1.

19. Benford, J.; Swegle, J. A.; Schamiloglu, E., *High power microwaves*. CRC Press: 2007.
20. Gold, S. H.; Nusinovich, G. S. *Review of Scientific instruments* **1997**, 68, (11), 3945-3974.
21. Barker, R. J.; Luhmann, N. C.; Booske, J. H.; Nusinovich, G. S. *Modern Microwave and Millimeter-Wave Power Electronics*, by Robert J. Barker (Editor), Neville C. Luhmann (Editor), John H. Booske (Editor), Gregory S. Nusinovich, pp. 872. ISBN 0-471-68372-8. Wiley-VCH, April 2005. **2005**, 1.
22. Brau, C. A. **1990**.
23. Wang, Q.; Setlur, A.; Lauerhaas, J.; Dai, J.; Seelig, E.; Chang, R. *Applied Physics Letters* **1998**, 72, (22), 2912.
24. Kartikeyan, M. V.; Borie, E.; Thumm, M., *Gyrotrons: high-power microwave and millimeter wave technology*. Springer Science & Business Media: 2013.
25. Yanagisawa, H.; Hengsberger, M.; Leuenberger, D.; Klöckner, M.; Hafner, C.; Greber, T.; Osterwalder, J. *Physical review letters* **2011**, 107, (8), 087601.
26. Wimmer, L.; Herink, G.; Solli, D.; Yalunin, S.; Echternkamp, K.; Ropers, C. *Nature Physics* **2014**, 10, (6), 432-436.
27. Jensen, K.; Lau, Y.; McGregor, D. *Applied Physics Letters* **2000**, 77, (4), 585-587.
28. Jensen, K. L.; Lau, Y.; McGregor, D. *Solid-State Electronics* **2001**, 45, (6), 831-840.
29. Hagmann, M. J. *Ultramicroscopy* **1999**, 79, (1), 115-124.
30. Xiong, X.; Zhou, Y.; Luo, Y.; Li, X.; Bosman, M.; Ang, L. K.; Zhang, P.; Wu, L. *ACS nano* **2020**, 14, (7), 8806-8815.
31. Luo, Y.; Zhang, P. *Physical Review Applied* **2019**, 12, (4), 044056.
32. Zhang, P.; Lau, Y. *Scientific reports* **2016**, 6, (1), 1-12.
33. Rezaeifar, F.; Ahsan, R.; Lin, Q.; Chae, H. U.; Kapadia, R. *Nature Photonics* **2019**, 1-6.
34. Blankemeier, L.; Rezaeifar, F.; Garg, A.; Kapadia, R. *Journal of Applied Physics* **2019**, 126, (3), 033102.
35. Rezaeifar, F.; Kapadia, R. In *Cavity coupled photon-enhanced thermionic electron emitter*, Vacuum Electronics Conference (IVEC), 2016 IEEE International, 2016; IEEE: pp 1-2.
36. Ahsan, R.; Sakib, M. A.; Chae, H. U.; Kapadia, R. *Physical Review Applied* **2020**, 13, (2), 024060.
37. Rezaeifar, F.; Chae, H. U.; Ahsan, R.; Kapadia, R. *Applied Physics Letters* **2021**, 118, (7), 071108.

Infrared Optics with Engineered Materials

Grant No. N00014-20-1-2297

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2021 to September 30, 2021

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Date Prepared: January 31, 2022

Project Title: Infrared Optics with Engineered Materials

Annual Summary Report: FY21, 1 October 2020 to 30 September 2021

Principle Investigator: PI Mikhail Kats, 608-890-3984, mkats@wisc.edu, University of Wisconsin-Madison

Section I: Project Summary

1. Overview of Project

Abstract: The major goals of this project are to explore innovative ways to engineer and characterize existing and emerging optical materials to enable next-generation infrared optics for emitting, manipulating, absorbing, and detecting infrared light. The ability to emit, manipulate, absorb, and detect infrared light has substantial long-term Naval relevance, especially due to the rapid development of infrared sensors and cameras, as well as high-power lasers that may be used to blind these instruments. This document describes progress made in FY21 toward these fundamental-science goals, and includes enhanced understanding of defect engineering and recovery in phase-change materials, demonstration of a new spectroscopy technique based on thermal radiation, demonstration of an inexpensive infrared polarizer design, and the design and demonstration of two dynamic devices based on phase-transition materials: a switchable induced transmission filter, and an ultrathin broadband reflective optical limiter.

Objective: The proposal had three key sections. In Chapter 1, we proposed new approaches to modify materials properties, focusing on spatial control of infrared optical properties, such that they can be engineered into devices. In Chapter 2, we proposed the development of new and improved methods of materials metrology to better understand infrared optical materials and to better characterize engineered optical structures. In Chapter 3, we proposed new infrared optical and optoelectronic devices for polarization control and infrared photodetection, based on materials-engineering and characterization techniques (to be) developed in Chapters 1 and 2. Specific goals include the development of new spectroscopic techniques, new types of flat and thin optical components for imaging and beam control, more-robust control over polarization of infrared light, new optical protective technologies, and new optical technology for thermoregulation using engineered thermal radiation.

Background: Our approach to reach the objectives described above is to carry out an interdisciplinary, integrated program where we simultaneously investigate new spectroscopic techniques for materials characterization, new ways of modifying materials, and new devices, with the devices building on the materials innovations developed within the project.

2. Activities and Accomplishments

Chapter 1 accomplishment: Fast recovery of ion-irradiation-induced defects in GST

One of the goals of this project is to enable the engineering of phase-change materials to broaden their applicability to tunable infrared devices. One of the most widely studied phase-change material is germanium-antimony-telluride, or GST. GST can be switched between amorphous and crystalline phases which are each stable, and therefore has been used for phase-change optical

storage as well as tunable optical devices. Here, we partnered with Carsten Ronning's group at the University of Jena to explore the role of disorder in the phase transition. In particular, we used Ar ion irradiation of GST films which started in different crystalline phases (rock salt or hexagonal GST) to observe at what point the accumulation of defects due to irradiation results in amorphization of GST. Example data is shown in Fig. 1, where the gradual amorphization in initially rock-salt GST is observed using visible and infrared spectroscopy, as well as XRD measurements of the crystal structure.

Through this work, we learned several pieces of important information about how disorder effects GST, observing that rock-salt GST progressively amorphizes via the accumulation of lattice defects, but in hexagonal GST, the situation is more complicated. Hexagonal GST first transitions to rock-salt GST via disordering of the intrinsic vacancy layers, and then finally amorphization occurs. We also observed different annealing behavior of defects of rock-salt and hexagonal GST, with a higher amorphization threshold in hexagonal GST due to an increase defect-annealing rate (i.e., higher resistance against disorder).

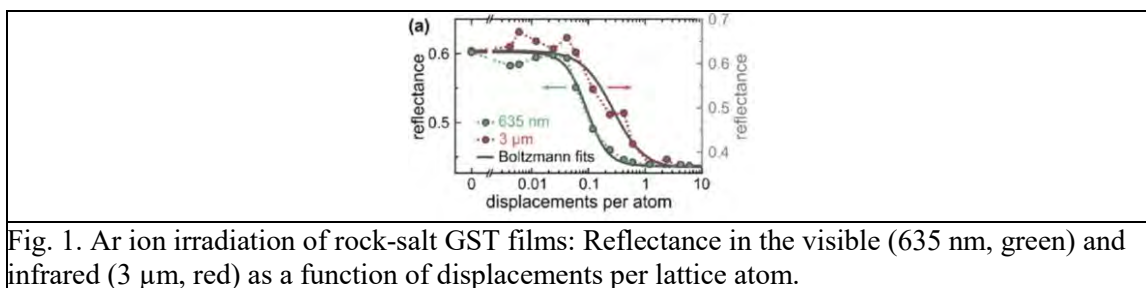


Fig. 1. Ar ion irradiation of rock-salt GST films: Reflectance in the visible (635 nm, green) and infrared (3 μm , red) as a function of displacements per lattice atom.

This work was published recently as M. Hafermann, *Optical Materials Express* 11, 3535 (2021). We are looking forward to a continuation of this collaboration, with the goal of being able to tailor the manner in which the phase change occurs to enable new types of optical switching.

Chapter 2 accomplishment: Planck spectroscopy

One of the objectives of this project was to develop a spectroscopy technique that does not require the conventional optical components of a spectrometer that segregate light by wavelength (prisms, gratings, interferometers with moving mirrors, filters, etc.). The technique we developed was based on the progress we made over the last five years (funded in significant part by the ONR YIP award) in precisely and accurately measuring thermal radiation.

In the new technique, called Planck spectroscopy, a sample with an unknown emissivity/absorptivity spectrum is positioned on a temperature-controlled stage, facing an infrared detector. The temperature of the sample is varied, and the power on the detector is recorded as a function of sample temperature. Then, this data can be inverted using inverse-problem techniques to yield the originally unknown emissivity spectrum (Fig. 2).

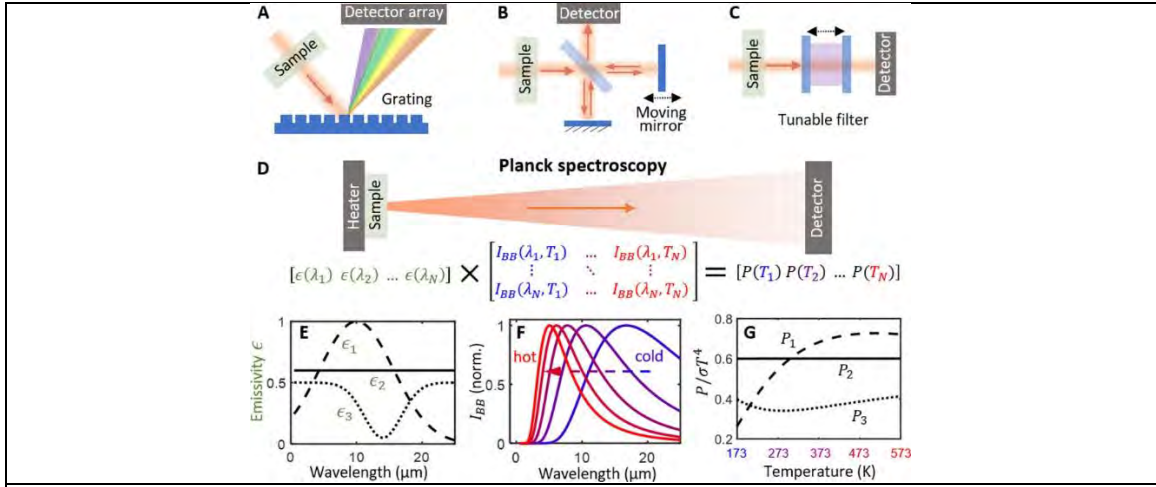


Fig. 2. Comparison between conventional spectroscopic methods and Planck spectroscopy. Three common spectroscopy mechanisms using A) a dispersive component, such as a grating; B) a moving mirror to modify the interference condition of an interferometer; and C) a tunable filter. D) Planck spectroscopy requires only a temperature stage and a detector.

We demonstrated this technique both theoretically and experimentally. In our experiment, we used a number of reference samples (wafers of sapphire, fused silica, and doped silicon with different doping densities) for which we knew the actual emissivity spectra. Our Planck spectroscopy technique was able to recover the unknown spectra with relatively good accuracy and precision (Fig. 3), achieving a resolution on the order of 1 micron in the mid infrared, across the 3-13 micron range, where this range was limited by the bandwidth of the detector we used.

Planck spectroscopy can be modified and expanded to achieve ellipsometry-like measurements, and can be used with a conventional mid-infrared camera to enable mid-infrared hyperspectral imaging at a lower price than existing infrared hyperspectral cameras. The work has now been published as Y. Xiao et al, “Planck Spectroscopy”, *Laser & Photonics Reviews*, 15 2100121 (2021).

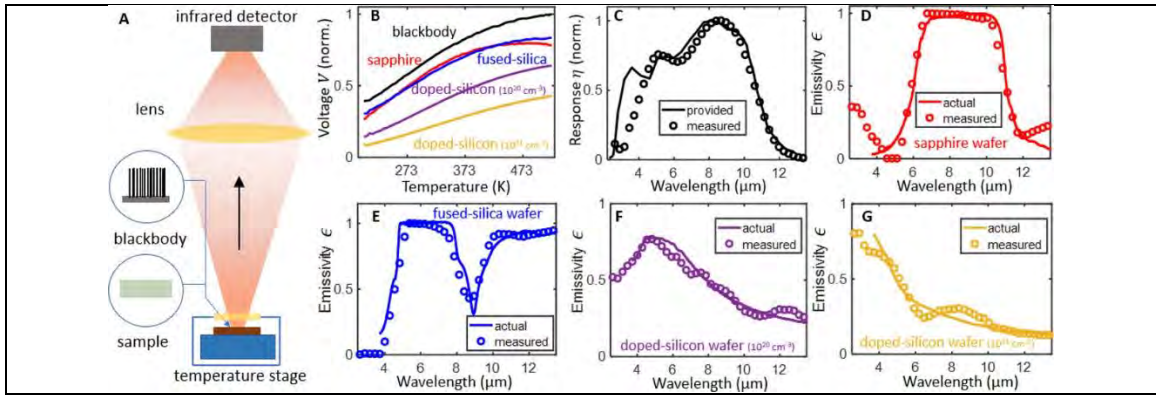


Fig. 3 Experimental demonstration of Planck spectroscopy. A) Schematic of the experimental setup. B) Normalized voltage versus temperature for five different samples: a laboratory blackbody, a sapphire wafer, a fused-silica wafer, and two n-doped silicon wafers with doping levels of 10^{20} and 10^{21} cm^{-3} . C) The extracted response function of the measurement setup, obtained by using the blackbody reference (dotted circle), is in good agreement with the expected response function based on vendor-provided properties of the detector, heater window, and lens. D–G) Measured emissivity of the samples using Planck spectroscopy (circles), and the corresponding spectra measured using a Fourier-transform spectrometer (solid line).

Chapter 3 accomplishment: Infrared polarizer based on direct coupling to surface plasmons

Our work primarily from the previous reporting period on a new type of infrared polarizer based on direct coupling to surface plasmon polaritons has been published in this reporting cycle as A. Shahsafi et al, *Nano Letters* 20, 8483 (2020). In this paper, we demonstrated a new type of reflective polarizer based on polarization-dependent coupling to surface plasmon polaritons (SPPs) from free space. This inexpensive polarizer is relatively narrowband but features an extinction ratio of up to 1000 with efficiency of up to 95% for the desired polarization (numbers from a calculation) and thus can be stacked to achieve extinction ratios of 10^6 or more. As a proof of concept, we experimentally realized a polarizer based on nanoporous aluminum oxide that operates around a wavelength of $10.6\text{ }\mu\text{m}$, corresponding to the output of a CO₂ laser, using aluminum anodization, a low-cost electrochemical process (Fig. 4).

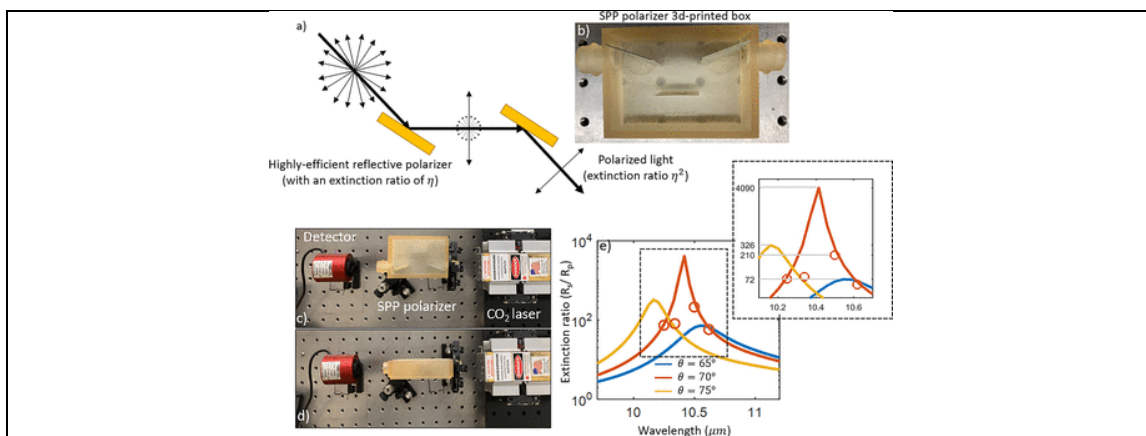


Fig. 4. Increasing the extinction ratio of our SPP polarizer by placing two samples next to each other (a) without using a mirror, and (b) by using a mirror, resulting in conservation of the beam position and direction. (c-e) Testing of the polarizer box in (b) with one polarizer element (instead of the 2 shown schematically in (a)),.

Chapter 3 accomplishment: Switchable induced-transmission filters enabled by vanadium dioxide

As part of this grant, we completed a paper on tunable infrared filters with a substantial part of the work under a DARPA STTR subcontract (through Physical Sciences Inc.) prior to the start of the present project, but that did not get to publication under the DARPA/PSI project. Fortunately, the topic is closely related to the present project, and therefore we were able to complete it here by finishing some of the analysis and writing it up. The paper is now published as C. Wan et al, "Switchable Induced-Transmission Filters Enabled by Vanadium Dioxide", *Nano Letters* 22, 6 (2022). The purpose of these filters is to eventually enabling the enhancement of imaging when there is something impeding the imaging (e.g., dust) with a particular infrared spectrum, such that the noise can be removed using a narrowband filter that can be switched on and off, or in situations where two objects are difficult to distinguish other than by a narrowband spectral feature.

The induced-transmission filter (ITF) is an old (out of favor now) filter design that uses an ultrathin metallic layer positioned at an electric-field node within a dielectric thin-film bandpass filter to select one transmission band while suppressing other bands that would have been present without

the metal layer. In this work, we introduced a switchable mid-infrared ITF where the metal can be “switched on and off”, enabling the modulation of the filter response from a single band to multiband. The switching is enabled by the reversible insulator-to-metal phase transition of a subwavelength film of vanadium dioxide (VO_2) (Fig. 5).

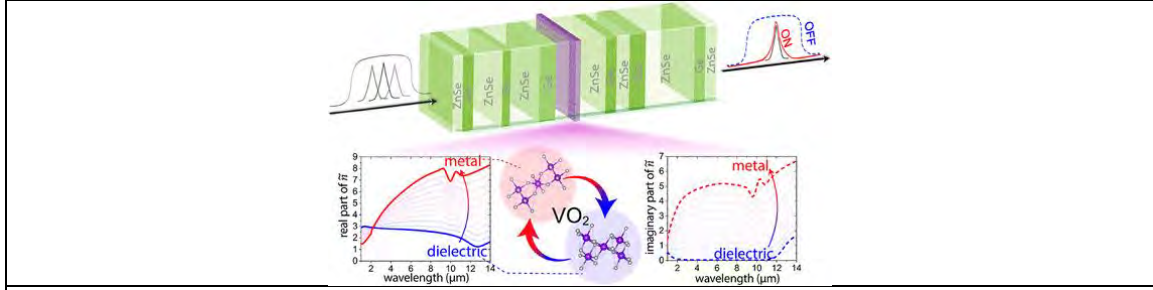


Fig. 5. Schematic of our switchable induced-transmission filter (ITF), based on specially designed thin-film stacks with a VO_2 switching layer inserted at a particular point in the stack.

The fabrication process of this filter, which begins with thin-film VO_2 being deposited on a suspended membrane, enables the integration of VO_2 into any thin-film assembly that is compatible with physical vapor deposition processes and is thus a new platform for realizing tunable thin-film filters (Fig. 6).

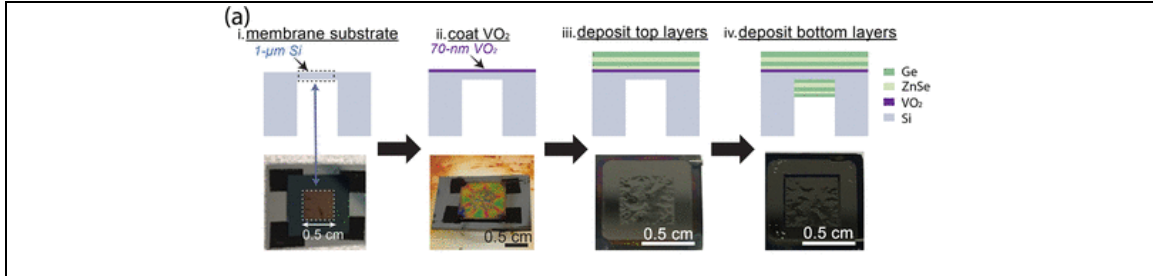
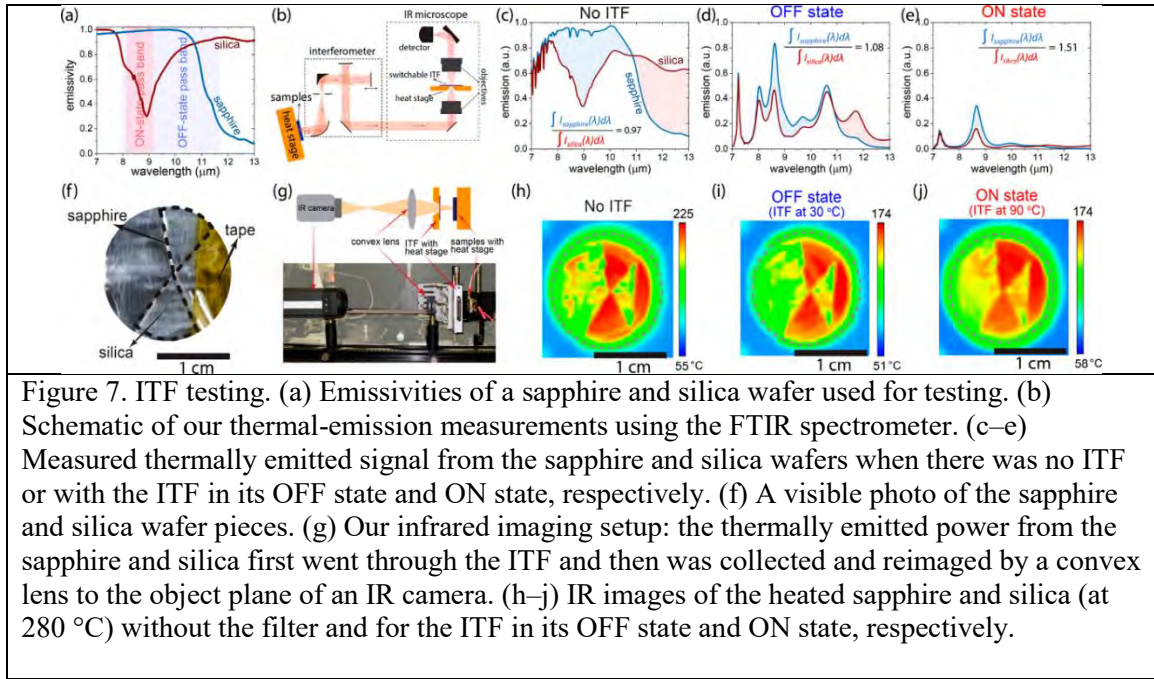


Fig. 6. (a) Fabrication process of the switchable induced transmission filter based on VO_2 .

Our experimental measurements are shown in Fig. 7. We used test samples that looked the same in the visible but had different emissivities, to see how they would appear when imaged with an infrared camera or directly measured with an infrared spectrometer. The data shows that the ITF is promising for applications where two objects that appear to be similar otherwise need to be distinguished based on a narrowband emissivity feature, but the current iteration of the ITF which requires temperature to be switched (and is in the ON state at 90 degrees C) is likely not good enough for imaging enhancement because the ITF itself ends up contributing to the thermal background, and further work needs to be done to enable lower-temperature switching.



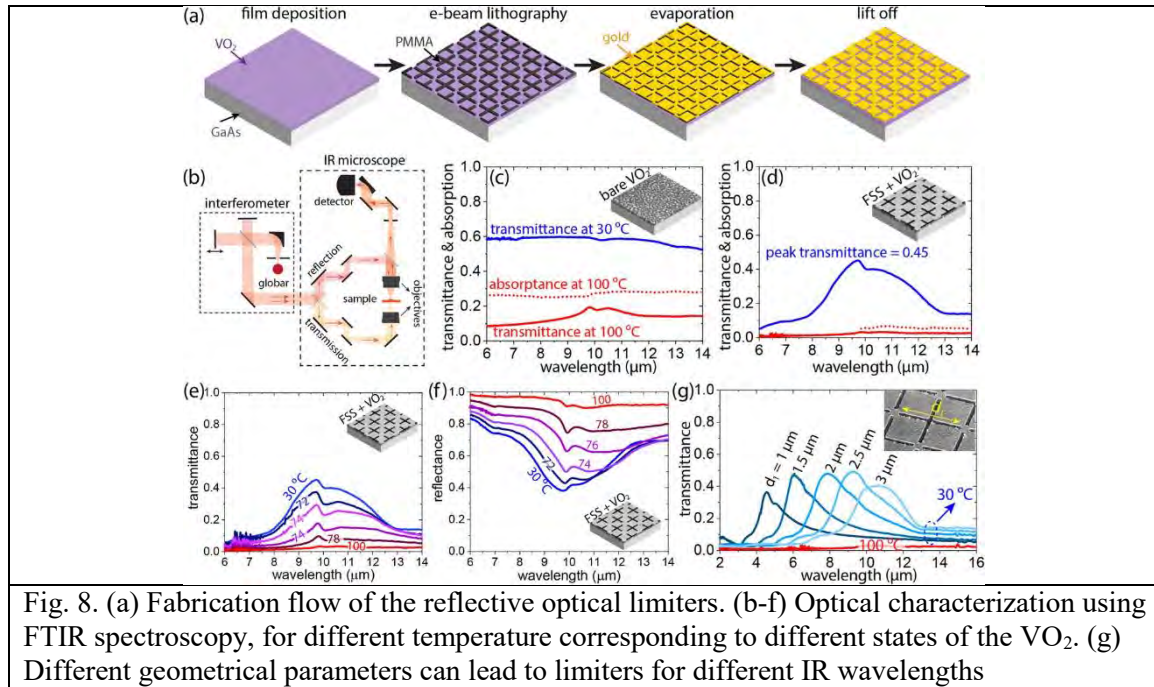
Chapter 3 accomplishment: Ultrathin broadband reflective optical limiter

Finally, we have continued to work on protective optical technologies based on phase-transition materials, in particular publishing a paper on ultrathin broadband reflective optical limiters that combine a tunable phase-transition layer and a frequency-selective surface. The paper has been published as C. Wan et al, *Laser & Photonics Reviews* 15, 210001 (2021).

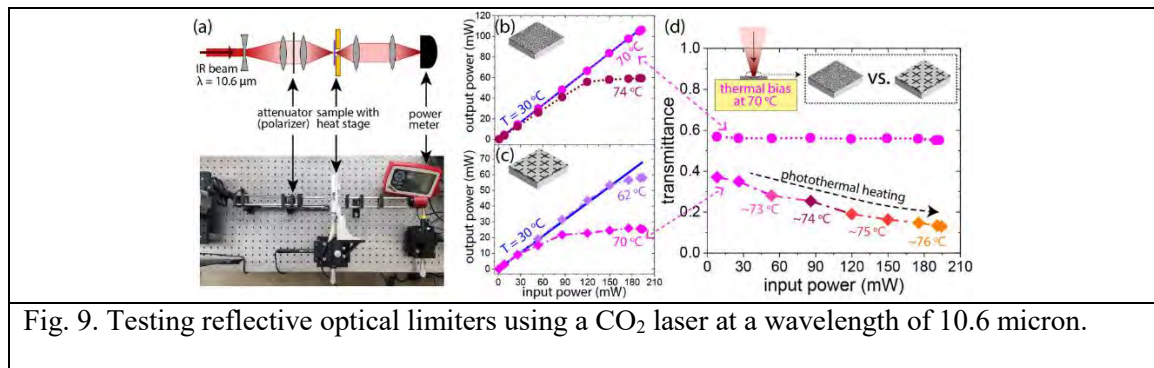
Optical limiters are nonlinear devices with decreasing transmittance with increasing incident optical intensity, and thus can protect sensitive components from high-intensity illumination. The ideal limiter reflects rather than absorbs light in its active (“limiting”) state, minimizing risk of damage to the limiter itself. Previous efforts to realize reflective (rather than absorbing) limiters were based on embedding nonlinear layers into thick multilayer photonic structures, resulting in substantial fabrication complexity, reduced speed and, in some instances, limited bandwidth. Here, these tradeoffs are overcome by using the insulator-to-metal transition (IMT) in VO₂ to achieve intensity-dependent modulation of resonant transmission through aperture antennas. Due to the large change of optical properties across the IMT, low-quality-factor resonators are sufficient to achieve high on–off ratios in the transmittance of the limiter. As a result, our ultrathin reflective limiter (thickness $\approx 1/100$ of the free-space wavelength) is broadband in terms of operating wavelength ($>2 \mu\text{m}$ at $10 \mu\text{m}$) and angle of incidence (up to $\approx 50^\circ$ away from the normal).

The fabrication flow using electron-beam lithography and the resulting structures are shown in Fig. 8. We characterized the devices with FTIR spectroscopy, changing the temperature, and observed the desired performance. We also tested frequency-selective surfaces of different geometries, and

confirmed that it is possible to create these reflective limiters for a variety of wavelength across the mid infrared, from around 3 micron to >10 micron.



The limiting performance is shown in Fig. 9, where we used a focused CO_2 laser as the source that the limiter should block. We observed limiting behavior (flattening of the output vs. input curve), as expected from these devices.



3. Findings and Conclusions

- Elucidated the effects of disorder on various phases of phase-change material GST; this knowledge will be relevant for tunable optical devices based on GST
 - Chapter 1 objective [new approaches to modify materials properties, focusing on spatial control of infrared optical properties]

- Developed and demonstrated a technique called "Planck spectroscopy, which is a new method of measuring absorption spectra that does not require conventional light-separating elements that are typically required in spectrometers. The measured resolution is approximately 1 micron in the mid-infrared range
 - Chapter 2 objective [new and improved methods of materials metrology to better understand infrared optical materials and to better characterized engineered optical structures]
- Developed a new type of infrared polarizer based on direct coupling to surface-plasmon polaritons that achieves narrowband polarization performance using a low-cost technique. For situations where polarization control need only be narrowband (specifically for infrared lasers), these polarizers may be ~5x less expensive than conventional wire-grid polarizers.
 - Chapter 3 objective [new infrared optical and optoelectronic devices for polarization control and infrared photodetection]
- Finalized a publication based primarily on earlier DARPA/PSI-funded work demonstrating a switchable induced-transmission filter
 - Chapter 3 objective [new infrared optical and optoelectronic devices for polarization control and infrared photodetection]
- Demonstrated an ultrathin broadband optical limiter based on the integration of frequency selective surfaces and phase-transition materials
 - Chapter 3 objective [new infrared optical and optoelectronic devices for polarization control and infrared photodetection]

Appendix (Data and Charts)

None

4. Plans and Upcoming Events

The plans are unchanged from the proposal, with no major upcoming events planned at this time.

5. Transitions and Impacts

No significant transitions to report.

6. Collaborations

In this reporting period on this project, we have collaborated with the following groups:

- Group of Carsten Ronning, University of Jena, Germany
- Group of Shriram Ramanathan, Purdue University
- PIs David Woolf and Joel Hensley, Physical Sciences Incorporated

7. Personnel

Principal investigator: Mikhail Kats, 1.4 person months [not a National Academy Member]

Team Members: Yuzhe Xiao, Assistant Scientist [not a National Academy Member]

8. Students

4, though 2 were only supported on the project for a short time

9. Technology Transfer

Patent application submitted for Planck spectroscopy:

Y. Xiao, C. Wan, J. Salman, M. A. Kats, “Planck spectrometer”, Patent application filed Dec 2020.

10. Products, Publications, Patents, License Agreements, etc.

Archival Publications (all peer reviewed)

C. Wan, D. Woolf, C. M. Hessel, J. Salman, Y. Xiao, C. Yao, A. Wright, J. M. Hensley, M. A. Kats, “Switchable induced-transmission filters enabled by vanadium dioxide”, *Nano Letters* 22, 6 (2022)

M. Hafermann, R. Schock, C. Wan, J. Rensberg, M. A. Kats, and C. Ronning, “Fast recovery of ion-irradiation-induced defects in Ge₂Sb₂Te₅ thin films at room temperature”, *Optical Materials Express* 11, 3535 (2021)

Y. Xiao, C. Wan, J. Salman, I. J. Maywar, J. King, A. Shahsafi, M. A. Kats, “Planck spectroscopy”, *Laser & Photonics Reviews* 15, 2100121 (2021) [featured on journal cover]

C. Wan, Z. Zhang, J. Salman, J. King, Y. Xiao, Z. Yu, A. Shahsafi, R. Wambold, S. Ramanathan, M. A. Kats, “Ultrathin broadband reflective optical limiter”, *Laser & Photonics Reviews* 15, 2100001 (2021) [featured on journal cover]

A. Shahsafi, J. Salman, B. E. Rubio Perez, Y. Xiao, C. Wan, M. A. Kats, “Infrared polarizer based on direct coupling to surface-plasmon polaritons”, *Nano Letters* 20, 8483 (2020)

Conference Papers

Note: in our group/field, we typically do not submit “conference papers”, but we do have conference presentations which are either oral or poster presentations. Sometimes (but not always) the abstract is published, but we do not typically submit full conference papers.

C. Wan, Z. Zhang, J. Salman, J. King, Y. Xiao, Z. Yu, A. Shahsafi, R. Wambold, S. Ramanathan, M. A. Kats, “Reflective optical limiters based on tunable frequency-selective surfaces modulated by vanadium dioxide”, MRS Fall meeting, Boston (2021)

C. Wan, M. Hafermann, T. J. Park, Z. Zhang, J. Rensberg, S. Ramanathan, C. Ronning, M. A. Kats, “Tunable photonics enabled by defect engineering of vanadium dioxide via ion implantation”, MRS Fall meeting, Boston (2021)

C. Wan, Z. Zhang, D. Woolf, C. Hessel, J. King, J. Salman, J. Hensley, S. Ramanathan, M. A. Kats, “Tunable photonics based on thin-film vanadium dioxide”, AVS 67, virtual due to COVID19 pandemic (2021)

C. Wan, D. Woolf, C. M. Hessel, J. Salman, Y. Xiao, C. Yao, A. Wright, J. M. Hensley, M. A. Kats, “Switchable thin-film filters enabled by the phase transition of vanadium dioxide”, SPIE Optics + Photonics (2021)

C. Wan, Z. Zhang, E. Horak, J. Rensberg, D. Woolf, J. King, J. Salman, Y. Xiao, R. Goldsmith, J. Hensley, C. Ronning, S. Ramanathan, M. A. Kats, “Reconfigurable infrared optics based on insulator-metal transition materials”, IEEE Photonics Society, Summer Topicals, virtual due to COVID19 pandemic (July, 2021) [invited talk]

H. Mei, A. Koch, C. Wan, J. Salman, J. Rensberg, Z. Zhang, M. Hafermann, R. Wambold, S. Ramanathan, C. Ronning, M. A. Kats, “Engineering Optical Materials Using Focused Ion Beams”, Novel Optical Materials and Applications (NOMA), virtual due to COVID19 pandemic (2021) [Best student talk award; 1st place]

Y. Xiao, C. Wan, J. Salman, I. J. Maywar, J. L. King, A. Shahsafi, M. A. Kats, “Planck spectroscopy”, Conference on Laser and Electro-Optics (CLEO), virtual due to the COVID19 pandemic (2021)

C. Wan, J. Rensberg, Z. Zhang, M. Hafermann, H. Mei, Y. Xiao, J. Salman, S. Ramanathan; C. Ronning, M. Kats, “Tunable Infrared Optics Enabled by Defect-Engineering of Vanadium Dioxide Using Focused Ion Beam”, Conference on Lasers and Electro-Optics (CLEO), virtual due to the COVID19 pandemic (2021)

Books

None

Book Chapter

None

Theses

- a. Title: Tunable infrared photonics enabled by materials with insulator-to-metal transitions
- b. Institution: University of Wisconsin-Madison
- c. Authors: Chenghao Wan
- d. Completion Date: 2021
- e. Acknowledgement of Federal Support? Yes

Websites

None

Patents

- a. Inventors: Y. Xiao, C. Wan, J. Salman, M. A. Kats
- b. Wisconsin Alumni Research Foundation
- c. Planck spectrometer
- d. P210084US01 [application reference number]

e. Filed Dec 2020

Other Products: Identify any other significant products that were developed under this project. Describe the product and how it is being shared.

None

11. Point of Contact in Navy

None at this time.

12. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research (ONR), under grant (or contract) number N00014-20-1-2297. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Multi-frequency High Power Microwave Generation and Amplification via Optically Gated Electron Beams

Grant No. N00014-20-1-2681

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to September 30, 2021

Prepared by:

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Project Title: Multi-frequency High Power Microwave Generation and Amplification via Optically Gated Electron Beams

Annual Summary Report: FY2021

Principle Investigator: Peng Zhang, 517-353-3654, pz@egr.msu.edu

Department of Electrical and Computer Engineering, Michigan State University

Section I: Project Summary

1. Overview of Project

Abstract: Electron beam based high power microwave (HPM) devices are critical to a variety of defense applications for Navy and more broadly the Department of Defense (DOD). This project explores the fundamental physics of density modulation of electron beam emission via combined mechanisms of thermionic/field/photo-emission and the interaction of such premodulated beams with circuits for HPM generation and amplification. This report provides an executive summary of our recent theoretical modeling efforts. Using an analytical quantum model, we explored the enhancement of field emission current from cathodes with thin dielectric coating. It is found that coatings of small dielectric constant and large electron affinity can greatly enhance the field emission current by up to two orders of magnitude compared to uncoated cases. We developed an exact time-dependent quantum theory for pulsed laser induced photoemission, which is valid for arbitrary pulse length from sub-cycle to continuous wave (CW) excitation, from the photon-driven regime to the optical-field-driven regime, and is applicable for arbitrary laser parameters, dc bias, and cathode material properties. We found that applying a large dc field to the photoemitter is able to significantly enhance the photoemission current and in the meantime substantially shorten the current pulse. We systematically investigated the photoemission quantum efficiency (QE) from metal surfaces with laser wavelengths from 200 to 1200 nm (i.e., ultraviolet to near-infrared). It is found that QE can be increased nonlinearly by the non-equilibrium electron heating produced by sub-picosecond laser pulses. We also wrote an Invited Perspective article on space-charge limited current in nanodiodes, which is important to the development of high power electromagnetic sources and amplifiers.

Objective: The objective of this project is to provide a foundational understanding of the underlying physics in optically gated electron emission and its interaction with microwave circuits. The goal is to provide a guideline for the design of compact HPM devices with the ultimate high power output and extremely flexible frequency tunability. The ultrafast electron emission due to pulsed laser, or optical gating, would potentially provide unrivaled precision in phase-control of electromagnetic signals from electron based HPM devices. The potential of selective gating of multiple beams would provide strong flexibility for multi-frequency HPM applications.

Introduction: Traveling wave devices utilize the collective interaction of an electron beam with a periodic structure to convert electron beam energy into electromagnetic radiation. They are key elements in telecommunication systems, satellite-based transmitters, military radar, communication data links, and electronic countermeasures. There continues to be strong interests in increasing the output power, frequency tunability, and bandwidth of traveling wave devices, for

uses as radiation sources and power amplifiers, from GHz to THz and beyond. For the development of coherent radiation sources, it is desirable to minimize the threshold beam current for triggering oscillation. In contrast, for high power traveling wave tube (TWT) amplifiers, unwanted oscillations pose a major threat to their operation. For novel contemporary traveling wave devices, such as metamaterial-, photonic crystal- and advanced Smith-Purcell-based traveling wave devices, improving efficiency remains a major challenge.

In vacuum microwave tubes, the energy conversion from electron beams into electromagnetic radiation relies on beam modulation, by either density modulation or velocity modulation. Density modulation is achieved by controlling the electron emission from the cathode. Velocity modulation is achieved by passing the electrons through an RF electric field that modulates the velocities of the electrons. At present, TWTs mainly rely on velocity modulation of the electron beam for power amplification. After the electron velocities are modulated, there is a substantial delay before velocity modulation becomes density modulation, until useful gain is produced. Significant improvements in TWT performance can be enabled by density modulation during emission. In particular, with density modulation, velocity dispersion in the beam can be minimized and the substantial portion of the interaction circuit for the purpose of converting velocity modulation into density modulation can be eliminated. This would result in compact devices with reductions in overall dimensions and weight, through the elimination of the premodulation circuit. Furthermore, density modulation during emission would eliminate the launching loss of the input RF signal, which is a serious intrinsic problem in TWTs based on velocity modulation.

In this project, we will explore density modulation in optically gated electron emission. This is motivated by the recent rapid development in ultrafast lasers and photonics, which has opened up unprecedented advances to control electron beam dynamics at ultrashort spatial-temporal scales. The research on implementing both high power and frequency tunability in HPM devices will provide a critical disruptive capability using high power microwaves. The theory will also be valuable to neighboring fields such as novel miniaturized electromagnetic radiation sources, nano-optoelectronics, ultrafast physics, material science, and accelerator technology.

Background: The idea of using direct current modulation of electron beams in microwave amplifiers has existed for decades. Historically, density modulation was accomplished with a grid that lays over the surface of a thermionic emitter to control the electron emission. Because of the finite transit time of the electrons across the cathode-grid space, this modulation technique is only effective up to 2 GHz for state-of-the-art devices. With the advancement of vacuum microelectronics and field emitter arrays (FEAs), the gate-to-emitter spacing has been reduced into submicron scale, which significantly decreases the electron transit time. Density modulation about 5 GHz by gate modulating of the FEA has been demonstrated; however, there are significant challenges for using FEAs in high power tubes, because the premature failure due to arcing often occurs at current levels much smaller than the design requirements. Breakdown is a major challenge for FEAs because of the high fields within the structure and the thin-film gate electrode. An electrical short between the gate and any individual emitter will burn out the entire FEA and render it unusable. While shields can be added to mitigate the damaging effects of the electrical shorts, high operating voltage is needed to field emitter arrays to draw sufficient current.

Photoemission provides an alternative method to generate premodulated electron beams, which relaxes the requirement of high operating voltage in field emission, thus eliminating possible arcing

and circuit breakdown. More importantly, pulsed laser induced (or assisted) electron emission offers the possibility of manipulation and control of coherent electron motion in ultrashort spatiotemporal scales. These advantages would greatly benefit the development of advanced compact HPM devices.

2. Activities and Accomplishments

The main new activities and accomplishments during this performance period (1 October 2020 to 30 September 2021) include: 1) Theory of field emission from dielectric coated surfaces; 2) Few-cycle optical-field-induced photoemission from biased surfaces: An exact quantum theory; 3) A review paper on space-charge limited current in nanodiodes: ballistic, collisional, and dynamical effects; and 4) Quantum efficiency of photoemission from biased metal surfaces with laser wavelengths from ultraviolet (UV) to near infrared (NIR).

THEORY OF FIELD EMISSION FROM DIELECTRIC COATED SURFACES

We studied field emission from dielectric coated surfaces [1]. Electron field emission is important to high power microwave sources and amplifiers, and high current cathodes, for its high efficiency, high brightness, low emittance, and miniaturized device size. It also attracts intensive attention in many other applications, such as flat panel display, electron microscopes, vacuum microelectronics, x-ray sources, and emerging vacuum nanodevices. Common challenges of field emission include the operation requirement of high vacuum condition and current instabilities. To overcome these problems, ultrathin coatings, such as graphene, graphene oxide, and zinc oxide are fabricated onto the emitter to provide chemical and mechanical protection. Coated emitters are demonstrated to not only have longer current stability, but also smaller turn-on electric field and enhanced current emission due to the lowering of the effective potential barrier. In addition to the artificially fabricated coatings, native oxides or foreign adsorbates can be easily formed on the surface of the emitter at low vacuum condition. The thin oxide film or the coated dielectric layer on the cathode surface forms a double-layer potential barrier, which strongly influences the field emission properties. The heterostructure in the emission barrier introduced by the coating also has its potential to change the electrons' mean transverse energy behavior that affects beam quality, which makes it an active area for photoinjectors for future x-ray free electron lasers (XFELs) [2]. However, there is still a lack of systematic analysis on the parametric scaling of field emission from coated surfaces and comprehensive understanding of the interplay of various parameters to optimize the design of coated field emitters.

In this study, we develop a quantum analytical solution for field emission from the dielectric coated cathode surface (Fig. 1), by solving the one-dimensional (1D) Schrödinger equation subject to the double barrier introduced by the coating layer [1]. The solution is applicable for arbitrary electric dc field, cathode properties (i.e., work function and Fermi level), and dielectric coating properties (i.e., dielectric constant, electron affinity, and thickness). It includes not only field emission but also thermionic emission, and can be further extended to include photoemission. The model predicts that for 1D flat surfaces, coatings of small dielectric constant and large electron affinity tend to enhance the field emission current. The enhancement can be even stronger for higher dimensional sharp emitters.

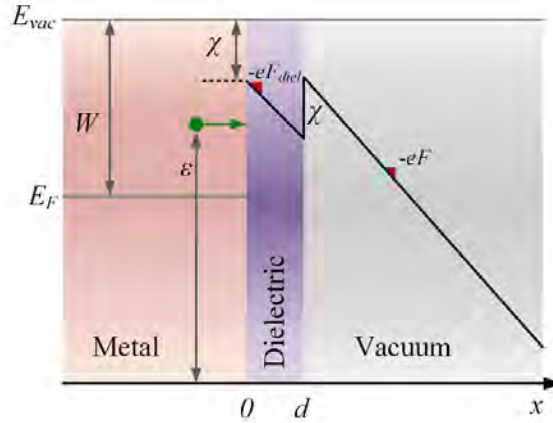


Figure 1 Field emission from a metal surface coated with a dielectric. The metal-dielectric interface is located at $x = 0$, and the coating's thickness is d . The metal has Fermi level E_F and work function W . The dielectric has electron affinity of χ and dielectric constant of ϵ_{diel} . The electron initial longitudinal energy is ϵ . The external dc field of F (in the vacuum) is applied to the emitter surface. The field in the dielectric is $F_{diel} = F/\epsilon_{diel}$.

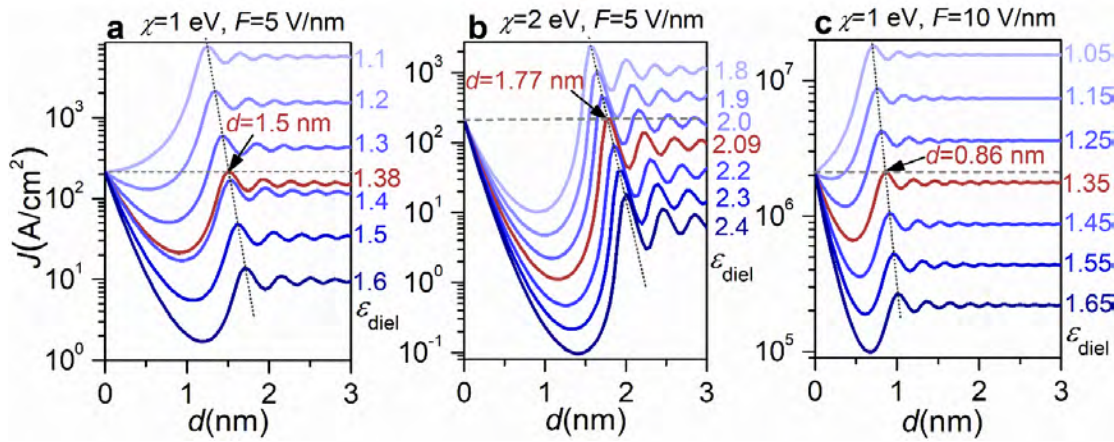


Figure 2. Emission current density as a function of dielectric thickness d under various dielectric constants ϵ_{diel} for (a) $\chi = 1$ eV and $F = 5$ V/nm; (b) $\chi = 2$ eV and $F = 5$ V/nm; and (c) $\chi = 1$ eV and $F = 10$ V/nm. The metal is assumed to be gold, with work function $W = 5.1$ eV and Fermi energy $E_F = 5.53$ eV.

Figure 2 shows the emission current density J as a function of dielectric thickness d for various dielectric constant ϵ_{diel} , electron affinity χ , and dc field F . These results can be used to determine the threshold values of dielectric thickness d_{th} and dielectric constant ϵ_{diel}^{th} , at which the emission current density J is equal to that from the bare metal, for a given dielectric electron affinity χ and dc electric field F . For example, when $\chi = 1$ eV and $F = 5$ V/nm, the thresholds are found to be $d_{th} = 1.5$ nm and $\epsilon_{diel}^{th} = 1.38$, as shown in Fig. 2(a). A dielectric constant smaller than ϵ_{diel}^{th} would enhance the electron emission compared to the uncoated case, with thicknesses corresponding to the curves above the horizontal dash line. More results are shown in Fig. 2(b)-(c).

It is found all the three cases in Fig. 2 roughly follow the empirical relation below at room temperature,

$$d_{th}[\text{nm}] = \frac{\varepsilon_{diel}^{th} W}{eF}, \quad (1)$$

whose physical origin is due to the change in the potential barrier profiles at this condition.

The work is published in Physical Review Research [1]. Our study provides insights for designing field emitters with higher efficiency and better stability using dielectric coatings.

FEW-CYCLE OPTICAL-FIELD-INDUCED PHOTOEMISSION FROM BIASED SURFACES: AN EXACT QUANTUM THEORY

We have investigated few-cycle optical-field-induced photoemission from biased surfaces, which is investigated using an exact quantum theory [3]. Our exact theory for photoemission due to pulsed lasers is based on the analytical solution of time-dependent Schrödinger equation (TDSE), which is valid for arbitrary pulse length from sub-cycle to CW excitation. Our solution is valid from the photon-driven regime to the optical-field-driven regime, and is applicable for arbitrary laser parameters (i.e., intensity, pulse duration, carrier frequency, and carrier envelope phase (CEP)), dc bias, and metal properties (i.e., work function and Fermi level). The model is also applicable to a train of laser pulses with arbitrary pulse repetition rate.

Photoelectron emission from metallic nanostructures due to ultrafast laser fields enables the spatiotemporal control of electron motion within femtosecond and nanometer scales, making it attractive to fundamental research and applications in high power electromagnetic sources and amplifiers, ultrafast electron microscopy, diffraction, attosecond electronics, strong-field nano-optics, and nanoscale vacuum devices. The photoemission process has been extensively studied, including multiphoton emission, optical-field emission, photo-assisted tunneling emission, carrier-envelope phase (CEP) sensitivity, and modulation effect of two-color lasers. A variety of models have been developed to understand the underlying emission mechanisms, such as perturbative theory, Floquet models, Fowler-Nordheim tunneling approximation [4], and directly solving the TDSE. While there have been recent efforts to develop analytical quantum models for continuous-wave laser excitation, numerical simulations are typically implemented to study photoemission due to ultrashort pulse lasers. Fowler-Nordheim based models are widely used to calculate the photoemission rate, but it is only applicable in the strong optical-field regime. To explicitly reveal the interplay of various emission processes under different regimes and to systematically characterize the parametric scalings of photoemission characteristics, an exact quantum model under ultrashort pulsed condition is highly desirable.

Our one-dimensional model considers electrons with the initial energy ε emitted from the metal-vacuum interface at $x = 0$ under a dc electric field F_0 and an optical electric field (Fig.3) of a Gaussian laser pulse train with a time period $T = 2L$ of the form,

$$F(t) = F_1 e^{-t^2/\sigma^2} \cos(\omega t + \phi), \quad (2l - 1)L < t \leq (2l + 1)L, \text{ with } l = 0, \pm 1, \pm 2, \dots, \quad (2)$$

where F_1 is the peak of optical field strength, $\sigma = \tau_p/(2\sqrt{\ln 2}) \cong \tau_p/1.665$ with τ_p being the full width at half maximum (FWHM) of the field envelope, ω is the angular frequency of the carrier

wave, and ϕ is the CEP. All the laser pulses are CEP stabilized with $\omega = m\pi/L = m\omega_E$, with m being a positive integer and ω_E the pulse repetition frequency. When $L/\tau_p \gg 1$, the temporal interaction between consecutive laser pulses becomes negligible and $F(t)$ can be used to study photoemission due to a single laser pulse. By taking the Fourier series, the laser field in Eq. (2) can be expressed as,

$$F(t) = F_1 a_0 \cos \phi + \sum_{\substack{n=-\infty \\ n \neq 0}}^{+\infty} F_1 a_n \cos(n\omega_E t + \phi) \quad (3)$$

where $a_0 = \frac{1}{L} \int_0^L e^{-t^2/\sigma^2} \cos(m\omega_E t) dt$, and $a_n = \frac{1}{L} \int_0^L e^{-t^2/\sigma^2} \cos[(n-m)\omega_E t] dt$. From Eq. (3), it is clear that the incident laser pulse train is a superposition of sine waves with frequencies separated by ω_E . We assume the laser electric field is spatially uniform and perpendicular to the metal surface; thus the time-dependent potential barrier near the metal-vacuum interface is,

$$\Phi(x, t) = \begin{cases} 0, & x < 0 \\ E_F + W_{eff} - eF_0 x - eF(t)x, & x \geq 0, \end{cases} \quad (4)$$

where E_F is the Fermi energy of the metal cathode, $W_{eff} = W - 2\sqrt{e^3 F_0 / 16\pi\epsilon_0}$ is the effective work function with Schottky effect, with W being the nominal work function, e is the elementary charge, ϵ_0 is the free space permittivity, and $F(t)$ is given by Eq. (3). Equation (4) is inserted into TDSE to derive the solution for the electron wave function.

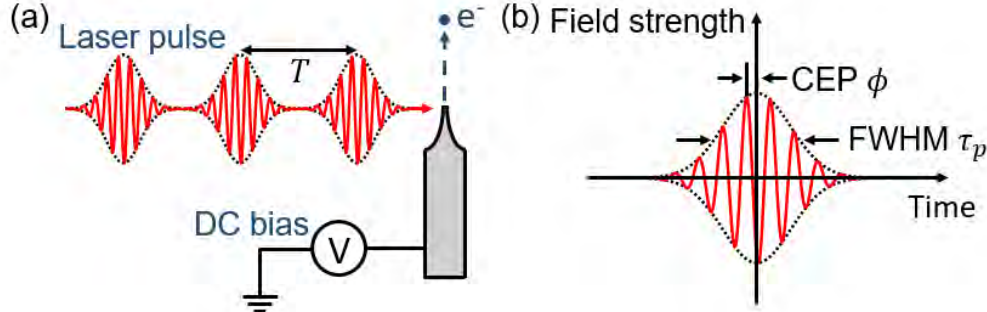


Figure 3. (a) Sketch of photoelectron emission from a biased emitter under the illumination of a laser pulse train with a time period T . (b) A single laser pulse with carrier-envelope phase (CEP) ϕ and full width at half maximum (FWHM) of the field envelope τ_p . The red curve and black dotted lines denote the time evolution of laser electric field and laser pulse envelope, respectively.

In Fig. 4, we plot the normalized total time-dependent photoemission current density $w(\bar{x}, t)$, including oscillatory surface currents, as a function of the space $\bar{x}$ and time t under different dc bias. It is found that increasing the dc field from $F_0 = 1 \times 10^4$ V/m to 1×10^9 V/m increases the time-averaged emission current density from $\langle w \rangle = 2.5 \times 10^{-11}$ to 2.1×10^{-7} . More importantly, the emission current pulse is significantly shortened (from 19.7 fs to 4.8 fs of FWHM at $\bar{x} = 50$). This may provide a practical way to shorten the photoemission current pulse by simply adding a large dc bias.

We also find the emitted charge per pulse oscillatorily increases with pulse repetition rate, due to varying coherent interaction of neighboring laser pulses. For a well-separated single pulse, our results recover the experimentally observed vanishing carrier-envelope phase sensitivity in the optical-field regime. Furthermore, we also find that applying a large dc field to the photoemitter is able to greatly enhance the photoemission current and in the meantime substantially shorten the current pulse.

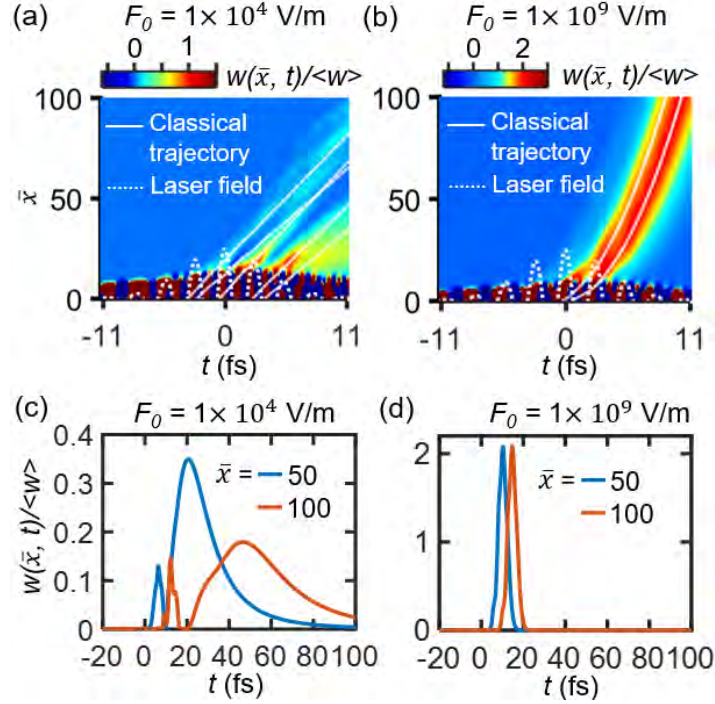


Figure 4. Total time-dependent emission current density $w(\bar{x}, t)$ under the dc field $F_0 = 1 \times 10^4$ V/m and 1×10^9 V/m. (a),(b) $w(\bar{x}, t)$ including surface oscillation currents as a function of the space $\bar{x}$ and time t . Solid white lines show the corresponding classical trajectories. Dotted white lines show the positive half cycles of the laser electric field. (c),(d) Emission current density $w(t)$ at $\bar{x} = 50$ and 100, as a function of time t . The time-dependent current in all figures is normalized in terms of the time-averaged emission current $\langle w \rangle$. Here, the laser pulse duration $\tau_p = 8.8$ fs and the peak laser field $F_1 = 1$ V/nm. When $F_0 = 1 \times 10^4$ V/m, $\langle w \rangle = 2.5 \times 10^{-11}$; When $F_0 = 1 \times 10^9$ V/m, $\langle w \rangle = 2.1 \times 10^{-7}$.

Our results are published in Physical Review B [3]. Our theory provides a general tool to model pulsed laser induced electron emission and offers insights into the control of electron bunching emission using lasers, which are important to high power electromagnetic waves applications.

SPACE-CHARGE LIMITED CURRENT IN NANODIODES: BALLISTIC, COLLISIONAL, AND DYNAMICAL EFFECTS

We have published an invited perspective article in Journal of Applied Physics on space charge effects in nanodiodes [5]. This paper is in collaboration with Prof. Allen Garner (Purdue), Dr. John Luginsland (Confluent Sciences), Profs. Ricky Ang and Y. S. Ang (Singapore), and Prof. Agust Valfells (Iceland).

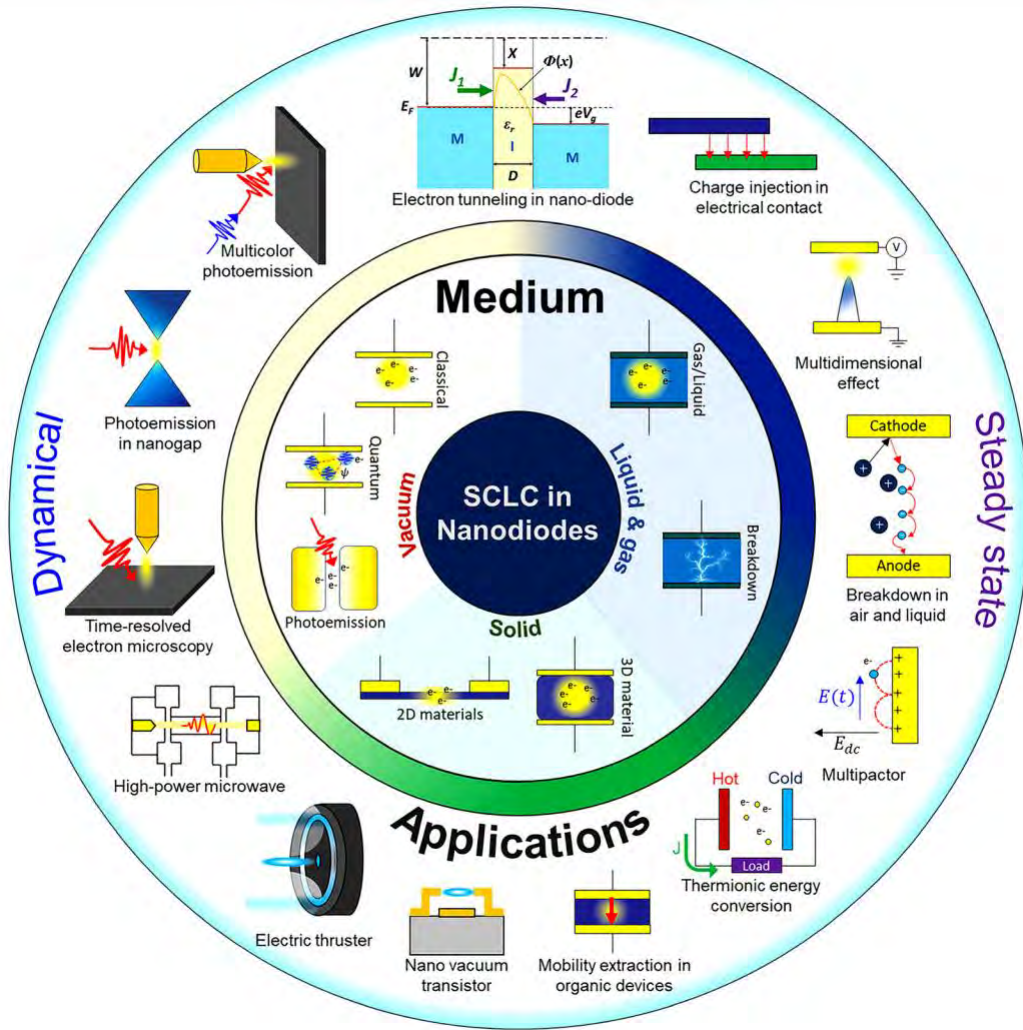


Figure 5. Schematic overview of space charge limited current (SCLC) in various media, steady-state and dynamical regimes, and several representative applications. SCLC occurs in vacuum, gas, liquid, and solid diodes. SCLC underlies the operations of a large variety of applications, including material characterizations, probing fundamental light-matter interactions, microwave generation, vacuum nanoelectronics, high-power microwave generation, energy conversion, and space technology.

This perspective reviews the fundamental physics of space-charge interactions that are important in various media: vacuum gap, air gap, liquids, and solids including quantum materials. It outlines the critical and recent developments since a previous review paper on diode physics [Zhang et al. Appl. Phys. Rev. 4, 011304 (2017)] with particular emphasis on various theoretical aspects of the space-charge limited current (SCLC) model: physics at the nano-scale, time-dependent, and transient behaviors; higher-dimensional models; and transitions between electron emission mechanisms and material properties. While many studies focus on steady-state SCLC, the increasing importance of fast-rise time electric pulses, high frequency microwave and terahertz sources, and ultrafast lasers has motivated theoretical investigations in time-dependent SCLC. We

particularly focus on recent studies in discrete particle effects, temporal phenomena, time-dependent photoemission to SCLC, and AC beam loading. Due to the reduction in the physical size and complicated geometries, we report recent studies in multi-dimensional SCLC, including finite particle effects, protrusive SCLC, novel techniques for exotic geometries, and fractional models. Due to the importance of using SCLC models in determining the mobility of organic materials, this paper shows the transition of the SCLC model between classical bulk solids and recent two-dimensional (2D) Dirac materials. Next, we describe some selected applications of SCLC in nanodiodes, including nanoscale vacuum-channel transistors, microplasma transistors, thermionic energy converters, and multipactor. Finally, we conclude by highlighting future directions in theoretical modeling and applications of SCLC.

Figure 5 illustrates the scope of this Perspective paper: the SCLC in various media and surrounding structures, the manifestation of SCLC in various dynamical and steady-state conditions, and some representative applications of SCLC. SCLC occurs in a broad spectrum of media, covering nearly all states of matter, including vacuum, gas, plasma, liquid, solids in both crystalline and amorphous states, and 2D layered nanomaterials. In both steady-state and dynamical regimes, SCLC has played a pivotal role in governing the operations of a large variety of applications and devices, ranging from vacuum nanoelectronics, space application, material characterizations, high-power microwave generations, fundamental physics of light-matter interactions, thermionic energy converters (TECs), and many others. These discussions should also provide insights into other applications such as coherent radiation sources, non-neutral charged particle beams, accelerators, and electric propulsion, where space-charge effects on the electron beam are critical.

QUANTUM EFFICIENCY OF PHOTOEMISSION FROM BIASED METAL SURFACES WITH LASER WAVELENGTHS FROM UV TO NIR

We have published a Journal of Applied Physics paper titled “Quantum efficiency of photoemission from biased metal surfaces with laser wavelengths from UV to NIR”. The paper is selected as a Featured article [6], and is highlighted in Scilight [7], and reported by Phys.org [8] and MSUToday [9].

This project studies photoelectron emission from metal surfaces with laser wavelengths from 200 to 1200 nm (i.e., ultraviolet to near-infrared), using a recent quantum model based on the exact solution of time-dependent Schrödinger equation. The dominant electron emission mechanism varies from different multiphoton emission processes to dc or optical field emission, depending on the laser intensity, wavelength, and dc bias field. The parametric dependence of the quantum efficiency (QE) is analyzed in detail. It is found that QE can be increased nonlinearly by the non-equilibrium electron heating produced by sub-picosecond laser pulses. This increase of QE due to laser heating is the strongest near laser wavelengths where the cathode work function is an integer multiple of the corresponding laser photon energy. The quantum model, with laser heating effects included, reproduces previous experimental results, which further validates our quantum model and the importance of laser heating.

Figure 6 shows a comparison of photoemission with laser heating effects (red curves) and without laser heating effects (blue curves, with $T = T_e \equiv 300\text{K}$). The peak laser field strength is taken to be 1 V/nm. The electron emission current density per electron initial energy, $J(\epsilon)$, extends to energy levels above the Fermi level as the laser heating effect is considered, as shown in Fig. 6(a) for $\lambda =$

200 nm, 600 nm, and 1000 nm. This is because more electrons are excited to energy levels above the Fermi level by absorbing the laser energy. The electron emission from initial energy levels above the Fermi energy accounts for 7.84%, 6.85%, and 91.1% of the total emission for $\lambda = 200$ nm, 600 nm, and 1000 nm, respectively, with laser heating effects, compared to 0.13%, 0.015%, and 0.73% without laser heating. Figure 6(b) shows the emission current density as a function of the laser wavelength. The quantum efficiency as a function of laser wavelength is shown in Fig. 6(c), showing the same trend as J vs. λ in Fig. 6(b). In summary, the increase of QE due to laser heating is the strongest near the step points (i.e. ratio of work function over photon energy $W_0/\hbar\omega = \text{integer}$) and is more profound for longer laser wavelengths.

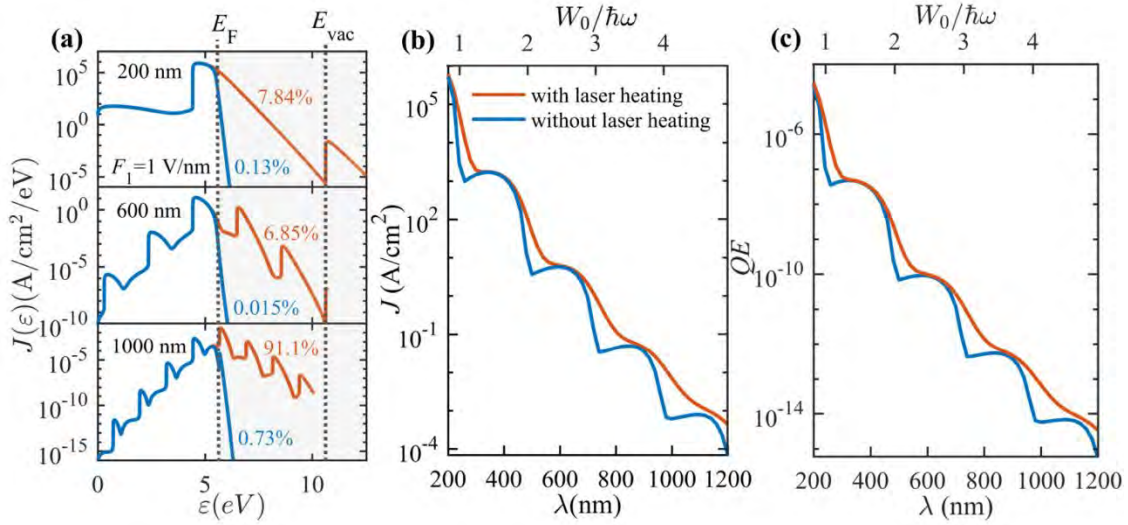


Figure 6. Laser heating effects on photoemission. (a) Electron emission current density per electron initial energy for $\lambda = 200$ nm, 600 nm, and 1000 nm, with laser field $F_1 = 1$ V/nm and dc field $F_0 = 0$; (b) Electron emission current density and (c) QE as a function of laser wavelength for $F_1 = 1$ V/nm and zero dc field $F_0 = 0$.

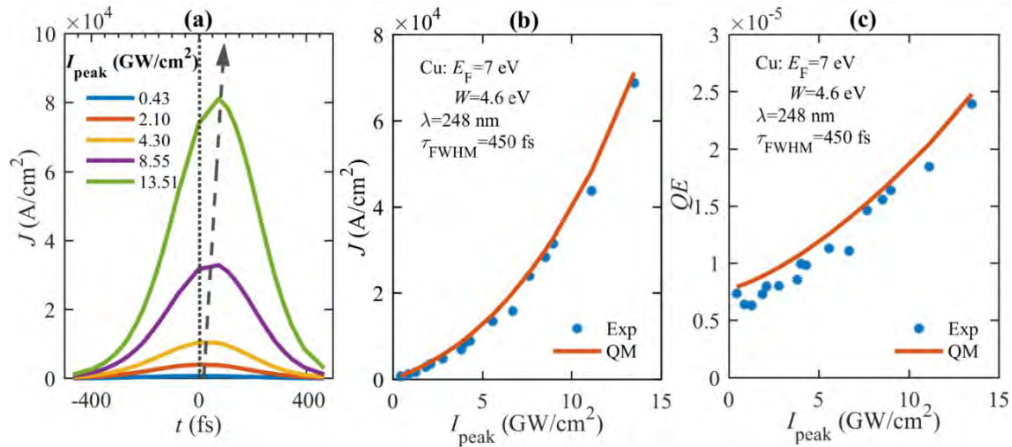


Figure 7. Comparison with experimental results. (a) Calculated emission current density temporal profile for various laser intensities used in the experiment [10]. (b) Emission current density as a function of the

peak laser intensity. Scatters are experimental data extracted from [10]. The red curve is calculated by our quantum model. (c) Quantum efficiency as a function of the peak laser intensity.

We demonstrate the validity of the above quantum model with laser heating, by comparing it with experimental results in Ref. [10]. In the experiment, a laser pulse of 450 fs duration at 248 nm is used. The metal is copper, with Fermi energy $E_F = 7$ eV and work function $W_0 = 4.6$ eV. The temporal profile of the emission current density is shown in Fig. 7(a). As the laser intensity increases, the emission current density increases, and the current density peak lags behind the laser intensity peak. This is due to the delay between the temperature peak and the laser intensity peak. The calculated current density by the quantum model is shown as red curve in Fig. 7(b), which is in good agreement with the experimental measured current density shown as blue scatter points. The quantum efficiency is plotted in Fig. 7(c). It is clear that QE increases with the laser intensity instead of being constant (as predicted in Einstein's photoelectric effect), which is ascribed to the laser heating induced electron redistribution.

- [1] Y. Zhou, and P. Zhang, "Theory of field emission from dielectric coated surfaces", Phys. Rev. Research 2, 043439 (2020).
- [2] K. L. Jensen, D. Finkenstadt, A. Shabaev, S. G. Lambrakos, N. A. Moody, J. J. Petillo, H. Yamaguchi, and F. Liu, A photoemission moments model using density functional and transfer matrix methods applied to coating layers on surfaces: Theory, J. Appl. Phys. 123, 045301 (2018).
- [3] Y. Luo, Y. Zhou, and P. Zhang, "Few-cycle optical-field-induced photoemission from biased surfaces: An exact quantum theory", Phys. Rev. B 103, 085410 (2021).
- [4] K. L. Jensen, Introduction to the Physics of Electron Emission, 1st ed. (Wiley, Hoboken, NJ, 2017).
- [5] P. Zhang, Y. S. Ang, A. L. Garner, A. Valfells, J. W. Luginsland, and L. K. Ang, "Space-charge limited current in nanodiodes: Ballistic, collisional, and dynamical effects", J. Appl. Phys. 129, 100902 (2021). **[Invited Perspective Article] [Featured Article]**
- [6] Y. Zhou and P. Zhang, "Quantum efficiency of photoemission from biased metal surfaces with laser wavelengths from UV to NIR", J. Appl. Phys. 130, 064902 (2021). **[Featured Article][Scilight][News Reports at MSUToday, Phys.org]**
- [7] AIP Scilight. 2021, 331106 -1; <https://doi.org/10.1063/10.0005951>
- [8] <https://phys.org/news/2021-09-photoelectric-efficiency.html>
- [9] <https://msutoday.msu.edu/news/2021/enhancing-photoelectric-efficiency>
- [10] N. A. Papadogiannis, S. D. Moustazis, and J. P. Girardeau-Montaut, "Electron relaxation phenomena on a copper surface via nonlinear ultrashort singlephoton photoelectric emission," J. Phys. D: Appl. Phys. 30, 2389 (1997).

3. Findings and Conclusions

We explored the enhancement of field emission current from cathodes with thin dielectric coating. It is found that coatings of small dielectric constant and large electron affinity tend to greatly enhance the field emission current. We developed an exact time-dependent quantum theory for pulsed laser induced photoemission. We found that applying a large dc field to the photoemitter is able to greatly enhance the photoemission current and substantially shorten the current pulse. We systematically investigated the quantum efficiency (QE) of photoelectron emission from metal surfaces with laser wavelengths from 200 to 1200 nm (i.e., ultraviolet to near-infrared). It is found that QE can be increased nonlinearly by the non-equilibrium electron heating produced by sub-

picosecond laser pulses. We have also reviewed the contemporary physics on space-charge limited current in nanodiodes, which is critical to the development of high power electromagnetic sources and amplifiers.

4. Plans and Upcoming Events

We will apply our electron emission models to evaluate the time-dependent current modulation of electron emission from cathodes, which is important to the generation of short electron bunches for HPM excitation. We will further explore the method of increasing electron emission current using quantum resonance and quantum interference. These studies will pave the way to achieve efficient density modulation of the electron beam immediately after emission. The optically modulated current from cathodes will be incorporated into the interaction with a slow wave structure to examine the RF outputs and determine the frequency optimums. We plan to develop new theory for beam-circuit interaction for density modulated beams using optical means. We will further explore the space charge effects in Pierce theory and identify the small q quantity for a realistic TWT. We also plan to run CST and XOOPIC simulations to test the beam-circuit theory and provide guidance to the source and circuit design of amplifiers and oscillators.

5. Transitions and Impacts

Not Applicable.

6. Collaborations

John Luginsland, Confluent Sciences/AFOSR.

Matt Franz, Air Force Research Laboratory.

Steve Fairchild, Air Force Research Laboratory.

Ricky Ang, international collaborator, Singapore University of Technology and Design, Singapore.

Yee Sin Ang, international collaborator, Singapore University of Technology and Design, Singapore.

Lin Wu, international collaborator, Institute of High Performance Computing, Singapore.

Y. Y. Lau, University of Michigan.

John Verboncoeur, Michigan State University.

Allen Garner, Purdue University.

Rehan Kapadia, University of Southern California.

Chengkun Huang, Los Alamos National Labs.

Sneha Banerjee, Sandia National Labs.

7. Personnel

Principal Investigator: Peng Zhang, 1 person-month, National Academy Member (N).

Teams Members:

Patrick Wong, Postdoc, 3 person-months, National Academy Member (N).

Yi Luo, graduate student, 3 person-months, National Academy Member (N).

Yang Zhou, graduate student, 12 person-months, National Academy Member (N).

Business Contact: Casie Medina

Subs: None

8. Students

Two graduate students assisting during reporting period.

9. Technology Transfer

We have filed a US Provisional Patent on the enhancement of photoelectron emission using thin dielectric coating: P. Zhang, L. Wu, X. Xiong, and Y. Zhou, “Thin Dielectric Coated Plasmonic Photoemitter”, US Patent Provisional, filed on 5/20/2021.

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project during the performance period of 10/1/2020-9/30/2021:

Archival Publications

1. Y. Zhou, and Peng Zhang, "Theory of field emission from dielectric coated surfaces", Phys. Rev. Research 2, 043439 (2020). Peer-reviewed, Distribution A, Federal Funding Acknowledged. <https://doi.org/10.1103/PhysRevResearch.2.043439>
2. Y. Luo, Y. Zhou, and Peng Zhang, "Few-cycle optical-field-induced photoemission from biased surfaces: An exact quantum theory", Phys. Rev. B 103, 085410 (2021). Peer-reviewed, Distribution A, Federal Funding Not Acknowledged. <https://doi.org/10.1103/PhysRevB.103.085410>
3. Peng Zhang, Y. S. Ang, A. L. Garner, A. Valfells, J. W. Luginsland, and L. K. Ang, "Space-charge limited current in nanodiodes: Ballistic, collisional, and dynamical effects", J. Appl. Phys. 129, 100902 (2021). **[Featured Article]** Peer-reviewed, Distribution A, Federal Funding Acknowledged. <https://doi.org/10.1063/5.0042355>
4. Y. Zhou and Peng Zhang, "Quantum efficiency of photoemission from biased metal surfaces with laser wavelengths from UV to NIR", J. Appl. Phys. 130, 064902 (2021). **[Featured Article][Scilight][News Reports at MSUToday, Phys.org]** Peer-reviewed, Distribution A, Federal Funding Acknowledged. <https://doi.org/10.1063/5.0059497>

Conference Papers

1. Peng Zhang, Y. Luo, Y. Zhou, “Exact Analytical Solution for Pulsed Laser Induced Photoemission from Biased Surfaces”, The 48th IEEE International Conference on Plasma Science (ICOPS), Sep 12-16, 2021, Virtual, USA. **[Invited Talk]** Federal Funding Acknowledged.
2. Peng Zhang, Y. Luo, and Y. Zhou, “A general quantum model for thermionic-field-photoelectron emission”, PIC-NIC Virtual Workshop, October 20 - 21, 2020, Sandia National Laboratories, Albuquerque, NM, USA. **[Invited Talk]** Federal Funding Acknowledged.
3. Y. Zhou, and Peng Zhang, “An exact quantum theory for photoemission from dielectric coated metal surfaces under a dc bias”, The 48th IEEE International Conference on Plasma Science (ICOPS), Sep 12-16, 2021, Virtual, USA. **[Oral]** Federal Funding Acknowledged.

4. Y. Zhou and Peng Zhang, “Field emission from dielectric coated metallic cathode surfaces: a theoretical study”, 22nd International Vacuum Electronic Conference (IVEC 2021), (April 28-30, 2021, Virtual) [Oral] Federal Funding Acknowledged.
5. Y. Zhou, X. Xiong, Y. Luo, L. K. Ang, L. Wu, and Peng Zhang, “Plasmon-Enhanced Resonant Photoemission from Metal Surfaces Coated with Ultrathin Dielectric”, 22nd International Vacuum Electronic Conference (IVEC 2021), (April 28-30, 2021, Virtual) [Poster] Federal Funding Acknowledged.
6. Y. Luo and Peng Zhang, “Exact Analytical Theory for Pulsed Laser Induced Photoelectron Emission from Biased Surfaces”, 22nd International Vacuum Electronic Conference (IVEC 2021), (April 28-30, 2021, Virtual) [Oral] Federal Funding Acknowledged.
7. Peng Zhang, Y. Zhou, and Y. Luo, “Theoretical study of field emission from dielectric coated surfaces”, 9th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2021), (7-12 March 2021, Virtual) [Oral] Federal Funding Acknowledged.
8. Y. Zhou and Peng Zhang, “Theoretical Study of Field Emission from Dielectric Coated Surfaces”, The Joint Conference on the 8th International Conference on Microelectronics and Plasma Technology (ICMAP) and the 9th International Symposium on Functional Materials (ISFM), (January 17-20, 2021, Virtual, Korea) [Oral] Federal Funding Acknowledged.
9. Y. Luo and Peng Zhang, “Analytical Solution for Pulsed Laser Induced Photoemission from Biased Surfaces”, The Joint Conference on the 8th International Conference on Microelectronics and Plasma Technology (ICMAP) and the 9th International Symposium on Functional Materials (ISFM), (January 17-20, 2021, Virtual, Korea) [Oral] Federal Funding Acknowledged.
10. Peng Zhang, “A general quantum model for thermionic-field-photoelectron emission”, Defense TechConnect Virtual Innovation Summit (November 17-19, 2020, Virtual, USA) [Poster] Federal Funding Acknowledged.
11. Y. Zhou, Y. Luo, and Peng Zhang, “FT2.00006 : Quantum Efficiency of Photoelectron Emission from Metal Surfaces with Laser Wavelengths from UV to NIR”, 73rd Annual Gaseous Electronics Virtual Conference (October 5–9, 2020, USA). [Oral] Federal Funding Acknowledged.

Theses

1. Y. Luo, “Theoretical modeling of ultrafast optical-field induced Photoelectron emission from biased metal surfaces”, Ph.D. dissertation, Dept. Elect. Comput. Eng., Michigan State Univ., East Lansing, MI, USA, 2021. Federal Funding Acknowledged.

Patents

1. P. Zhang, L. Wu, X. Xiong, and Y. Zhou, “Thin Dielectric Coated Plasmonic Photoemitter”, US Patent Provisional, filed on 5/20/2021.

11. Point of Contact in Navy

Kevin Jensen, NRL, 25AUG2021; Matt Franzi, AFRL, 10SEP2021; Steve Fairchild, AFRL, 8SEP2021; Jason Marshall, NRL, 7JUN2021; Joe Schumer, NRL, 7JUN2021.

12. Acknowledgement/Disclaimer

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Homoepitaxial Ga₂O₃ Structures for Power Device Applications

Grant No. N62909-20-1-2055

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to September 30, 2021

Prepared by:

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Grant or Contract Number: N62909-20-1-2055

Date Prepared: 2/18/2022

Project Title: Homoepitaxial Ga₂O₃ Structures for Power Device Applications

Annual Summary Report: FY21

Principle Investigator: Akito Kuramata, +81-4-2900-0072, kuramata@novelcrystal.co.jp

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Section I: Project Summary

1. Overview of Project

Abstract:

β -Ga₂O₃ is a very attractive semiconducting material for next generation power devices due to its excellent material properties and ease of mass production. Ga₂O₃ has extremely large bandgap of 4.5-4.8 eV and high breakdown electric field strength of about 8 MV/cm, yielding a nearly ten-fold higher Baliga's figure of merit than that of 4H-SiC. Therefore, realization of Ga₂O₃ power devices will bring huge reduction of energy loss for industrial instruments, power plant, or military equipment, etc.

In this project, we will develop the high-quality growth of Ga₂O₃ bulk substrates by using EFG and homoepitaxial thick films by using HVPE, both with large size up to 4-inch in diameter. The Ga₂O₃-based power devices will be optimized for doping scheme, termination structure, etc. to fully take advantage of the material properties. The techniques of wafer bonding onto foreign substrates with higher thermal conductivity and integrating (Al_xGa_{1-x})₂O₃/Ga₂O₃ heterostructures will also be developed as a solution to the heat dissipation issue in Ga₂O₃ devices. By using those techniques, we will be able to demonstrate the ultra-high power Ga₂O₃ diode and transistor of kV-class.

Objective:

Advance the state-of-the-art of ultra-wide bandgap steady-state and pulsed power electronics by developing benchmark device structures based on high quality homoepitaxial Ga₂O₃ on native β -Ga₂O₃ substrates. Demonstrate that high quality, large-area Ga₂O₃ substrates and low-defect density epilayers grown by Novel Crystal Technology are a viable platform for the development of commercial β -Ga₂O₃-based high voltage, high power devices. Demonstrate a vertical Ga₂O₃ power Schottky Barrier Diode (SBD) with breakdown voltage of 5-10 kV while maintaining on resistance R_{on} below 1 m Ω -cm². Building on this technology, demonstrate a vertical Ga₂O₃ power transistor with breakdown voltage limited only by the intrinsic breakdown of the dielectrics in the device.

Introduction:

The single-crystal gallium oxide (Ga₂O₃) is an advantageous material for high-power, high-temperature electronic device applications due to its high energy direct gap (~4.9 eV) and high breakdown field (8 MV/cm), yielding a nearly ten-fold higher Baliga figure of merit than that of 4H-SiC (BFOM_{Ga2O3} = 3444, BFOM_{4H-SiC} = 300). An additional feature of the gallium oxide technology is that commercially available large diameter gallium oxide substrates, grown

inexpensively from the melt, are available with 2-inch diameter with prototype 4-inch diameter substrates having been demonstrated (Figure 1). Additional important feature of the gallium oxide technology is that high quality homoepitaxial growth of gallium oxide epitaxial layers on gallium oxide substrates with growth rates of 8 microns/hour have been demonstrated for hydride vapor phase epitaxial (HVPE) growth. In addition, good N-type doping control has been demonstrated with doping from the range of low 10^{15} cm^{-3} to 10^{19} cm^{-3} (Figure 1). Highly doped N-type regions by ion implantation has also been demonstrated. Thus, the gallium oxide material technology has many of the features needed for low cost, high performance next generation high voltage power switch technology.

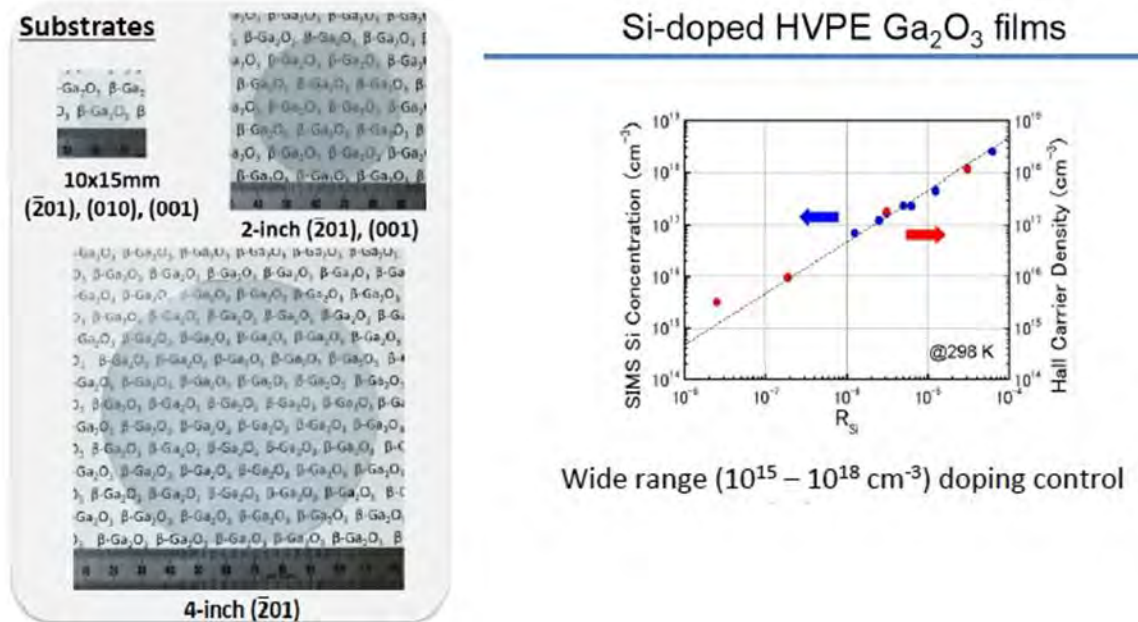


Figure 1. Examples of gallium oxide substrates and N-type doping control.

Background:

Since 2015, NCT/NRL have been a leader in this field with a number of vertical Schottky barrier diode demonstrations. However, only recently has the quality of epitaxy been sufficiently optimized to fully take advantage of the predicted 8 MV/cm critical field of Ga_2O_3 . This program will aim towards extending breakdown voltage beyond the 5 kV milestone using the approaches learned in the first NICOP program, under which a 2.3 kV and 33 A SBDs were demonstrated.

2. Activities and Accomplishments

During the first year, a total of 91 Ga_2O_3 and $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ substrates and epiwafers were provided to NRL as program deliverables. This number includes both custom growths for novel experiments such as $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ critical thickness to commercialized 100 mm Ga_2O_3 epiwafers. In addition, a number of boules of Ga_2O_3 are currently at Novel Crystal technology and are expected to provide additional samples of Ga_2O_3 to NRL in the near future.

We have developed 100-mm β -Ga₂O₃ epitaxial growth system by applying our high-quality 2-inch epitaxial wafer technology. Figure 2 shows a photograph of prototype β -Ga₂O₃ SBDs fabricated on 100-mm β -Ga₂O₃ epitaxial wafers. The epitaxial film is about 10- μ m thick, and the donor concentration is about 2×10^{16} cm⁻³. The yellow circles and squares on the wafer surface are gallium-oxide SBDs with different anode electrode sizes.

Figure 2 shows the current-voltage characteristics of the diode. The measurements of 86 elements on the wafer surface are overlaid on each graph. The theoretical characteristics are drawn with a red dotted line in the graph. The forward characteristics in Fig. 3 (a) show that the current increases linearly from a low threshold voltage of 0.8-0.9 V, and ideal diode characteristics are obtained.

The graph of the reverse characteristics in Fig. 3 (b) shows that 62 of the 86 diodes show characteristics in line with the theoretical ones, and they can be judged as non-defective products. The killer defect density calculated from this non-defective rate is 13 /cm². This means that the 100-mm epitaxial wafer has the same quality as a high-quality 2-inch epitaxial wafer. Accordingly, 10-A β -Ga₂O₃ power devices can be produced on a 100-mm wafer with a yield of 80%.

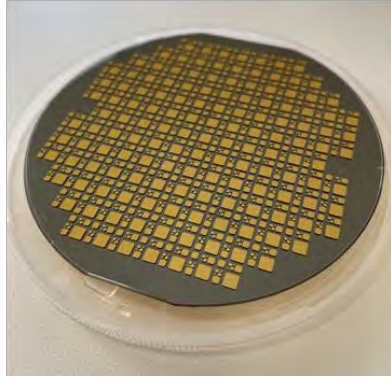


Figure 2. Image of β -Ga₂O₃ Schottky barrier diodes fabricated on 100 mm β -Ga₂O₃ epitaxial wafer.

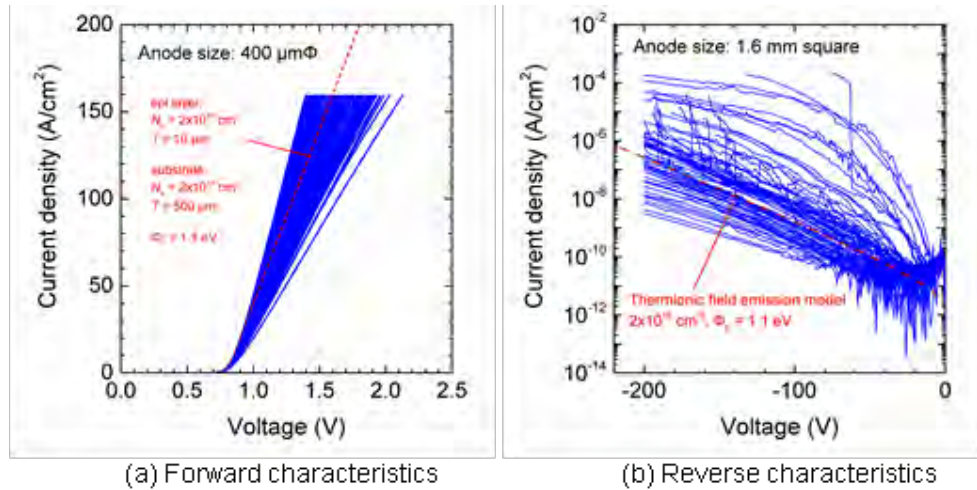


Figure 3. (left) Forward and (right) reverse characteristics of β -Ga₂O₃ Schottky barrier diodes fabricated on 100 mm β -Ga₂O₃ epitaxial wafers.

Our achievement lists of Year 1 are as below.

1. Ga₂O₃ substrates

No.	Specification data							Measured data				
	Dimensions			Surface orientation	Surface finish		Dopant	Donor concentration *2)	Off set angle (deg) *3)		FWHM (arcsec) *3)	
	A—B (mm)	C—D (mm)	Thickness (mm)		Front	Back			Towards (102)	Towards ⊥ (102)	⟨102⟩ azimuth	⊥⟨102⟩ azimuth
ESNB047a_1-7-4	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP *1)	Grinding	Sn	2.5E+18	0.1	0.1	37	31
ESNB047a_1-8-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.4E+18	0.0	0.0	54	33
ESNB047a_1-8-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.6E+18	0.0	0.0	45	35
ESNB047a_1-8-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.3E+18	0.0	0.0	64	31
ESNB047a_1-8-4	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.3E+18	0.0	0.1	35	34
ESNB047a_1-9-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.7E+18	0.1	0.1	53	37
ESNB047a_1-9-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.8E+18	0.1	0.2	62	31
ESNB047a_1-9-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.4E+18	0.1	0.1	56	32
ESNB047a_1-9-4	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.3E+18	0.0	0.2	39	40
ESNB047a_1-10-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	2.7E+18	0.1	0.1	68	28
ESNB047a_1-10-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	4.0E+18	0.5	0.1	100	48
ESNB047a_1-11-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.4E+18	0.5	0.1	100	48
ESNB047a_1-11-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	4.0E+18	0.0	0.0	74	45
ESNB047a_1-12-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.2E+18	0.0	0.2	90	50
ESNB047a_1-12-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.7E+18	0.0	0.1	71	44
ESNB047a_1-12-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.9E+18	0.0	0.1	78	36
ESNB047a_1-12-4	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.3E+18	0.1	0.1	98	47
ESNB047a_1-13-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.2E+18	0.0	0.0	86	33
ESNB047a_1-13-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.9E+18	0.0	0.0	69	31
ESNB047a_1-13-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Sn	3.7E+18	0.0	0.1	95	75
EFEB041a_1-19-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.0	0.0	36	26
EFEB041a_1-20-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.2	0.0	51	31
EFEB041a_1-21-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.1	0.1	41	27
EFEB041a_1-21-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.0	0.1	36	26
EFEB041a_1-21-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.1	0.0	44	26
EFEB041a_1-23-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.0	0.1	42	27
EFEB041a_2-1-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.1	0.0	37	27
EFEB041a_2-2-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.0	0.1	47	28
EFEB041a_2-2-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.0	0.0	40	27
EFEB041a_2-2-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	✓ (010)	CMP	Grinding	Fe	-	0.1	0.0	41	28

No.	Specification data							Measured data				
	Dimensions			Surface orientation	Surface finish		Dopant	Donor concentration *2)	Off set angle (deg) *3)		FWHM (arcsec) *3)	
	A—B (mm)	C—D (mm)	Thickness (mm)		Front	Back			Towards (102)	Towards ⊥ (102)	⟨102⟩ azimuth	⊥ (102) azimuth
EFEB041a_2-3-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP *1)	Grinding	Fe	-	0.0	0.0	48	26
EFEB041a_2-3-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	40	27
EFEB041a_2-4-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.1	0.0	46	27
EFEB041a_2-4-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	35	31
EFEB041a_2-5-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	35	30
EFEB041a_2-5-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	40	26
EFEB041a_2-6-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	51	30
EFEB041a_2-6-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.1	0.1	35	31
EFEB041a_2-6-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	40	31
EFEB041a_2-7-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.1	0.1	53	33
EFEB041a_2-7-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.1	0.1	39	28
EFEB041a_2-8-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	45	27
EFEB041a_2-9-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	45	25
EFEB041a_2-10-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.1	0.0	43	30
EFEB041a_2-11-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	40	32
EFEB041a_2-11-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	37	30
EFEB041a_2-12-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	41	31
EFEB041a_2-12-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	44	33
EFEB041a_2-13-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.1	0.0	37	31
EFEB041a_2-13-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	70	44
EFEB041a_2-14-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	40	34
EFEB041a_2-14-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	67	42
EFEB041a_2-14-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	59	37
EFEB041a_2-15-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	63	37
EFEB041a_2-15-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	75	42
EFEB041a_2-16-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.1	69	39
EFEB041a_2-16-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	82	47
EFEB041a_2-16-3	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	69	41
EFEB041a_2-17-1	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	..	Grinding	Fe	-	0.0	0.1	61	37
EFEB041a_2-17-2	15.0 ±0.3	10.0 ±0.3	0.50 ±0.02	(010)	CMP	Grinding	Fe	-	0.0	0.0	73	40

Items	Dimensions			Surface orientation	Surface finish		Dopant	Inspection Results
	A—B (mm)	C—D (mm)	Thickness (mm)		Front	Back		
Spec. Substrate No.	-	-	-	(100)	Cleavage	Cleavage	Fe	
EFEA35b_1-2	19	10	0.53	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-3	19	10	0.50	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-4	21	10	0.44	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-5	21	10	0.41	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-6	21	10	0.56	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-7	21	10	0.44	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-8	21	10	0.42	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-9	21	10	0.51	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-10	21	10	0.46	(100)	Cleavage	Cleavage	Fe	good
EFEA35b_1-11	21	10	0.50	(100)	Cleavage	Cleavage	Fe	good

Items	Dimensions				Surface orientation	Surface finish		Dopant	$N_p \cdot N_a$ (cm ⁻²) ⁽²⁾	Offset angle (degree) ⁽³⁾		FWHM (arcsec) ⁽³⁾		Inspection Results
	Diameter (mm)	OF (mm)	IF (mm)	Thickness (mm)		Front	Back			Toward [100]	Toward [010]	[100] azimuth	[010] azimuth	
Spec. Substrate No.	50,8 ±0,3	15,9 ±2,5	8,0 ±2,5	Average: 0,65 ±0,02	(001)	CMP ⁽¹⁾	CMP	Sn	Average: 1×10 ¹⁸ ~2×10 ¹⁹	0±1	0±1	350 or less	350 or less	
N01852	50,8	16,2	8,2	0,65	(001)	CMP	CMP	Sn	3,8×10 ¹⁸	0,0	0,0	21	21	good
N01854	50,9	16,2	8,3	0,65	(001)	CMP	CMP	Sn	4,7×10 ¹⁸	0,0	0,0	21	21	good

Items	Dimensions				Surface orientation	Surface finish		Dopant	$N_p \cdot N_a$ (cm ⁻²) ⁽²⁾	Offset angle (degree) ⁽³⁾		FWHM (arcsec) ⁽³⁾		Inspection Results
	Diameter (mm)	OF (mm)	IF (mm)	Thickness (mm)		Front	Back			Toward [100]	Toward [010]	[100] azimuth	[010] azimuth	
Spec. Substrate No.	50,8 ±0,3	15,9 ±2,5	8,0 ±2,5	Average: 0,65 ±0,02	(001)	CMP ⁽¹⁾	CMP	Sn	Average: 1×10 ¹⁸ ~2×10 ¹⁹	0±1	0±1	350 or less	350 or less	
N02255	50,9	15,9	8,0	0,65	(001)	CMP	CMP	Sn	5,5×10 ¹⁸	0,0	-0,2	23	22	good
N02257	50,9	15,9	8,0	0,65	(001)	CMP	CMP	Sn	5,0×10 ¹⁸	0,0	-0,2	23	23	good
N02258	50,9	15,9	8,0	0,65	(001)	CMP	CMP	Sn	4,9×10 ¹⁸	0,0	-0,2	23	24	good
N02259	50,8	15,9	8,0	0,66	(001)	CMP	CMP	Sn	9,0×10 ¹⁸	0,0	-0,2	23	22	good

2. Ga₂O₃ epitaxial wafers grown by molecular beam epitaxy

We have performed O₃-MBE growth of β -(Al_xGa_{1-x})₂O₃ on (010) and (100) β -Ga₂O₃ simultaneously in order to evaluate critical thickness limits for β -(Al_xGa_{1-x})₂O₃ as a function of substrate orientation, Al mole fraction (5-20% Al), and β -(Al_xGa_{1-x})₂O₃ film thickness (50-400 nm). Above a certain thickness, epitaxial AlGaO suffered from cracks whose density increased as the AlGaO film grew thicker. Films grown on (010) Ga₂O₃ exhibited cracking at much lower thickness than films grown on (100) Ga₂O₃. This observation is consistent with the Griffith criterion in order to provide a critical thickness h_c lower bound for β -(Al_xGa_{1-x})₂O₃/Ga₂O₃ based on crystal fracture strength Γ , elastic constants C_{xy} , and strain components ϵ .

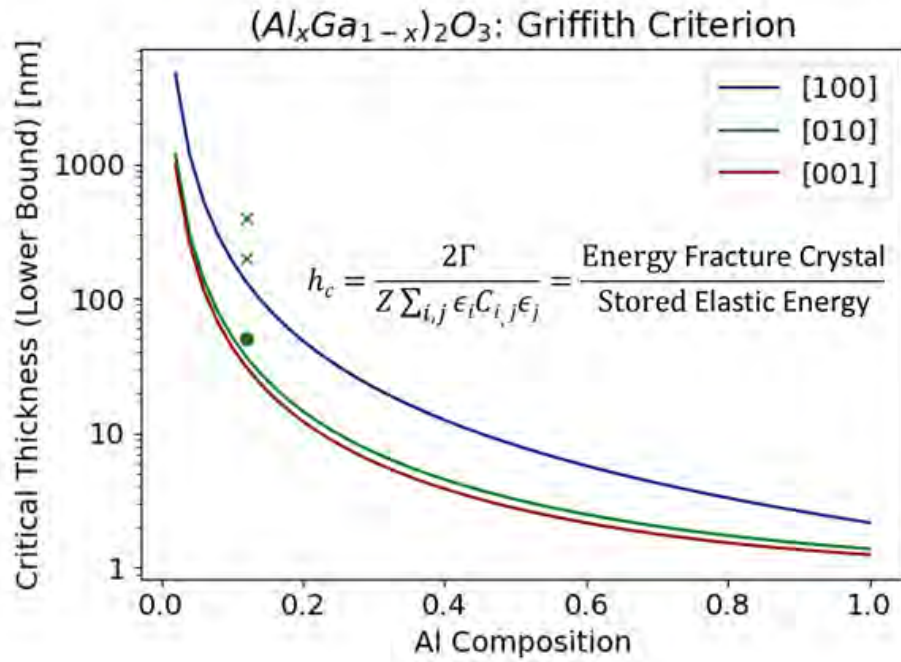


Figure 4. Critical thickness of epitaxial (Al_xGa_{1-x})₂O₃ as a function of Al composition and substrate orientation estimated using the Griffith criterion. Data points show samples of (Al_xGa_{1-x})₂O₃ without (circle) and with (X-symbols) cracks observed on the (010) sample.

Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	400	~20%	-			
M2562L	UID	~400	-	unmeasured	EFEA14-2 B1-01		Good
M2562R	UID	~400	-	unmeasured	EFEB048b 1-2-1		Good
Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	200	~20%	-			
M2563L	UID	~200	-	unmeasured	EFEA14-2 B1-02		Good
M2563R	UID	~200	-	unmeasured	EFEB048b 1-2-2		Good
Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	50	~20%	-			
M2564L	UID	~50	-	unmeasured	EFEA14-2 B1-03		Good
M2564R	UID	~50	-	unmeasured	EFEB048b 1-2-3		Good
Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	200	~5%	-			
M2625L	UID	~200	-	unmeasured	EFEA14-2 B1-04		Good
M2625R	UID	~200	-	unmeasured	EFEB049a 2-16-2		Good
Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	100	~5%	-			
M2626L	UID	~100	-	unmeasured	EFEA14-2 B1-06		Good
M2626R	UID	~100	-	unmeasured	EFEB049a 2-17-1		Good
Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	50	~5%	-			
M2627L	UID	~50	-	unmeasured	EFEA14-2 B1-05		Good
M2627R	UID	~50	-	unmeasured	EFEB049a 2-17-2		Good

Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	200	~20%	-			
M2629L	UID	~200	-	unmeasured	EFEA14-2 B1-07		Good
M2629R	UID	~200	-	unmeasured	EFEB049a 2-18-1		Good
Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	100	~20%	-			
M2630L	UID	~100	-	unmeasured	EFEA14-2 B1-08		Good
M2630R	UID	~100	-	unmeasured	EFEB049a 2-18-2		Good
Items	Specification data				Substrate No.	Memo	Inspection Results
	1st layer						
	Dopant	Thickness (nm) ⁽¹⁾	Al composition ratio (%) ⁽²⁾	N_d-N_a (cm ⁻³) ⁽³⁾			
Spec. Epi No.	UID	50	~20%	-			
M2631L	UID	~50	-	unmeasured	EFEA14-2 B1-09		Good
M2631R	UID	~50	-	unmeasured	EFEB049a 2-19-1		Good

3. Ga₂O₃ epitaxial wafers grown by halide vapor phase epitaxy (HVPE)

Items	Epitaxial layer			Epi-wafer			Items	(001) substrate						Inspection Results
	Dopant	Thickness (μm) ⁽¹⁾	N_d-N_a (cm ⁻³) ⁽²⁾	Wafer thickness (μm)	Surface finish	Backside finish		Dopant	N_d-N_a (cm ⁻³) ^(2, 3)	Offset angle (degree) ^(5, 6)		FWHM (arcsec) ^(5, 6)		
										Toward [100]	Toward [010]	[100] azimuth	[010] azimuth	
Spec. Epi No.	Si	Average: 8~12	Average: 1x10 ¹⁶ ~5x10 ¹⁶	Average 600±20	CMP ⁽³⁾	CMP ⁽³⁾	Sub No.	Sn	≥ 1 x 10 ¹⁸	0±1	0±1	350 or less	350 or less	
V2-454	Si	9.6	1.5x10 ¹⁶	604	CMP	CMP	N02160	Sn	5.2 × 10 ¹⁸	0.0	-0.1	23	23	Good

Items	Epitaxial layer			Epi-wafer			Items	(001) substrate						Inspection Results
	Dopant	Thickness (μm) ⁽¹⁾	N_c-N_d (cm ⁻³) ⁽²⁾	Wafer thickness (μm)	Surface finish	Backside finish		Dopant	N_c-N_d (cm ⁻³) ^{(2), (6)}	Offset angle (degree) ⁽⁵⁾⁽⁶⁾		FWHM (arcsec) ⁽⁵⁾⁽⁶⁾		
										Toward [100]	Toward [010]	[100] azimuth	[010] azimuth	
Spec. Epi No.	Si	Average: 8~12	Average: 1x10 ¹⁶ ~5x10 ¹⁶	Average 600±20	CMP ⁽³⁾	CMP ⁽³⁾	Sub. No.	Sn	≥ 1 x10 ¹⁸	0±1	0±1	350 or less	350 or less	
V2-471b	Si	10.7	3.9x10 ¹⁶	607	CMP	CMP	N02228	Sn	3.9 × 10 ¹⁸	0.0	0.1	22	23	Good

Items	Epitaxial layer			Epi-wafer			Items	(001) substrate						Inspection Results
	Dopant	Thickness (μm) ⁽¹⁾	N_c-N_d (cm ⁻³) ⁽²⁾	Wafer thickness (μm)	Surface finish	Backside finish		Dopant	N_c-N_d (cm ⁻³) ^{(2), (6)}	Offset angle (degree) ⁽⁵⁾⁽⁶⁾		FWHM (arcsec) ⁽⁵⁾⁽⁶⁾		
										Toward [100]	Toward [010]	[100] azimuth	[010] azimuth	
Spec. Epi No.	Si	Average: 3~7	Average: 5x10 ¹⁶ ~2x10 ¹⁷	Average 600±20	CMP ⁽³⁾	CMP ⁽³⁾	Sub. No.	Sn	≥ 1 x 10 ¹⁸	0±1	0±1	350 or less	350 or less	
V2-476a	Si	5.8	1.8x10 ¹⁷	600	CMP	CMP	N02229	Sn	4.0 × 10 ¹⁸	0.0	0.1	23	22	Good

3. Findings and Conclusions

In the first year, high quality 100-mm β -Ga₂O₃ epitaxial wafers were achieved. Ampere-class β -Ga₂O₃ power devices can be produced by using it. This achievement will bring higher performance, especially energy saving performance to future naval equipment.

4. Plans and Upcoming Events

Recommendations for Future Work:

In year 2, growth efforts of epitaxial Ga₂O₃ and (Al_xGa_{1-x})₂O₃ films are expected to continue. Deliverables will focus on:

- (Al_xGa_{1-x})₂O₃/Ga₂O₃ heterostructure field effect transistors grown by molecular beam epitaxy for lateral power electronic devices
- Thick Ga₂O₃ homoepitaxial films on conductive substrates grown by halide vapor phase epitaxy for vertical power devices
- Additional performance of growth and characterization depending on experimental needs at NRL:
 - custom growths for unique experiments, such as Nitrogen-doped Ga₂O₃
 - custom services such as wafer dicing and secondary ion-mass spectroscopy
 - characterization such as X-Ray diffraction and electrochemical capacitance-voltage measurements

5. Transitions and Impacts

The current and prior NICOPs with Novel Crystal Technology have supported internal research at NRL in the field of Ga₂O₃ for several years now. The prior NICOP has impacted almost every research publication on Ga₂O₃ at NRL in the 2016-2020 period, and we expect research under the present NICOP to elevate Ga₂O₃ technology to TRL 4 where transition opportunities can be identified.

6. Collaborations

Agency/Org	Performer	Project Name	Purpose of Research/ Collaboration
ONR	Capt. Lynn Petersen	Homoepitaxial Ga ₂ O ₃ Structures for Power Device Applications	Program Co-sponsor

OUSDA(A&S)	Capt. James McMullin	Homoepitaxial Ga ₂ O ₃ Structures for Power Device Applications	Potential DoD/METI collaboration discussion
US Embassy, Japan	J. William Wade	Homoepitaxial Ga ₂ O ₃ Structures for Power Device Applications	Potential DoD/METI collaboration discussion

7. Personnel

Principal investigator: Akito Kuramata
 Business Contact: Akito Kuramata
 Team Members: Kohei Sasaki

8. Students

Not applicable

9. Technology Transfer

Not applicable

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Conference Papers

- a. Progress in Ga₂O₃ Growth and Devices for High Voltage Switching Applications
- b. Marko J. Tadjer
- c. MRS Spring Meeting
- d. May 12, 2022
- e. Honolulu, HI, USA
- f. Invited Presentation
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- h. Publication Identifier Type: N/A
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- j. Acknowledgement of Federal Support? Yes

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Novel Crystal Technology has been in continuous contact with Dr. Tadjer, usually once or twice per week, over the course of this program.

12. Acknowledgement/Disclaimer

This work was sponsored by the Office of Naval Research (ONR), under grant (or contract) number N62909-20-1-2055. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Compact High-Power Microwave Oscillators

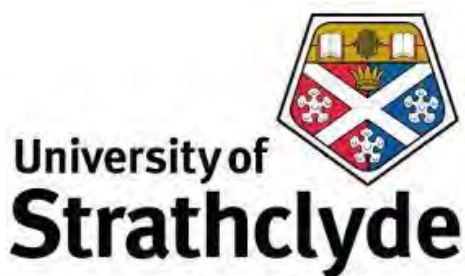
Contract No. N62909-18-1-2122

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to September 30, 2021

Prepared by:

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This work was sponsored by the Office of Naval Research (ONR), under grant number N00014 - 18-1-2122. The views and conclusions contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy or the U.S. Government.

Grant or Contract Number: N62909-18-1-2122-GRANT12538355, N00014-18-S-B001

Date Prepared: 31 January 2022

Project Title: Compact High-Power Microwave Oscillators

Annual Summary Report: ONR HPM 2021 Program – FY21 Annual Report

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Section I: Project Summary

1. Overview of Project

Abstract:

The ABP group, of the University of Strathclyde, Scotland, UK, have been investigating the operation of a novel high-power microwave oscillator. Designed to operate in the X-band (8 – 12GHz) without the application of external magnetic insulation, the source radiates Cherenkov radiation due to efficient modulation of an electron beam, propagated solely under the influence of the beam's self-forces. Named the 'Self-Insulating Backward-Wave Oscillator,' a prototype design has been progressed to manufacture for proof of principle experiments. Numerical modeling of this design indicates efficiencies of ~25%, corresponding to ~220MW from a 500keV, 1.7kA electron beam, with efficiencies of ~30% obtained as the quality of the electron beam improves (e.g. through revision of the electron accelerator, to be informed by the results of the experimental program).

Objective:

Develop a compact X-band High Power Microwave (HPM) source that operates without the use of externally applied magnetic insulation. The reductions in the size, weight, complexity and total energy requirements of this HPM source provide advantages for exploitation in applications. Over this reporting period the primary aim was to recover the significant amount of time lost due the impact of the Covid-19 pandemic on the progress of the experimental program.

Introduction:

The work presented is part of a project that began on 15 June 2018, giving a Project Year (PY) that runs to mid-June in subsequent years. The current reporting period (Oct 1 2020 – Sept 30 2021) therefore spans a portion of PY 3 and PY 4. The work was originally intended to conclude at the end of PY 3, however the impact of Covid-19/Sars-Cov-2 resulted in the extension of the project through to the close of PY 4 (14 June 2022). The following report covers the work undertaken, at the University of Strathclyde (UoS), to mitigate against issues arising from Covid-19 related restrictions (both prior to and continuing throughout the reporting period) and the progression of the project towards experiment.

This work was sponsored by the Office of Naval Research (ONR), under grant (or contract) number N62909-18-1-2122, GRANT 12538355, N00014-18-S-B001. The views and conclusions

contained herein are those of the authors only and should not be interpreted as representing those of ONR, the U.S. Navy, or the U.S. Government.

Table 5: List of Abbreviations/Terminology

ABP group	Atoms Beams and Plasmas research group, based in the Physics Department of the University of Strathclyde.
A-K gap	Anode – Cathode (German “Kathode”) gap: refers to the spacing between the cathodic emitter and anode plane of the electron accelerating diode
BWO	Backward-Wave Oscillator
CST MWS	Computer Simulation Technology MicroWave Studio: The MicroWave Studio licensed professional code is used for electromagnetic and particle simulations. The CST company is owned by Dassault Systèmes.
GHz	Giga-Hertz: 1,000,000,000 Hertz or 1,000,000,000 full-wave oscillations of the field-pattern per second.
HPM	High Power Microwave: refers to microwave sources / amplifiers with output powers >100MW
keV / kA	Kilo-electron-Volt / kilo-ampere: 1000 Volts / 1000 Amperes
MW	Mega-Watt: 1,000,000 Watts
ns	Nano-second: 0.000,000,001 seconds
PiC	Particle in Cell: a numerical code that considers both the electromagnetic fields and discrete particles within the “cells” used to define the simulation volume.
PY	Project Year: for the present project it refers to the period running from June 15 in one year to June 14 in the following year
S-band	A region of the EM spectrum between 2 – 4 GHz
SIBWO	Self-Insulating Backward-Wave Oscillator
UoS	University of Strathclyde.
X-band	A region of the EM spectrum between 8 – 12GHz
PPS	Pulsed Power Supply: a high voltage, high current single-shot power supply located at the UoS, capable of producing ~200 – 250ns long pulses of up to 750kV (max as configured) at multiple tens of kiloamperes of current

Background:

The Self-Insulating Backward-Wave Oscillator (SIBWO), is a novel variant of the conventional Backward-Wave Oscillator (BWO), operating at mildly relativistic energies of $\gtrsim 500\text{keV}$. The

concept originated in work conducted at the Institute of High Current Electronics (IHCE), in Russia, conducted at $\sim 3\text{GHz}$ [1,2]. A variation of the concept, was investigated at X-band, at the National University of Defense Technology (NUDT), China [3]. The UoS undertook at this same time an investigation of the SIBWO concept, operating at S-band, with results presented at the 2015 Joint UK/US Directed Energy Workshop [4].

The current work involves the development of an X-band variant of the earlier UoS work, with the addition of elements common to the klystron used to enhance efficiency [5 – 10]. Results from the project, reported at conferences, may be found in [11 – 14].

The dominant characteristics of the SIBWO remain BWO-like, with the klystron-like elements primarily setting the oscillation frequency for the design currently progressing to experiment. A schematic of the prototype is shown in cross-section in Figure 63.

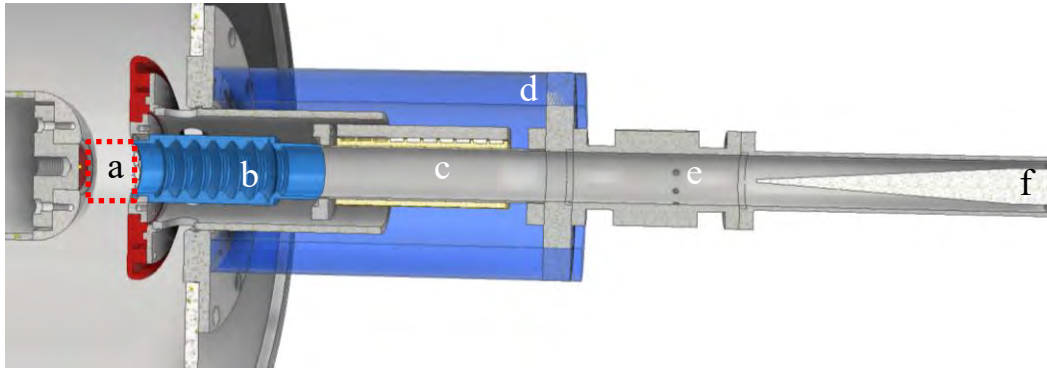


Figure 63: Schematic cross-section of SIBWO prototype assembly noting (a) A-K gap of accelerating diode (b) interaction region (c) beam dump (d) linear-stage location for A-K gap adjustment (e) field probe diagnostics (f) attenuating load termination.

The accelerating diode is formed by a grounded anode-grid, located some distance downstream of a negatively biased cathode emitter, forming an anode-cathode gap (A-K gap, Figure 63(a)) that determines the current drawn from the emitter for a given applied potential. The interaction region (Figure 63(b)) is located directly following the anode-grid, mounted within a movable support structure, allowing adjustment of the A-K gap via translation of a linear stage (Figure 63(d)). A set of discrete rare-earth magnets are used to form a beam-dump (Figure 63(c)), prior to sampling of the output, using a set of distributed D-dot field probes (Figure 63(e)), to determine operating mode and output power. The bulk of the output pulse is absorbed in a load termination (Figure 63(f)).

Over the reporting period work focused on the progression of the project through manufacture to experiment. Section 2 describes the progress made across different aspects of source construction.

References

1. Totmeninov, E.M. et al., 2009, *IEEE Trans. Plasma Sci.*, **37**(7), pp. 1242 – 1245.
2. Totmeninov, E.M., et al., 2011, *IEEE Trans. Plasma Sci.*, **39**(4), pp. 1150 – 1153.
3. Guo, L.M., et al., 2017, *Rev. Sci. Instrum.*, **88**(2), article 024708.

4. MacInnes, P., et al., 2015, 15-19 June 2015 UK / US Directed Energy Workshop, Swindon, UK.
5. Phelps, A.D.R., 2018, *ONR HPM Program FY 2018 Report*.
6. Phelps, A.D.R., 2019, *ONR HPM RPPR 2019*.
7. Phelps, A.D.R., 2019, *ONR HPM Program FY 2019 Report*.
8. Phelps, A.D.R. 2020, *ONR, HPM RPPR 2020*.
9. Phelps, A.D.R. 2021, *ONR, HPM Program FY 2020 Report*.
10. Phelps, A.D.R. 2021, *ONR, HPM RPPR 2021*.
11. MacInnes, P., et al., 2019, *UK / US Directed Energy Workshop, Swindon, UK, 22-26 July 2019*.
12. MacInnes, P., et al., 2020, *47th Int. Conf. on Plasma Sci. (ICOPS 2020)*, 6-10 Dec. 2020.
13. Crampsey, B., et al., 2020, *47th Int. Conf. on Plasma Sci. (ICOPS 2020)*, 6-10 Dec. 2020.
14. MacInnes, P., et al., 2021, *UK Institute of Physics, 47th Plasma Physics Conference*, 6-9 April 2021.

2. Activities and Accomplishments

Pulsed Power Supply:

The UoS possesses a single-shot, pulsed power supply (PPS) formed by a Marx band of fifteen 100kV, 25kA capable, 0.3 μ F capacitors, discharging into a deionized-water-filled pulse forming transmission line. This was configured for use with the SIBWO prototype and characterized against a representative load. Example traces of the output are shown in Figure 64.

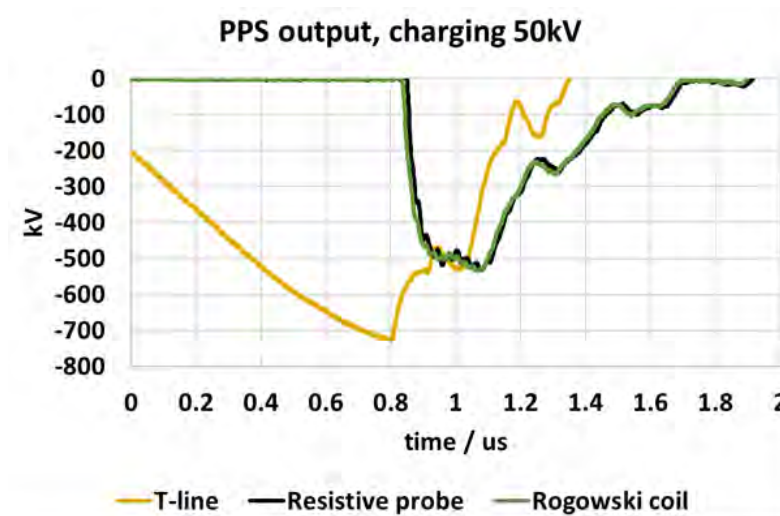


Figure 64: Shows the output from the pulsed power supply, with the initial Marx capacitors charged to 50kV. Three diagnostics were employed, a D-dot probe at the output of the pulse forming transmission-line (T-line), a resistive probe in parallel with the dummy load and a Rogowski coil reading the current flowing to ground from the load.

The PPS incorporates a D-dot field probe (capacitive pick-up probe) at the output of the pulse forming line. From Figure 64, this shows the charging of the line, from the Marx capacitor bank, followed by the closure of the output spark-gap and subsequent discharge to the attached load. The output pulse is then monitored by a resistive probe, placed in parallel with the load, and a Rogowski coil, placed around the current path from the load to ground.

Accelerating Diode:

The manufacture of the accelerating diode was completed during the reporting period, with key components placed, and held, under vacuum. The bounding anode vacuum vessel, with cathode stalk and emitter assembly, can be seen in Figure 65(a), with the diode under vacuum shown in Figure 65(b). Vacuum was maintained in the low 10^{-6} mbar range.

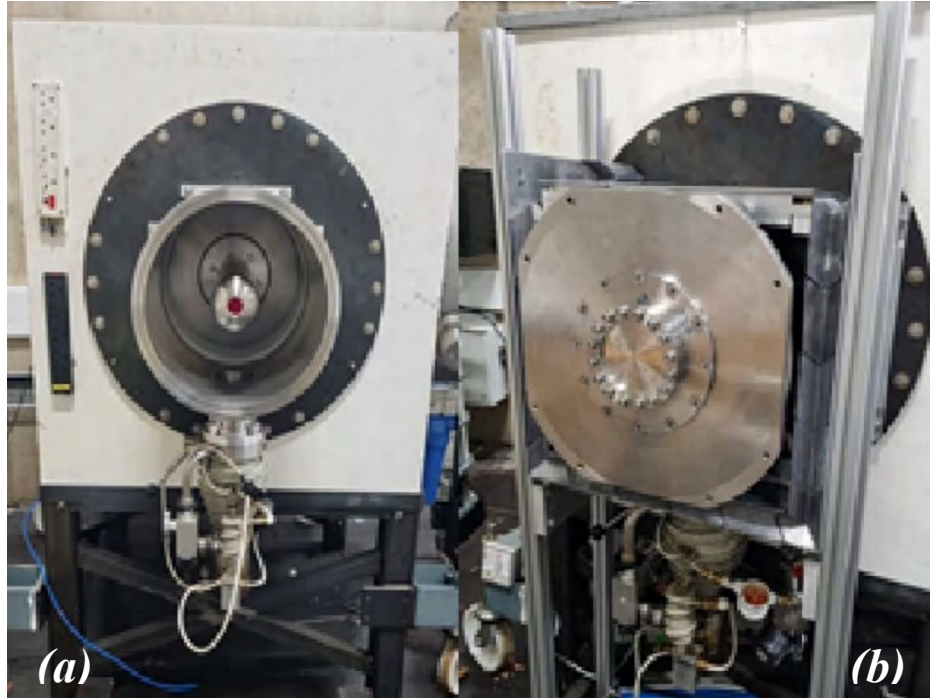


Figure 65: (a) The accelerating diode, showing the internal cathode stalk assembly, (b) the accelerating diode under vacuum.

Numerical modeling of the accelerating diode was used to estimate performance, with the electron beam parameters then input to the Particle in Cell (PiC) model of the SIBWO interaction region. The SIBWO model incorporated both the field diagnostic and load termination to better approximate the experimental setup. The output power envelopes, of the pulses received across 4 probes of the field diagnostic, are shown in Figure 66, which indicates $\sim 220 \text{ MW}$ of output power, corresponding to $\sim 25\%$ efficiency from a $\sim 500 \text{ keV}$, $\sim 1.7 \text{ kA}$ electron beam.

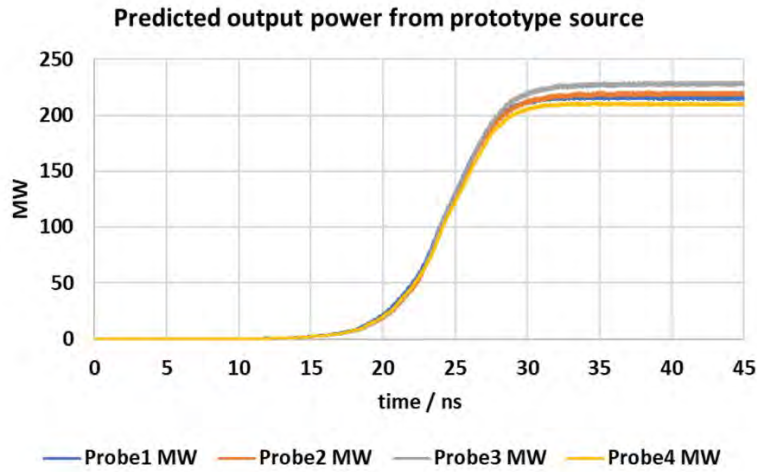


Figure 66: Shows the output power envelopes from the CST MWS PiC model of the SIBWO prototype, as sampled by the 4 D-dot probes of the field diagnostic.

Electron beam dump:

The electron beam dump, formed by a series of compact $\text{Sm}_2\text{Co}_{17}$ rare-earth magnets, was constructed and measured using both axial and transverse Hall probes. The measured results are shown in Figure 67, and compared with the predicted performance simulations obtained using Computer Simulation Technology Microwave Studio (CST MWS).

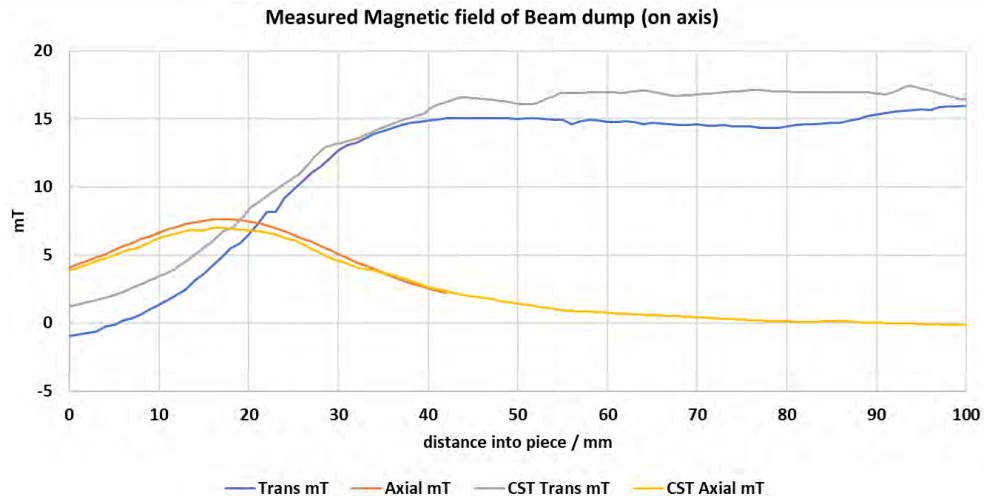


Figure 67: Shows the measured transverse and axial B-fields of the beam dump, compared against the equivalent fields simulated by CST Microwave Studio.

The deviation in magnitude observed in the predicted and measured transverse field strength was attributed to a systematic error in the location of the probe tip relative to the central axis; the transverse probe suffers a “droop” over its length. After this is accounted for, the agreement between simulation and experiment is good.

Support infrastructure:

For ease of adjustment the shielding arrangement for the SIBWO has been designed to be mobile, rolling into, and out of, position on a rail. In the reporting period the base rail, carriage and the majority of the shield support were assembled.

Remaining components:

The manufacture of the SIBWO interaction region was completed prior to the current reporting period and the hot-test variant of the field diagnostic is currently under manufacture.

3. Findings and Conclusions

Over the reporting period the commissioning and characterization of the pulsed power supply was completed. The expected performance was observed, when discharging into a load representative of the impedance expected from the accelerating diode, generating $\sim 200\text{ns}$ peak output pulses at 500kV . The assembly of the accelerating diode was also completed during the reporting period and held under vacuum in the low 10^{-6}mbar range. The electron beam dump was assembled and tested using axial and transverse Hall probes, showing close agreement with numerical prediction.

The impact of Covid-19 on the progression of the project has been significant and ongoing. A No Cost Extension (NCE) to 14 June 2022 was granted. During FY21 UoS has been able to mitigate against many of the additional delays, with all the SIBWO components either complete, or nearing completion. The assembly of the experiment as a whole is near completion, with experimental results from the SIBWO prototype expected in the coming months.

4. Plans and Upcoming Events

- FY22 [1 October 2021 to NCE project end date 14 June 2022] Characterization of the accelerating diode and complete experimental measurements of SIBWO prototype.
- FY22 [1 October 2021 to NCE project end date 14 June 2022] Compare the SIBWO experimental measurements with the numerical simulations produced earlier in this project.
- FY22 [1 October 2021 to NCE project end date 14 June 2022] Complete the numerical modeling of a suitable radiative antenna.

5. Transitions and Impacts

Not applicable at this stage.

6. Collaborations

Collaboration with Dr. Simon Cooke and Dr. Igor Chernyavskiy at NRL in modeling and design of the electron accelerator.

7. Personnel

Principal investigator: Prof. Dr. Alan D. R. Phelps
Person months worked: 4
National Academy Member: yes
Nationality: UK

Co-investigator or Co-PI: Prof. Dr. Kevin Ronald
Person months worked: 4
National Academy Member: Yes
Nationality: UK

Team Members: Dr. Philip MacInnes
Person months worked: 12
National Academy Member: No
Nationality: UK

Business Contact: Research & Knowledge Exchange Services (RKES), University of Strathclyde

8. Students

One undergraduate Masters (M.S.) student undertook a final year research project with direct relevance to the current work program; investigating the feasibility of operating a SIBWO at lower electron energy.

9. Technology Transfer

We have undertaken collaborative discussions with Dr. Simon Cooke, NRL, regarding the configuration and simulation of the electron accelerator and interaction region.

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Conference Papers

- (1) Self-insulation of a high-power Cherenkov oscillator, operating in the X-band, P. MacInnes, S. J. Cooke, I. A. Chernyavskiy, K. Ronald, A. D. R. Phelps, *47th IEEE International Conference on Plasma Science (ICOPS-2020)*, Virtual Conference, 6-10 December 2020.
- (2) Dynamics of highly energetic electrons in novel accelerating diodes, B. Crampsey, P. MacInnes, K. Ronald, A. D. R. Phelps, *47th IEEE International Conference on Plasma Science (ICOPS-2020)*, Virtual Conference, 6-10 December 2020.
- (3) A self-confined high-power Cherenkov oscillator operating at high-frequency, P. MacInnes, S. J. Cooke, I. A. Chernyavskiy, K. Ronald, A. D. R. Phelps, *47th UK Institute of Physics, Plasma Physics Conference*, Virtual Conference, 6 – 9 April 2021.

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12. Acknowledgement/Disclaimer

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Geodesic Luneburg Lenses for High Power Applications

Grant No. N62909-20-1-2040

Annual Report for Fiscal Year 2021

Period of Performance: October 1, 2020 to September 30, 2021

Prepared by:

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Grant or Contract Number: N62909-20-1-2040

Date Prepared: 28th Jan. 2022

Project Title: Geodesic Luneburg Lenses for High Power Application

Annual Summary Report: FY21

PI: Prof. Oscar Quevedo-Teruel, +46-72-844 41 64, oscarqt@kth.se

KTH Royal Institute of Technology

Section I: Project Summary

1. Overview of Project

Abstract:

Fully metallic geodesic Luneburg lens antennas are investigated in this project, specifically for high-power applications. In the previous reporting period a ray tracing model determining the radiation pattern of a rotationally symmetric case was investigated. This model was extended in this reporting period to accommodate non-rotationally symmetric cases. Two profile types were explored, firstly where a compression was applied along the y-axis (elliptical case) and secondly where a mirror plane along the central axis was introduced, which effectively cut the lens in half (half-lens case). A rotationally symmetric prototype, operating over 10 GHz – 20 GHz, has been designed using the ray tracing code. In terms of dissemination, two presentations discussing project work were given at the IEEE AP-S/URSI 2021 International Symposium, held both online and in Singapore. Two journal papers have been accepted for publication, one in *IEEE Commun. Mag.* (indexed Q1) and one in *IEEE Trans. Antennas Propag* (indexed Q1). Future work plans include the addition of losses into the ray tracing model; experimental validation of the designed prototype; investigating the high-power limitations of geodesic lenses and further modifying the model to account for a folded lens case.

Objective:

The primary objective of this project is to investigate the suitability of geodesic lenses for high-power antenna applications, which can be applied to radar systems. As geodesic lenses can take a long time to model using commercial software, the development of a time efficient model was deemed necessary. In addition to this, the project aims to determine the fundamental limitations of geodesic lenses and their limitations at high-power. The project will also explore the potential use of fully metallic geodesic lenses at X- and Ku- bands.

Introduction:

A Luneburg lens is a graded-index lens that perfectly transforms a spherical/cylindrical wave into a plane wave at the opposing side of the excitation. Luneburg lenses are an attractive solution for communications and radar systems since they have low scan losses. However, their principal drawback for high-power applications is that they must be implemented with dielectric materials, which are lossy and limit the amount of handled power. Equivalents to dielectric Luneburg lenses can be achieved with geodesic lenses. As geodesic lenses are fully metallic, they can cope with high-power.

Geodesic lenses consist of two parallel curved conductive plates, with a homogenous refractive index between the plates. The refractive index profile of a conventional dielectric lens is then replicated with an appropriate height profile. A rotationally symmetric structure is assumed during the calculation of the height profile. This profile can be reduced via the introduction of folds, which maintain the optical path length required of the lens.

Geodesic Luneburg lenses are highly relevant for both naval and civilian applications as they can be used in radar systems; 5G/6G communications systems and satellite communications.

Background:

Ray tracing has been successfully implemented in the design process of a wide range of microwave technologies where commercial software is either inefficient or inconvenient. In this approach, the propagation of electromagnetic waves is modelled in terms of rays, where each ray is defined as the normal to the wave front at that location. In doing so, the problem is simplified allowing for the possibility of an algorithm to be developed.

The ray tracing model that has been engineered over the course of this project can be split into three regimes, firstly geometric optics to determine the ray path through the lens, secondly the concept of ray tubes to approximate the amplitude at the lens edge and finally Kirchhoff diffraction to determine the radiation pattern exhibited by the lens.

2. Activities and Accomplishments

During the first four months of the project (the first reporting period), initial work on the ray tracing code was conducted for a rotationally symmetric case. The radiation patterns generated from this initial study matched closely with the radiation patterns taken from commercial software (CST/HFSS).

Building on from this, non-rotationally symmetric cases were explored during this reporting period. Firstly the fully rotationally symmetric structure was compressed along the y-axis in order to generate an elliptical profile, as shown in Fig.1 (a). The height profile of the lens needed to be adjusted in order to account for the variation in path length the compression adds. In terms of the model, the major modification occurred in the meshing of the lens, i.e. the shape in which the ray trajectory is determined. The results have been validated using HFSS, and shows a strong agreement between the modified ray tracing model and the commercial software, as demonstrated in Fig.1 (b). These results were presented in the 2021 IEEE AP-S/URSI Symposium held online and in Singapore and a journal paper will be submitted to *IEEE Trans. Antennas Propag.* in Feb 2022. The second non-rotationally symmetric structure explored was the half-Luneburg lens. In this case a mirror plane was added to the central axis, where the illuminating wave is reflected from before exiting the lens as a planar wave front, Fig. 2 (a). The modification to the ray tracing model mostly occurred in how the ray tube amplitude and the radiation pattern of the lens were calculated. A close match for the main beam between ray tracing and HFSS/CST was generated for this case, as shown in Fig. 2 (b). This model is still under development, aiming to improve matching of the side lobe levels. This work was also presented at the 2021 IEEE AP-S/URSI Symposium, in a different presentation to the elliptical case.

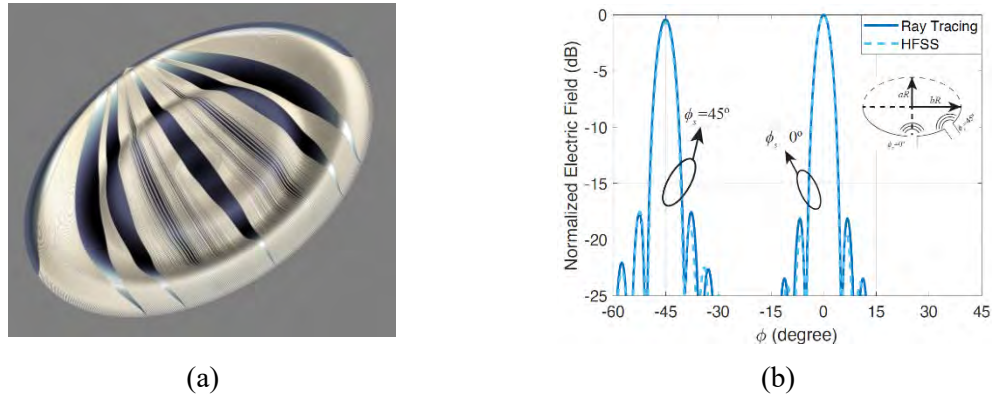


Fig. 1 (a) Electric Field profile over the elliptical lens case and (b) the radiation pattern determined from ray tracing and commercial software for the elliptical lens

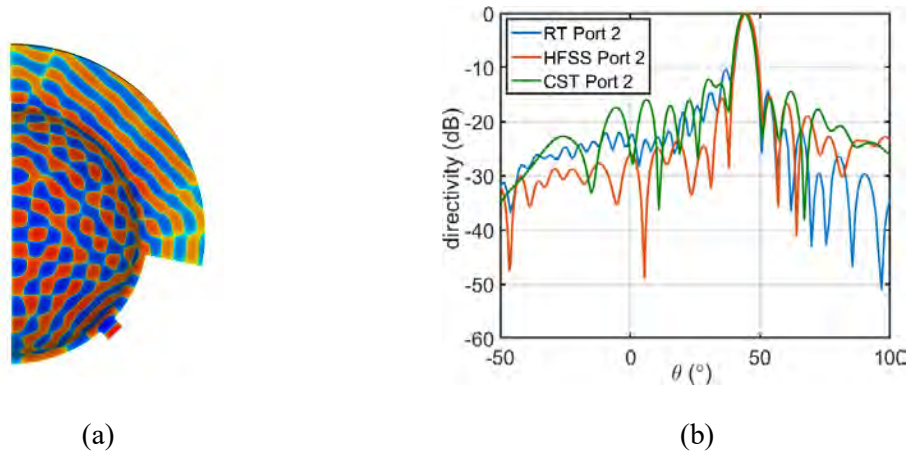


Fig. 2 (a) Electric field profile of the half-Luneburg lens and (b) the radiation pattern determined from ray tracing and commercial software

A prototype has been designed to operate over the frequency band 10 GHz to 20 GHz (Fig.3). The lens has a radius of 15 cm (5λ at 10 GHz) and a plate spacing of 4 mm. A flare structure has been included in the design to produce highly efficient radiation. 13 feeds have been added to scan over a 120° range. The directivity at 10 GHz is 18.0 dBi while at 20 GHz this is 21.5 dBi and performs

consistently when illuminated by each port. The prototype will be milled and an estimated quotation of 6,000€ was provided by Idonial (company located in Spain) for the manufacture of the prototype.

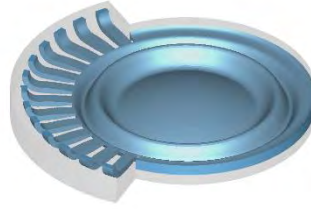


Fig. 3 Image of the prototype designed for operation from 10 GHz to 20 GHz

3. Findings and Conclusions

The ray tracing tool has been verified and is capable of accurately describing the operation of geodesic lenses in a significantly shorter timeframe when compared with commercial software tools. Additionally, the computation time using the ray tracing tool is independent of the lens size/profile shape whereas commercial software is heavily dependent on this. This finding is significant as ray tracing allows for the optimization of the lens profiles, particularly in larger high gain antennas. The flexibility of the code has also been demonstrated, in the sense that it can be tailored to accurately model non-rotationally symmetric cases, i.e. the elliptical case and half-lens, where the profile of the antenna can be reduced from the rotationally symmetric case.

It has been shown through the development of a prototype using the ray tracing tool that broadband operation (over a range of 10 GHz to 20 GHz) is possible with geodesic Luneburg lens antennas. This will be experimentally validated in 2022.

4. Plans and Upcoming Events

The code will be further developed by the introduction of a loss term into the ray tracing model, which will allow for the gain of the antennas modelled to be calculated. Currently the model assumes that the antennas are constructed of ideal materials, and so it would be of benefit to include this term. It is also planned to further extend the code to work for a folded lens case, which should significantly reduce the size of the lens while maintaining a wide scanning range.

The prototype designed to operate from 10-20 GHz will be manufactured and experimentally tested. Another experimental test will be performed in order to determine the high-power handling capability of these geodesic lenses.

In terms of dissemination, a paper titled ‘Numerical Aspects of the Application of Ray Tracing to Geodesic Lenses’ has been accepted to be presented at the 2022 European Conference on Antennas and Propagation (EuCAP) in Madrid. This is the largest European conference relevant to our research. We also intend to present work related to the project at the IEEE APS/URSI 2022 symposium to be held in Sydney, Australia. It is anticipated that a journal paper will be submitted

to IEEE Transactions on Antennas and Propagation in Feb. 2022 reporting an elliptical geodesic lens antenna which has been designed using the ray tracing tool.

5. Transitions and Impacts

There have been no transitions as of yet within this project.

6. Collaborations

Over the past year the team at KTH have collaborated with Prof. Francisco Mesa (University of Seville in Spain) and Dr. Nelson Fonseca (European Space Agency) in the development of the ray tracing tool. The team have also collaborated with Dr. Miguel Camacho (University of Seville) for the design of an elliptical lens using the developed ray tracing tool.

7. Personnel

All the participants in this project are at KTH Royal Institute of Technology. None of them are members of the National Academy members.

Principal investigator: Prof. Oscar Quevedo-Teruel (Full Professor)

Team Members:

- Dr. Sarah Clendinning (Post-doc).
- Shiyi Yang (PhD student).
- Pilar Castillo-Tapia (PhD student).
- Dr. Qingbi Liao (ex-PhD student).
- Federico Giusti (ex-MSc student).

8. Students

Qingbi Liao (PhD student) and Federico Giusti (MSc student) contributed to the project for several months of 2021. Both are students at KTH Royal Institute of Technology and graduated in 2021.

9. Technology Transfer

No transfer of technology has been conducted over the reporting period.

10. Products, Publications, Patents, License Agreements, etc.

Publications resulting from this project:

Archival Publications

O. Orgeira, G. León, N. J. G. Fonseca, P. Mongelos and O. Quevedo-Teruel, "Near-Field Focusing Multibeam Geodesic Lens Antenna for Stable Aggregate Gain in Far-Field," in *IEEE Transactions on Antennas and Propagation*, doi: 10.1109/TAP.2021.3139093.

O. Quevedo-Teruel, Q. Liao, Q. Chen, P. Castillo-Tapia, F. Mesa, K. Zhao, N. J. G. Fonseca, "Geodesic lens antennas for 5G and beyond", *IEEE Communication Magazine* (in press).

Conference Papers

Q. Liao, F. Mesa, N. J. G. Fonseca, O. Quevedo-Teruel, "Ray-tracing model of elliptic Geodesic lens antennas", IEEE APS/URSI 2021, Singapore, Singapore.

S. Clendinning, Q. Chen, Q. Liao, F. Mesa, O. Quevedo-Teruel, "Non-Rotationally Symmetric Geodesic Lens Antennas Modelled Using a Raytracing Model", IEEE APS/URSI 2021, Singapore, Singapore.

Books

N/A

Book Chapter

N/A

Theses

- a. Fully metallic antennas for millimeter wave applications
- b. KTH Royal Institute of Technology
- c. Qingbi Liao
- d. Completion Date: 8th of June 2021
- e. Acknowledgement of Federal Support? (Yes/No)

Websites

N/A

Patents

N/A

Other Products:

N/A

11. Point of Contact in Navy

The main contacts during the year 2022 were:

- Navy: Ryan Hoffman (ryan.hoffman@navy.mil), 3 Mar 2022
- ONR Global London: Charles R. Eddy, Jr. (charles.r.eddy12.civ@mail.mil)

12. Acknowledgement/Disclaimer

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ONR Industry Contract Summaries

Contract Number: N00014-19-C-1008

Project Title: Active/Passive Limiters for High Power Radio Frequency (HPRF)

Contract Period of Performance: 23 Jan. 2019 – 22 Jan. 2023

Principal Investigator: Dr. Sameer Hemmady, sameer.hemmady@verusresearch.net, (805)-558-5604

Organization: Verus Research, Albuquerque, NM

Project Summary

In this body of research, Verus studied physical mechanisms for High Power Radio-Frequency induced nonlinear responses of front-end components typically found in RF receivers. Verus categorized the physical mechanisms from the small-signal linear regime of operation to the large signal nonlinear regime which comprises a continuum of states spanning non-persistent effects and persistent effects (which includes degradation and eventual damage). Similar responses were characterized for other RF front-end components, such as mixers and analog-to-digital convertors (ADCs). This body of research is anticipated to benefit the Navy's High Power Electronic Warfare (HPEW) applications and missions by way of developing prescriptions for more effective HPRF waveforms against RF receivers of interest.

Contract Number: N00014-20-C-1083

Project Title: Leveraging Predictive Effects for Devising Collaborative HPRF/Cyber Engagement Paradigms

Contract Period of Performance: 9 June 2020 – 8 June 2023

Principal Investigator: Dr. Sameer Hemmady, sameer.hemmady@verusresearch.net, (805)-558-5604

Organization: Verus Research, Albuquerque, NM

Project Summary

The focus of this research effort is to leverage recent advancements in predictive effects research for devising collaborative High Power Radio Frequency (HPRF)/Cyber engagement paradigms for complex electronic targets of interest. In the current base effort, Verus Research has focused on performing experiments that establish how software pre-conditioning of an electronic asset can demonstrably alter its HPRF susceptibility, as quantified through its empirically generated Probability of Effects (Pe) curves. In the current Option, Verus Research has utilized predictive effects to devise agile attack waveforms. This has direct implications to mission-level concept of operations (CONOPS) for HPRF platforms in terms of extending its range to effect or alternatively increase its ability to penetrate and affect electronic assets housed deeper inside targeted infrastructure facilities.

SBIR/STTR Summaries

Contract Number: N6833522C0070

Project Title: Improved Marx Generator for HPM Loads

Contract Period of Performance: Oct 20, 2021 – Apr 20, 2022

Principle Investigator: Jon Mayes, Ph.D., mayes@apelc.com, (512) 264-1804

Organization: Applied Physical Electronics, L.C.

Project Summary

Marx generators remain a central component to high power microwave (HPM) and high power RF (HPRF) systems. Traditionally, these systems are large and cumbersome, due to outdated designs with the Marx generator. In brief, Marx generators have been used as a voltage multiplier, converting a relative low charge voltage (10's of kV) to the much higher peak voltages (100's of kV to MVs) required by the application. Legacy Marx generator designs also yielded high source impedances not necessarily compatible with the load. As a result, designers often had to include intermediate pulse forming networks, or some type of transfer capacitance to better drive the low impedance loads. Alternatively, Marx generators can be designed with substantially higher energy storage to lower the impedance of the Marx generator, thereby matching the load impedance. However, the cost comes with lower energy efficiency and a larger footprint for the generator. Applied Physical Electronics, L.C. (APELC) has developed a patented Marx generator topology that results in a much lower source impedance, making it ideal for both HPM and HPRF applications. This topology has worked well for single shot to low repetition rates, but has not had vigorous testing and design for pulse repetition frequencies (PRF). While the topology was not specifically designed for high PRF, the geometry does cater to many of the problems associated with high repetition rate operation. High PRF operation stresses the materials in a Marx generator to a very high degree. APELC has previously life-time tested one of our Marx generators for both shot life, PRF and duty cycle to the point of failure, which resulted in the internal non-metallic components melting due to the inability of the system to dissipate the heat. Clearly, thermal issues must be addressed to produce a Marx generator that can reliably, and safely, operate with high repetition rates. With this effort, APELC is studying the mechanisms leading to thermal failures through various experiments and analysis. By understanding the thermal problem, we can design features to enable active cooling of the system. The Phase 1 effort is designed to model heat-transfer within the Marx, and conduct experiments to both validate the models and demonstrate the ability to manage the thermal problem. A Phase 2 effort will produce a fully characterized Marx generator capable of operating with a high repetition rate, long bursts and shorter recovery periods (i.e. higher duty-cycle). APELC believes that the successful development of this Marx generator will result in a highly useful and marketable system, for both the HPM and HPRF communities.

SBIR/STTR Summaries

Grant or Contract Number: N68335-19-C-0255, SBIR Phase II

Project Title: Miniaturization of High Average Power, High Peak Power, Wide Bandwidth Antennas and DSRDs

Period of Performance: 3 Jul 2019 to 22 Jun 2023

Principle Investigator: Michael Abdalla, 505-830-3000, mda@asrcorporation.com

Organization: ASR Corporation

Project Summary

The ultimate goal of the Phase II effort is to build DSRDs that can meet specific requirements of interest to source developers and the development of an appropriate antenna for use with a DSRD based source. During the Phase II base effort the team has made significant progress toward the goals. The ESA antenna effort has resulted in the development of a true ESA array and a moderate bandwidth array. Further development of the DSRD and the antenna in Option II is discussed below. The overall problem addressed here is one of dopant and heterostructure optimization of tried-and-true silicon drift step recovery diodes (DSRDs), with decreased rise time and increased reverse current density ratings from structures that enable higher current and lower internal impedance operation. Silicon is the material of choice as it provides a sustainable commercial path and can perform in excess of required performance metrics. New DSRD fabrication process flows has been developed with focus on leveraging gas-phase and solid-phase epitaxy, as well as traditional diffused diode junction manufacturing. New wet processing methods for beveling and passivating DSRD diodes have been developed to address the voltage-holding reliability and die-to-die consistency issues seen in prior work. Potential advantages of the new DSRD process flow over traditional methods has been analyzed and described in two patent applications and three presentations at conferences.

The primary area of research focus in Phase II Base was to investigate strategies to incorporate focusing into the antennas to reduce overall volume. True electrically small antennas (ESA) have been considered. Due to bandwidth limitations for true ESA designs, alternate compact antennas have been considered. The ESA work will thus be transitioned to bi-conical resonators or comparable ultra-wide-band and high-power radiating structures. In the Phase II Option I, these radiating structures shall include TEM horns, bi-cones, quarter-wave oscillators and continued advances in high efficiency wideband resonant radiators. These antennas will be larger with higher radiating efficiency. As the DSRD pulse generator parameters become clearer, the antenna design will be finalized.

SBIR/STTR Summaries

Grant or Contract Number: N68335-21-C-0062, SBIR Phase II

Project Title: Drift Step Recovery Diode (DSRD) for Wideband (WB) and Ultra-Wideband (UWB) Pulse Generation

Period of Performance: 8 Oct 2020 to 31 Oct 2022

Principal Investigator: Ranbir Singh, (703) 996-8200, ranbir.singh@genesicsemi.com

Organization: GeneSiC Semiconductor Inc.

Project Summary

Drift step recovery diodes (DSRDs) are the fastest semiconductor opening switches reported to-date and are a critical enabling technology for realizing ultra-wide band (UWB) high-power microwave sources which are of great interest for US Navy applications. The main goal of this two-Phase SBIR project is to develop silicon carbide drift step recovery diodes as a reliable and qualified product for insertion into the next-generation ultra-wide band, high-power microwave sources. Capitalizing on the superior intrinsic advantages of the semiconductor material silicon carbide (SiC) over silicon, this project will develop ultra-high speed SiC based DSRDs with single-chip ratings of > 2 kV and ≥ 100 A, with significantly faster switching capability. This will reduce the number of series-connected devices necessary to realize ultra-high voltage 20-50 kV pulse generators with sub-nanosecond switching capability.

Grant or Contract Number: N68335-21-C-0851, SBIR Phase I

Project Title: Improved Marx Pulse Generator for HPM Systems

Period of Performance: 20 Oct 2021 to 20 Apr 2022

Principal Investigator: Sam Dickerson, SDickerson@sara.com, (719) 302-3117

Organization: Scientific Applications & Research Associates, Inc., Colorado Springs, CO

Project Summary

SARA intends to help usher in a new generation of high-power microwave (HPM) systems by completing a design for an improved, highly reliable, Marx based pulse generator intended to drive state of the art HPM sources. The effort will begin with a trade study between a spark gap switched gas insulated Marx generator and a solid-state Marx driving a solid-state opening switch output stage. The trade study will analyze the competing pulse generator topologies by considering expected size, weight, performance, cost and developmental risk. Upon completion of the study, the preferred topology will be down selected for complete design. The pulse generator design will be based upon custom components manufactured by SARA. Key among these components are custom solid-state switch packages which are optimized for low duty, high peak power operation. Further, SARA's line of custom, application specific, dry metalized film capacitors will be central to the design. The capacitors are capable of being specifically designed for the end application enabling a much higher degree of system integration. Once the preliminary design is started, the concept will be fully simulated in COMSOL Multiphysics. The simulation effort will seek to optimize crucial components and verify the designs performance. Key things to determine via simulation include (depending on the down selected topology) spark gap electrostatics, spark gap gas flow dynamics, solid-state impedance, solid-state heat transfer, and pressure vessel/enclosure hydrostatics and electrostatics. Upon completion of simulation/optimization, the design will be finalized and delivered as part of the final report. All work for the effort will be carried out by SARA's High-Power Electromagnetics division at their facility in Colorado Springs, CO.

SBIR/STTR Summaries

Grant or Contract Number: N68335-17-C-0112, SBIR Phase II

Project Title: Affordable Compact HPRF/HPM Attack Warning System

Period of Performance: 5 Apr 2017 to 28 Jun 2022

Principle Investigator: Todd Chauvin, t.chauvin@saphotonics.com, (408)702-8066

Organization: OneLight Sensing LLC formerly SA Photonics

Project Summary

SA Photonics' Wideband Agile Threat Sensor (WATS) addresses the Navy's need for an affordable and compact High-Power Radio Frequency / High-Power Microwave (HPRF/HPM) attack warning technology that detects, characterizes and precisely geo-locates HPRF threats while being fully immune to HPRFs. WATS consists of multiple completely passive HPM probes connected by fiber optic cables to an electronic processing system. In addition to characterizing key statistics of detected attacks, the WATS system when deployed with multiple sensors at well-known locations is able to localize the direction the attack originated from as well as estimate the range of the HPM attack source.

Grant or Contract Number: N68335-21-C-0398, SBIR Phase I option

Project Title: Pulsed Power Modulation System

Period of Performance: 7 Jun 2021 to 15 Aug 2022

Principle Investigator: Landon Collier, lcollier@sara.com, (719) 302-3117

Organization: Scientific Applications & Research Associates, Inc., Colorado Springs, CO

Project Summary

High power microwave (HPM) sources have conventionally been driven by gas-switched pulsed power generators due to high voltage, high current, and fast rise-time requirements. However, these traditional technologies impose significant limitations on advancements in HPM technology due to low repetition rate, short lifetime, limited waveshaping capabilities, and difficulty of synchronization. Recent advancements in solid state device technology, including wide bandgap semiconductors such as silicon carbide (SiC), have opened the door for development of a next generation of pulsed power drivers capable of overcoming these limitations, with rep-rates in the 10's to 100's of kHz, million-shot lifetime, arbitrary waveform capability, and sub-ns jitter. Further, optimization of solid-state device characteristics and packaging techniques tailored towards pulsed power application can result in smaller, lighter, and more efficient systems than can currently be achieved with commercially available devices. A solid-state alternative to traditional HPM drivers was developed during Phase I leveraging SARA's ability to evaluate, test, and package state-of-the-art (SotA) silicon carbide die into large pulsed power systems. Building upon this development effort, the modulator design will be refined and experimentally demonstrated during Phase II.

SBIR/STTR Summaries

Grant or Contract Number: N68335-21-C-0852, SBIR Phase I

Project Title: Improved Single Switch Distributed Marx Pulse Generator for High-Power Microwave (HPM)

Period of Performance: 20 Oct 2021 to 20 Apr 2022

Principle Investigator: Zac Shotts, zac.shotts@is4s.com

Organization: Integrated Solutions for Systems

Project Summary

The development of a compact high-performance high voltage source that achieves the objectives laid out in *N212- 121 Improved Marx Pulse Generator for High Power Microwave (HPM) Systems* would be an enabling technology for a wide range of applications including as the prime power source for driving a new range of novel Directed Energy Weapons (DEW) suitable for attack of C4I2 facilities, and industrial/civil infrastructure targets while providing a reduced risk of collateral damage to civilian/non-combatants versus that of typical Kinetic Energy (KE) munitions. The technology development proposed herein, if successful and continued under a Phase II would eventually support the defeat/destruction of not only the previously discussed equipment but also a wide range of soft targets with minimal risk of collateral damage. High-Power Microwave (HPM) has been shown capable of disabling and damaging a wide range of sophisticated electronic targets including Vehicles, Vessels, and Unmanned Air Systems (UAS). The ability to integrate HPM DEW systems into smaller, more compact weapons systems would allow for significantly greater utility by the warfighter. However, to achieve widescale adoption where these systems would be capable of making a greater impact for the warfighter, the logistical burden associated with deployment into hostile environments, maintenance, and reliability must be improved. Principle to these are: 1.) The complicated procedures associated with oil insulation and the vacuum potting of dielectric fluids typically used in high voltage insulation of these systems, 2.) The logistical burden associated with specialty gases used in the high-pressure gas switches and the leakage associated with the fittings and gas diffusion, and 3.) The excessive weight associated with oil insulation versus that of similar gas insulated systems. Integrated Solutions for Systems (IS4S), in an effort to accomplish the goals laid out by *N212-121*, will leverage the Principal Investigators (PI) previous experience in the development and testing of compact pulse power system and components suitable for driving a wide range of loads including HPM systems, as well as similar flash X-ray systems. To accomplish this task the IS4S team proposes the investigation, adaptation, and leveraging of various components of a Vector Inversion Generator previously designed to drive a 400 kV 60-ohm load as an alternative to the typical Marx Generator based systems currently in use. This approach has several advantages to Marx Generator based systems as it is simpler in design and has fewer components requiring only a single switch to operate, and a single peaking switch to reduce the risetime delivered to the load thereby reducing the maintenance, size/weight, cost, and associated logistics burden of deployment allowing for wider spread adoption and use.

SBIR/STTR Summaries

Grant or Contract Number: N68335-22-C-0076, SBIR Phase I

Project Title: Compact Air-insulated Marx (CAM)

Period of Performance: 20 Oct 2021 to 20- Apr 2022

Principle Investigator: David Cooperstock, david.cooperstock@sem-sol.com, 505-506-6772

Organization: SEM-SOL

Project Summary

The U.S. Department of the Navy has awarded Sem-Sol a Small Business Innovation Research (SBIR) Phase I contract to develop an Improved Marx Pulse Generator for High Power Microwave (HPM) Systems. Sem-Sol's approach is based on a low-inductance, multichannel spark gap switch to achieve a very fast risetime high voltage output pulse. During Phase I they will be designing and simulating key aspects of their innovative approach to demonstrate feasibility. Marx Pulse Generators have applications for the Department of Defense, Department of Energy, as well as commercial applications, wherever very brief and powerful electrical pulses are required. Sem-Sol is a small business located in Albuquerque, NM that specializes in pulsed power, high power microwave, and charged particle beam systems.

Grant or Contract Number: N68335-20-C-0435, SBIR Phase II

Project Title: Solid-state, Sub-nanosecond Pulse Sharpener for Generating High Power Impulses

Period of Performance: 27 Jul 2021 to 31 Jul 2023

Principle Investigator: Jason Sanders, jason@transientplasmasystems.com, (615) 424-1467

Organization: Transient Plasma Systems

Project Summary

The Office of Naval Research issued this SBIR topic to fund the development of a solid-state closing switch capable of producing high power UWB electrical pulses. This proposed effort will investigate Silicon Avalanche Shaping/Sharpening (SAS) device structures for both Si and SiC, with Si being viewed as the conservative approach for achieving the threshold specifications of this topic. Less work has been done to investigate the capabilities of SiC for SAS devices, but its superior material properties suggest it is likely well suited for impact-ionization avalanche switching, which does not rely on long minority carrier lifetime for practical implementation in the same way Drift Step Recovery Diodes (DSRDs) do. The significantly shorter intrinsic region that can be achieved with a SiC SAS-type device is expected to result in higher dV/dt capability compared to Si due to shorter transit distance through the device and reduced effective resistance. Devices have been designed and simulated during Phase I, and a Phase II effort has been awarded. In Phase II solid-state devices capable of switching kW-MW power pulses with risetimes faster than 300 ps at high pulse repetition rate will be fabricated and tested. These devices will add to the United States' high power UWB technology portfolio and will advance system capabilities for directed energy applications. The Phase II effort kicked off in December 2021, and materials to fabricate the first batch of SAS devices have been ordered. Preparation for fabrication runs in both Si and SiC are underway. In the meantime, work is being conducted to evaluate edge termination techniques for these devices and also to test dicing and coating techniques for realizing effective cross-sectional areas that were shown to provide the best performance in simulation.

SBIR/STTR Summaries

Grant or Contract Number: N68335-19-C-0445, SBIR Phase II

Project Title: Navy-Electronic Battle Damage Indicator (eBDI) Tool for Non-Kinetic High-Power Radio-Frequency (RF) Engagements

Period of Performance: 29 Aug 2019 to 31 May 2022

Principle Investigator: Donald Voss, 505-255-4201, donv@vosssci.com

Organization: Voss Scientific

Project Summary

A critical need exists for a compact and reliable electronic Battle Damage Indicator (eBDI) tool for use in a directed energy (DE) battlefield in which High Power Radio Frequency (HPRF) devices are employed. In the Phase I effort, Voss Scientific demonstrated the feasibility of building an Autonomous Damage Assessment Module (ADAM) capable of meeting the Navy electronic Battle Damage Indicator (eBDI) requirements by utilizing a man- or UAV-portable electronics package with multiple methods of emplacement, both covert and overt. In addition to broad-spectrum data collection, ADAM will use an extremely-narrowband data collection methodology in the brass-board eBDI device. The resulting ADAM eBDI system will be denoted as ADAM Gen-I. The performance of ADAM Gen-I will be demonstrated in both laboratory and in one or more field tests, with the goal of reaching TRL 5.

Grant or Contract Number: N68335-21-C-0396, SBIR Phase I

Project Title: Precision Pulse Compressor

Period of Performance: 7 Jun 2021 to 7 Dec 2021

Principle Investigator: Nate Schoeneberg, nathan.schoeneberg@verusresearch.net,
(505) 338-2254

Organization: XL Scientific LLC, dba Verus Research

Project Summary

The technical objective of the Precision Pulse Compressor (PPC) Phase I SBIR was to conceptualize, design, and model an all-solid-state power modulator that could drive 50-kV, <10-ns risetime, >30-ns pulse width, <1-ns jitter pulses across a 100- Ω nonlinear transmission line (NLTL) load at a repetition rate of 10-kHz. The fast risetime and tight jitter performance are required to support power scaling and phase-controlled beam steering applications based on NLTL RF sources. To achieve the demanding electrical and temporal characteristics of such a driver, the highest performing, high voltage solid state switch devices were sought and incorporated into the design. The primary technical approach to achieve this result was to employ magnetic pulse compression to allow the high voltage SiC devices to operate within safe operating areas while still providing the demanding driver output across the load. The Verus Research Precision Pulse Compressor design utilizes two stages of magnetic pulse compression to deliver the required pulse characteristics in a design that is 79% efficient, weighs less than 30-lbs, and occupies a volume of 0.3-ft³. The mechanical design of the system is rugged in terms of shock and vibration and supports a straightforward and easily achievable thermal management approach.

SBIR/STTR Summaries

Grant or Contract Number: N68335-21-C-0397, SBIR Phase I

Project Title: Compact, Fast, Low-Impedance Solid-State High Voltage Power Modulator

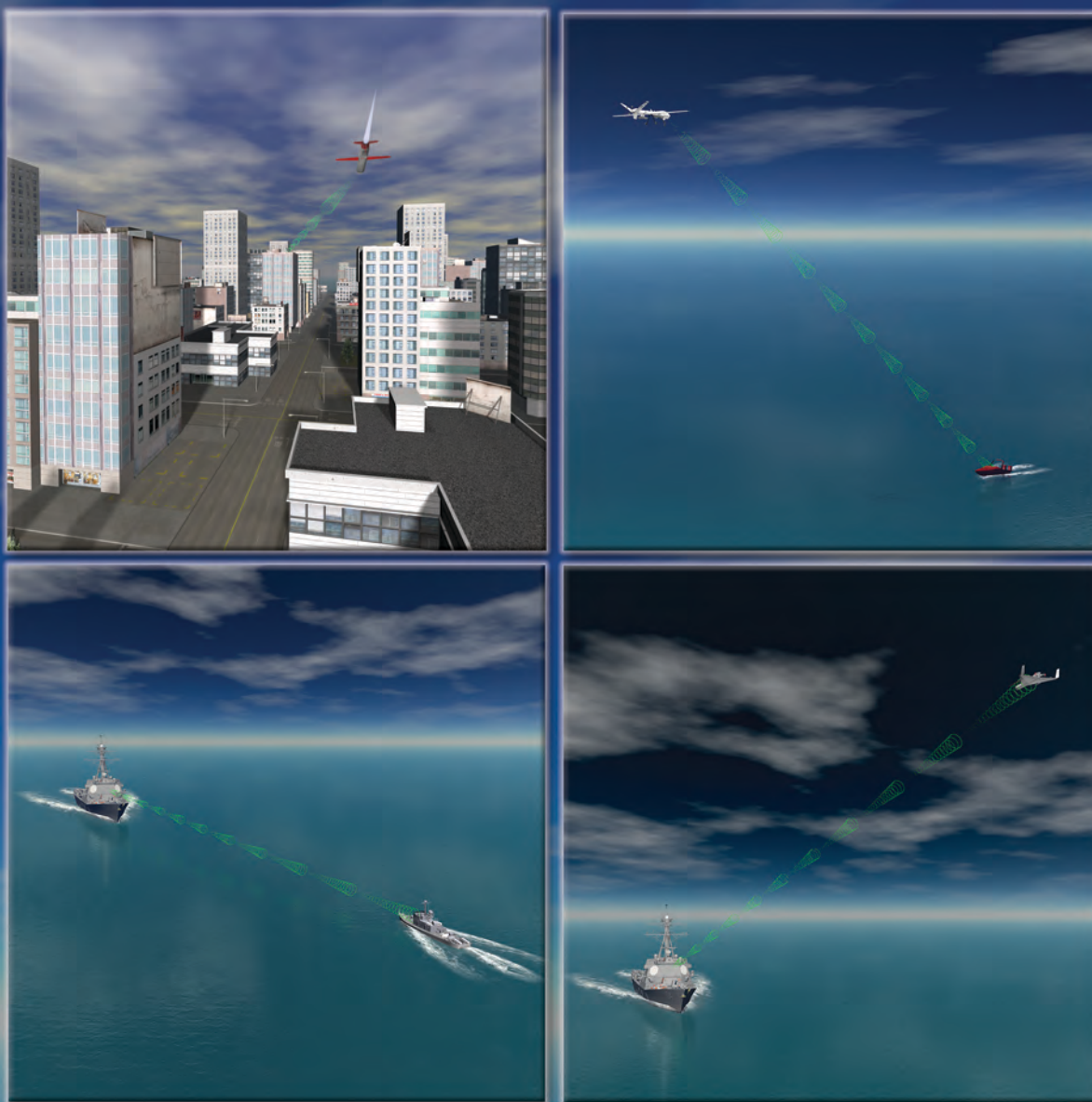
Period of Performance: 7 Jun 2021 to 7 Dec 2021

Principle Investigator Ian Roth, roth@divtecs.com

Organization: Diversified Technologies, Inc.

Project Summary

This SBIR developed a pulser for a high-power microwave source. The pulser is an inductive adder based on solid-state switches, which allow repetitive operation, unlike the gas switches presently used. DTI selected the commercially-available transistor with the highest power available, and developed a gate drive to enable a risetime that is much faster than the 20-ns listed in the data sheet. A test circuit was built to test a small series-parallel array of devices to characterize their performance. The test results demonstrated a 4.6 nanosecond rise at a current of 85 A per device, and a jitter of 540 ps, which exceed the project goals. DTI also developed the inductive-adder architecture that scales to a 100 kV output with an expected risetime of 6 nanoseconds.



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