Conference Schedule

Monday, June 20

7:15am - 8:15am Ballroom AB	Breakfast
7:15am - 8:15am 300AB	Authors' Breakfast
8:30am - 9:30am Ballroom EF	IPMHVC Plenary Lecture J. Verboncoeur
9:30am - 10:00am Ballroom AB	Coffee Break
10:00am - 11:00am Ballroom C	Multipactor
11:00am - 12:00pm Ballroom C	Panel Discussion: High Gradient Multipactor and Breakdown
10:00am - 12:00pm 301B	Power Electronics
12:00pm - 1:30pm	Lunch
1:30pm - 3:00pm Exhibition Hall D / Henley Concourse	Posters: HPM, Repetitive Pulsed Power, Plasmas, Dielectrics, & Analytical Methods
3:00pm - 3:30pm Ballroom AB	Coffee Break
3:30pm - 5:30pm Ballroom C	Dielectrics I

Tuesday, June 21

7:15am - 8:15am Ballroom AB	Breakfast
7:15am - 8:15am 300AB	Authors' Breakfast
8:00am - 8:30am Ballroom EF	IPMHVC Magna Stangenese Memorial
9:30am - 10:00am Ballroom AB	Coffee Break
10:00am - 12:00pm Ballroom C	Plasmas, Discharges, and Electromagnetic Phenomena
10:00am - 12:00pm 301B	Solid State Modulators
12:00pm - 1:30pm	Lunch
1:30pm - 3:00pm Exhibition Hall D / Henley Concourse	Posters: Solid State, Power Electronics, High Voltage, Biomedical

3:00pm - 3:30pm Ballroom AB	Coffee Break
3:30pm - 5:30pm Ballroom C	Dielectrics II
3:30pm - 5:30pm 301B	High Power Microwaves
7:30pm - 9:00pm Ballroom ABC	Conference Banquet

Wednesday, June 22

7:15am - 8:15am Ballroom AB	Breakfast
7:15am - 8:15am 300AB	Authors' Breakfast
9:30am - 10:00am Ballroom AB	Coffee Break
10:00am - 12:00pm Ballroom C	Repetitive Pulsed Power
10:00am - 12:00pm 301B	Biomedical and Applications
12:00pm - 1:30pm	Lunch
1:30pm - 3:00pm Ballroom EF	IPMHVC Plenary Lecture R. Joshi
3:00pm - 3:30pm Ballroom AB	Coffee Break
3:30pm - 5:30pm Ballroom C	High Voltage
3:30pm - 5:30pm 301B	Analytical Methods

Presentations

IPMHVC Plenary Lecture - J. Verboncoeur

Time: Monday, 20/June/2022: 8:30am - 9:30am · *Location:* Ballroom EF

8:30am - 9:30am

From Multipactor to Ionization Breakdown: Review and Recent Advances

J. P. Verboncoeur[1], D.-Q. Wen[1], A. Iqbal[1], Y. Fu[2], P. Wong[1], P. Zhang[1]
[1]Michigan State University; [2]Tsinghua University

Multipactor and its transition to gaseous ionization breakdown remain persistent limitations in RF device operation, particularly at high power. Nonlinear effects can couple multiple carrier frequencies, cause instabilities and dispersion, and result in temporary failure as well as permanent damage. These phenomena are relevant to conducting and dielectric surfaces, in devices ranging from communications to high power microwave sources, to accelerators and even high gradient microwave circuits and devices.

We update this ongoing work, carried out over the past decade, examining the process of initial multipactor growth, surface heating and gas desorption, and subsequent evolution to ionization breakdown. We look at a variety of mitigation schemes, from spatio-temporal signal modulation and wave mode configuration to surface morphology and materials properties. Both single-surface dielectric multipactor and two-surface conductive electrode multipactor are considered.

This work is part of a larger effort which includes development of standardized platforms in planar, coaxial, and stripline configurations, with both computational and experimental analogs to enable validation and develop analytic and predictive capability integrated with well-tested experiments. The test cells enable study of multipactor susceptibility and transition to ionization breakdown, as well as novel material, geometric, and electrical mitigation schemes in isolation or as a system. Test cell designs allow variations in gap spacing, driving frequency, waveform shape, ambient and desorbed gas, surface morphology, and many other key parameters. The cells will motivate integration and development of novel diagnostics, such as direct multipactor electron detection, optical/VUV emission spectroscopy, and X-ray imaging, at ns timescales and sub-mm- spatial scales.

The test cells and corresponding models will be published in detail and made available to the community as standard reference platforms on which repeatable basic physics results can be studied, validated, benchmarked, and openly published.

*This work was supported by AFOSR MURI Grant No. FA9550-18-1-0062 and AFOSR BAA Grant FA9550-21-1-0367. The contributions of the entire MURI team are gratefully acknowledged: Texas Tech University (led by A.A. Neuber), University of Michigan (led by R.M. Gilgenbach), University of New Mexico (led by E. Schamiloglu), and University of Wisconsin led by J.H. Booske).

Multipactor

Time: Monday, 20/June/2022: 10:00am - 11:00am · *Location:* Ballroom C
Session Chair: Nicholas M Jordan

10:00am - 10:20am

High Power Multipactor Suppression in S-band Waveguide

D. Wright, A. Gregory, H. Spencer, J. Mankowski, J. Stephens, J. Dickens, A. Neuber
Texas Tech University, United States of America

To investigate multipactor (MP), a rectangular waveguide testbed was designed for S-band frequencies with the broad wall dimension matching the standard WR-284 waveguide geometry. Setting the waveguide height to 5.5 mm yielded a frequency-gap product susceptible to MP. One of the test sources, a coaxial magnetron provides test input power at a frequency of 2.85 GHz with a peak power output of 4 MW and 3.5 µs pulse width. The other, a RF solid-state source using GaN HEMTs delivers a pulse width of 100 µs with a test input power of 3 kW for comparison of threshold power. With the two sources a range of 3 kW to 4 MW of input power was accessed.

For MP detection, local (electron multiplier tube) and global (phase/power) diagnostic methods were implemented. At power levels tested (MW) and a 5.5 mm gap, low multipactor orders (N = 1) are observed, whereas an order of N = 9 are observed at the lower power level. To suppress MP, previous numerical simulations of the geometry have shown that adding a grooved structure to one of the broadsides should aid in mitigating multipactor. In this case, grooves are machined into the broad wall in the direction of propagation, which avoids continuous impedance mismatching and large E-field perturbations. The efficacy of this mitigation technique was experimentally evaluated. Experimentally, there were distinct differences between the standard case (smooth broadside wall) and the case with grooves in MP delay and magnitude. The difference in power transmitted before MP onset was limited, however, an about 12% improvement was measured.

This research was supported by the Air Force Office of Scientific Research under contracts FA9550-18-1-0062 and FA9550-21-1-0367

10:20am - 10:40am

Monte Carlo Analysis of Electron Trapping in Nested Cave Structures for Mitigation of Secondary Electron Emission for Potential Multipactor Control in Waveguide

M. Brown, W. Milestone, R. Joshi
Texas Tech University, United States of America

The multipactor phenomenon is a resonant vacuum phenomenon frequently observed in microwave systems, accelerator structures, and high power radio-frequency (RF) satellite components. Electrons produced under multipactor resonance conditions can lead to rapid charge growth that can potentially decrease power throughout, damage the structure, cause internal heating, and lead to unexpected breakdown events. Thus, mitigation of multipactor, and hence ultimately, the secondary electron yield (SEY), remains an important objective in the pulsed power context. Geometry modifications of rectangular waveguide surfaces and/or the application of an axial magnetic field have been investigated for suppressing multipactor growth both through simulations and in experiments. While the results appear promising at lower fields, the task becomes challenging with increase in the microwave power and field intensity. Besides, the problem of finding optimal combinations of suppression for a given parameter space consisting of the electric field, geometric length scales, and operating frequency remains.

Here as part of the surface geometry modification strategy for rectangular waveguides, the fabrication of nested holes to trap the emitted electrons in examined for suppressing the overall secondary electron yield. A simulation scheme based on the kinetic Monte Carlo (MC) method is employed to probe the electron swarm dynamic. Our work also examines possible SEY suppression and quantifies the time dependence of electron population growth on the operating frequency, electric fields intensity, geometric size of the nested holes, and their relative density. The energy-dependent SEY curves required for the MC simulations are taken from the literature for copper material.

The results obtained will be presented and discussed. In particular, the percentage suppression effect and possible mitigation of electron swarm growth will be analyzed for structures with two-sized nested surface holes.

*This Research was supported by the Air Force Office of Scientific Research under Contract No. FA9550-19-1-0056.

10:40am - 11:00am

Probing Multipactor in X-band Waveguide Components

A. Gregory, D. Wright, H. Spencer, J. Mankowski, J. Stephens, J. Dickens, A. Neuber

Texas Tech University, United States of America

Multipactor is a vacuum-based resonant effect that causes detuning, heating, and ultimately component damage in microwave systems. Suppression of this effect then becomes important in high power systems such as satellite communications. To study multipactor, a plug and play setup was designed and built in to allow for quick testing in a waveguide-like structure. A tunable X-band magnetron, tuned to 9.4 GHz, with a typical pulse length of 2.5 µs delivers peak power output of 130 kW. The magnetron driver pulse duration and amplitude are freely adjustable, utilizing a modern hard-switched semiconductor-based topology. This project's primary device under test is a waveguide stepped impedance transformer that reduces the side-wall dimension of a typical WR90 waveguide down to a gap size conducive to multipactor formation.

This research evaluates the efficacy of varying methods of multipactor suppression as well as conditioning of surfaces through repeated multipactor. In this context, a residual gas analyzer is added as a diagnostic tool to check the species of gas desorbed from different surfaces. Phase detection is used as a diagnostic to determine when a multipactor event has occurred, alongside an electron multiplier tube (EMT) that allows analysis of the multipacting electron cloud.

This research was supported by the Air Force Office of Scientific Research under contracts FA9550-18-1-0062 and FA9550-21-1-0367

Power Electronics

Time: Monday, 20/June/2022: 10:00am - 12:00pm · *Location:* 301B
Session Chair: Katie Sheets

10:00am - 10:20am

A new topology for DC-DC converter with enhanced current multiplication

O. Zucker, T. Le

Polarix Corporation

Electronic DC to DC converters[1] divide into those that use transformers[2] for impedance transformation and those that use resonant transfer between capacitors and inductors. In the latter, an inductance is used as intermediate storage that is energized at one voltage and deenergized at another. Some circuits combine the two approaches in one circuit such as opening a current carrying primary of a transformer. In general, the resonant transfer type such as the buck or buck boost circuits come in several basic variations and are inherently limited in their impedance transformation. For higher transformation ratios multiple stages are used which reduce the efficiency of the total system.

A circuit termed the “Meatgrinder”[3] was developed in the 1980s to enhance the energy transfer between an energy storage inductor and an uncoupled inductive load by breaking the energy storage inductor into coupled sections interspersed with intermediate switches and a prescribed sequential switching scheme. The arrangement increased the total energy transfer efficiency with the number of sections. Significantly, a variation of this circuit termed the “Ringer” and developed principally for energizing electromagnetic guns which used only two sections; and furthermore, used the ringing of the source capacitor to perform the opening switch function and thereby eliminating the opening switch altogether. This Ringer circuit has now been modified to energize various PWM inverters for motor control and related. Applications with substantially increased impedance transformation and efficiency and with more relaxed switching requirement.

Converter switch requirements include both opening and closing switches. Opening switches are affected by the ever-present leakage inductance whose inductive kick must be suppressed with capacitors and resistors to protect the switch from over voltage surges. Alternative approaches are to open the switch only when the current is zero. This often goes counter to the function we would like the switch to perform. the circuit described in this paper combines the switch opening of the inductive circuit with both enhanced current multiplication and efficiency and substantially reduced switch requirement.

The circuit perceived application is predominantly in compact high efficiency converters requiring large impedance ratio transformations.

[1] B. W. Williams, "Basic DC-to-DC Converters," IEEE Trans. Power Electron., vol. 23, no. 1, pp. 387,401, Jan. 2008.

[2] Hua, G., Leu, C.S., Jiang, Y., et al.: ‘Novel zero-voltage-transition PWM converters’, IEEE Trans. Power Electron., 1994, 9, (2), pp. 213–219

[3] O. Zucker, J. Wyatt and K. Lindner, "The meat grinder: Theoretical and practical limitations," in IEEE Transactions on Magnetics, vol. 20, no. 2, pp. 391-394, March 1984, doi: 10.1109/TMAG.1984.1063078.

10:20am - 10:40am

In-depth Analysis of current-fed resonant Full-bridge Converter Application for high voltage DC Power Supply

R. Grinberg[1], A. Reichert[2]

[1]Bern University of Applied Sciences, Switzerland; [2]Industrial X-Ray, Comet AG, Switzerland

In-depth analysis of current-fed resonant full-bridge converter application for high voltage DC power supply

Introduction

In [1], current –fed full-bridge converter with resonant switching and constant on-time control for high–voltage (HV) application is introduced and demonstrated on 1kV/600W prototype converter with single rectifier output stage. While taking into account major parasitic components of HV transformer, theoretical analysis and demonstrator design in [1] does not cover the following aspects:

- influence of multistage multiplier and its component characteristics on converter performance and design for high output voltages e.g. 100kV
- impact of current-source implementation on the overall converter characteristics
- sensitivity of converter design to variation and uncertainties of HV transformer model parameters
- implementation aspects of current-fed converter.

Contribution

This paper provides in-depth analysis of the aspects listed above. Using analytical and simulation approach, non-negligible effect of the multistage multiplier on the converter design is shown. Specifically, presence of significant HV diode junction capacitance leads to reduction of converter operating range. It is also shown that, in case of thin winding wire and multiple insulation mediums in the winding, analytical approach for HV-transformer capacitance calculation [2] does not provide estimates that are accurate enough. As an alternative, measurement-based approach, introduced and tested for two-winding transformers in [3], is pursued for parasitic parameter extraction and associated challenges are shown. Design trade-offs for current source implementation (in this case, buck converter) vs full-bridge converter on-time selection are shown. Specifically, it is demonstrated that time shift between constant on-time of full-bridge converter and buck converter significantly impacts current source output ripple and must be considered during the design. Finally, selected simulation results are compared with measurements on oil-insulated 150kV/300W high-voltage power supply prototype, discrepancies discussed and opportunities for future work identified.

References

[1] R.Y. Chen ; R.L. Lin ; T.J. Liang ; J.F. Chen ; K.C. Tseng, "Current-fed full-bridge boost converter with zero current switching for high voltage applications" in *IEEE 2005 Industrial Applications Conference*, 2005, pp.2000-2006

[2] L. Dalessandro ; F. Cavalcante ; J. Kolar, "Self-Capacitance of High-Voltage Transformers", in *IEEE Transactions on Power Electronics, 2007, vol22, pp.2081-2092*

[3] F. Blache ; J.P. Keradec ; B. Cogitore, "Stray capacitances of two winding transformers: equivalent circuit, measurements, calculation and lowering" in *IEEE Industry Applications Society Annual Meeting, 1994,* pp.1211-1217

10:40am - 11:00am

Study of a Medium Voltage AC/DC Testbed Employing Electrochemical Energy Storage and Power Electronic Regulation

A. N. Wetz[1], D. A. Wetz[1], J. M. Heinzel[2]

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Electrical power system architectures that are more intellingent are needed to meet the ever changing power requirements in both civilian and defense applications, respectively. Countless migrogrid topologies are being designed, modeled, and experimentally studied everyday to identify and hopefully overcome the many challenges that arise when distributed power sources and loads are interconnected and controlled autonomously. The Pulsed Power and Energy Laboratory (PPEL) at the University of Texas at Arlington (UTA) has developed a real-world testbed for the purpose of investigating control topologies that can be used to reliably control the power electronic distribution system when transient loads are sourced such that power quality is maintained. The testbed, operating at power levels in excess of 300 kW, utilizes distributed AC and DC power sources and loads operating at 480 VAC, 4160 VAC, 1 kVDC, 6 kVDC, and 12 kVDC, respectively. The testbed is being extended utilizing a hardware in the loop (HIL) simulator. The presentation will discuss the design of the testbed, the test plan methodology, and some results collected so far.

11:00am - 11:20am

Analysis of Resonant Behavior of Voltage Multiplier

A. Pokryvailo

Spellman High Voltage Electronics Corp., United States of America

By "resonant" behavior, in broad terms, we mean influence of the multiplier on the current waveforms of the HV transformer. The multiplier is seen by the transformer as an impedance, usually, a capacitive one. For a linearized circuitry, the multiplier can be substituted by a lumped capacitance, C_{add}, connected to the transformer secondary terminals. Such an approach was actively investigated and formalized in the early years of Cockroft-Walton type multiplier developments. It is being equally actively and eagerly reinvented now, many decades later.

Parasitic capacitances Cp's of the multiplier include geometrical capacitances, which are, in general, linear, and nonlinear capacitances of the semiconductors. Early researchers and those who followed them were fully aware of the complex nature of the parasitics. Schemes, of mostly inductive compensation, were suggested to alleviate Cp's negative impact, including improved voltage sharing, or smaller "compression", between the stages.

Usually, Cp's are most prominent at no-load or at a light load. They were mostly how treated this way in the past. It was shown that even at no-load the output voltage would be lower than the expected $2NV_0$, where V_0 is the peak transformer output voltage, and N is the number of cascades (for a classic CW multiplier). However, even under load, Cp's are important, especially if the transformer is fed by a square- or other waveform containing higher harmonics. Cp's are an unalienable part of the converter.

An interplay between the multiplier construction capacitances, C_m, and its C_p's results in complex current waveforms. It is shown both theoretically and experimentally that at a low duty cycle, the transformer windings can be subjected to a "backlash" from the multiplier Cp's, which generates spurious currents in the primary winding. Another non-trivial consequence is that with low C_m/C_p ratio, the leakage inductance is compensated more effectively, and higher power can be made, at a price of a larger compression. Yet another peculiarity is that even with very high C_m/C_p ratio, low Cm values result in the current waveforms that are more resonant, *under heavy load, with N exceeding certain number of stages*. This report concentrates on a classical CW multiplier. Special attention is given to analyzing compression caused by parasitics at no-load.

11:20am - 11:40am

Compact Magnetron Power Supply for Industrial Heating Applications

S. Wei, A. J. Watson, M. R. Ahmed, J. C. Clare
University of Nottingham, United Kingdom

This paper proposes a high-power Magnetron power supply for industrial heating applications with a rated power in excess of 120 kW and an operating voltage over 20 kV. With the aid of silicon carbide MOSFETs, the switching frequency of the power supply can reach 100 kHz, enabling a physical footprint reduction in which is advantageous in some target heating applications, such as those undertaken offshore. The converter modelling analysis and the combined voltage and current control methodology are presented. A non-linear Magnetron type load emulator circuit for the simulation work is also introduced.

The magnetron is an RF vacuum tube capable of generating microwaves. In industrial heating applications, the use of microwaves is much more efficient than traditional approaches using fossil fuels. One such application where the footprint of the heating system is critical is in offshore waste material treatment, where the cost of physical space is very high. Recent advances in the development of wide bandgap semiconductors and magnetic materials enable the potential for operating at a higher switching frequency potentially leading to a size reduction in the overall microwave generation system.

Due to the non-linearity of the magnetron load, a resistor is not sufficient to represent its characteristic in simulation environments, and hence an emulator circuit has been constructed. This provides a better approximation to the voltage-current curve for different working regions of the magnetron.

The proposed converter structure is a single active bridge (SAB). An AC input is rectified to produce a DC bus which forms the source of an H-Bridge circuit. This is connected to a high voltage transformer-rectifier unit (HVTRU) via an inductor for current control. The output of the transformer is then rectified and filtered before being connected to the anode and cathode of the Magnetron. Further details on the topology will be given in the final paper.

The SAB can operate under both continuous and discontinuous current conduction modes (CCM and DCM), and hence the transfer functions should be derived separately. Also, due to the requirement of the magnetron load, a voltage controller needs to be used when increasing the voltage before the tube conducts current and a current controller is required once the tube is conducting. Since the voltage controller works in DCM for start-up and the current controller works in both CCM and DCM, 3 different control approaches are required for the full operation of the system. The controllers are tuned to ensure that the output power of the RF tube can be controlled with an acceptable response and speed, limiting the possibility of arcs and being able to respond quickly to limit input power into the magnetron if one occurs, extending lifetime.

In the final paper, full details of the system design will be presented. The control design challenges and solutions will be presented and simulation results used to validate the operation of the power supply.

11:40am - 12:00pm

Impulse Generator for Simulating Lightning-Induced Pulse Transients for Airborne Equipment Test

S.-M. Park, W.-C. Jeong, H.-J. Ryoo
Chung-Ang University, Korea, Republic of (South Korea)

This paper deals with design and implementation of the test equipment capable of simulating various types of lightning-induced pulse transients required by an international standard which defines the test condition and procedures of airborne equipment. The impulse waveforms required by the standard are composed of dozens of types based on various criteria such as voltage and current level, shape, rising/falling time, and repetition rate. Therefore, existing commercialized test facilities use a method of charging a storage capacitor using high-voltage capacitor charging power supply (CCPS), and configuring PFN circuit with the capacitor to generate a required test waveform. However, according to various conditions as mentioned earlier, multiple PFN circuits are designed and the storage capacitors of each PFN have a wide capacitance range from several nF to hundreds of μF; so the CCPS is also manufactured in two or more units, and the method of selecting and replacing each CCPS and PFN according to the test condition is currently used. However, in this study, 11 PFN circuits for each waveform and a single high-voltage CCPS that can cover a wide range of load capacitances ranging from 1 nF to 150 μF with maximum ratings of 12 kV charging voltage, 20 kHz repetition rate, and 245 kW peak power were designed and developed. Since the CCPS should be able to charge the load capacitor with a relatively large capacitance in a short time while considering the precision of the charging voltage for the loads of several nF level, the proposed single CCPS is designed as a dual-converter configuration consisting of a high-power (HP) and low-power (LP) converter. Each converter is designed based on the modified LCC resonant converter for high-efficient operation, and is capable of being operated independently or in parallel depending on the type of test waveform. In addition, considering the required level and precision of charging voltage for each load, the HP converter is designed to automatically stop generating the gate signal when the charging voltage reaches approximately 7 kV. Finally, a single CCPS was developed in a volume of 29.3 L, with design considerations such as high voltage isolation and development of high voltage and high frequency transformers. Through the experiments using the developed CCPS and each PFN load, it was confirmed that all test waveforms defined in the standard could be generated.

Poster 1: HPM, Repetitive Pulsed Power, Plasmas, Dielectrics, & Analytical Methods

Time: Monday, 20/June/2022: 1:30pm - 3:00pm · *Location:* Exhibition Hall D / Henley Concourse
Session Chair: Matt Lara

Multipactor Suppression in X-band Waveguide Utilizing Surface Coatings

H. N. Spencer, D. Wright, A. Gregory, J. Stephens, A. Neuber
TTU, United States of America

Multipactor (MP) is a phenomenon where electron multiplication via secondary electron emission (SEE) can occur in waveguides under vacuum conditions. The effects of multipactor can lead to component damage or destruction. This study will explore techniques to suppress MP via modification of the secondary electron yield (SEY) using surface coatings and surface treatments.

This study applies a previously developed X-band high power microwave system and TE_{10} impedance transformer to test and compare MP formation in a pure copper sample versus samples with surface coatings and treatments. Surface coatings such as Titanium Nitride and Titanium Chromide are of particular interest to this research as they can shift the first crossover point to higher primary electron energies, thus potentially improving the longevity of space-based communication systems and accelerators. The maximum threshold power achievable by such systems may consequently be further increased. Experimental findings are reported and compared against simulations and available literature.

This research was supported by the Air Force Office of Scientific Research under contracts FA9550-18-1-0062 and FA9550-21-1-0367

Development of GaN HEMT based positive and negative, 5 kV, nanosecond pulse generator for the SLS 2.0 fast injection kicker

M. Paraliev
Paul Scherrer Institute, Switzerland

The SLS 2.0 project aims upgrading the existing 3rd generation Swiss Light Source (SLS) at the Paul Scherrer Institute in to a 4th generation, diffraction limited light source down to soft X-ray wavelengths, to substantially increase its brightness and to ameliorate the photon beam stability in top-up mode.

Conventional (four kicker) top-up injection in a Storage Ring (SR) perturbs the stored electron beam, causing disturbance or interruption in the photon beam provided to the experimental stations. This creates inconveniences to sensitive experiments and reduces the total available photon flux. To minimize this effect, parallel to the baseline four kicker injection system, SLS 2.0 plans to adopt a novel electron injection scheme (aperture sharing) that should limit the perturbed portion of the stored beam to only about 3%, leaving the rest of the beam to radiate undisturbed.

A fast injection kicker, with deflection duration of less than 30 ns, kicks the injected and a small portion of the stored beam in such way that they both are accommodated in the SR dynamic aperture. After some damping time, the injected and the displaced stored electron bunches join together returning to the nominal beam orbit, replenishing the stored beam. To power such fast kicker, short (<30 ns), positive and negative electrical pulses with up to 5 kV amplitude are necessary. We describe the progress in the development of a GaN HEMT based Marx pulse generator, capable of satisfying these requirements.

Improvements of a Branch Module for an Inductive Voltage Adder based on Measurements and Circuit Simulations

J. Ruf[1,2], M. J. Barnes[1], T. Kramer[1], M. Sack[2]
[1]CERN, Switzerland; [2]Karlsruhe Institute of Technology, Germany

For future upgrades of some CERN kicker systems, doubling of the driving current by replacing a matched impedance by a short circuit termination is of interest, because it allows a doubling of the kick strength, without an increase in magnet length or generator voltage.
Therefore, for driving kicker magnets featuring a short-circuit termination, a novel approach for a pulse generator architecture based on an inductive voltage adder is currently being investigated. The primary of the inductive adder consists of layers - the number of layers is dependent upon the required output voltage. Each layer has parallel connected branch modules – the number is dependent upon the required output current. The short circuit termination leads to a traveling wave that is reflected back from the load to the generator. This results in a doubling of the current flowing through the kicker magnet and, thus, the magnetic field for a given system impedance and magnet length.

For this application, a branch module for an inductive voltage adder has been designed and built. To account for the reflection at the short circuit, the branch module has a topology comprising two independently controlled semiconductor switches. This allows energy to first be injected into the kicker magnet, then to circulate the resulting current in a freewheeling-interval, and the energy to be reabsorbed at the end of the pulse. To avoid perturbations in the waveform of the generated pulse, fast and precise switching is of importance. To validate the operation of the module, it has been tested with a resistive load of 10Ω. This test revealed undesired oscillations of the pulse shape. In order to investigate these issues and to improve the circuit, a circuit simulation model has been developed including relevant parasitic parameters of the circuit elements. The simulation showed good agreement with the measurements. Hence, it was possible to identify and implement measures to damp the oscillations, both in the simulation and the real circuit as required for the application. The contribution describes in detail the measurements and simulation results as well as the implemented improvements to the circuit.

A Compact GNLTL Using Permanent Magnet Rings With Improved H-field Uniformity

J. O. Rossi[1], F. S. Yamasaki[2], J. J. Barroso[2], A. F. Teixeira[2], A. F. Gudes Greco[2], E. G. Lopes Rangel[2], L. P. Silva Neto[3], E. Schamiloglu[4]

[1]FUNCATE; [2]National Institute for Space Research; [3]UNIFESP; [4]UNM

There has been a great interest in using gyromagnetic nonlinear transmission lines (GNLTLs) for compact applications in defense platforms, radars, and space as pulsed RF transmitting sources. The reason is that the GNLTL is all solid-state and does not require vacuum and heating as power electronic tubes. As these devices employ axial magnetic bias, permanent magnets can replace the solenoid to reduce weight and dimension. The ideal case for this is to use neodymium rings along the line. However, the magnet ring configuration produces lower H-field uniformity to the solenoid [1], producing very low pulse modulation in the RF signal generated with a longer line (50 cm or more). Therefore, the solution appears to be using a small line length of 10 cm as we verified the H-field is improved using a low number of magnets that could lead to a better pulse modulation [2]. Then, in this work, we will present the results obtained with a bench compact shorter line (10 cm) using neodymium ring magnets operating with a Gaussian shape input pulse in the range of 6-12 kV and with a width of about 15 ns.

[1] J. Bragg, J. Dickens, and A. Neuber, "Magnetic biasing of ferrite filled nonlinear transmission lines," *2010 IEEE International Power Modulator and High Voltage Conference*, 2010, pp. 600-603, DOI: 10.1109/IPMHVC.2010.5958430.

[2] J. O. Rossi *et al*., "RF Generation Using a Compact Gyromagnetic NLTL with Permanent Magnets *," *2021 IEEE International Conference on Plasma Science (ICOPS)*, 2021, pp. 1-1, DOI: 10.1109/ICOPS36761.2021.9588544.

-Work supported by SOARD/AFOSR, FAPESP, and CNPq under contracts no. FA9550-18-1-0111, 2018/26086-2 and 306540/2019-3, respectively.

Initial Development of an Inductive Adder for High-Energy Beam Kickers

J. R Prager, K. E Miller, K. Muggli, C. Schmidt, S. Wilson, H. Yeager

Eagle Harbor Technologies, Inc., United States of America

The Electron Ion Collider being constructed at Brookhaven National Laboratory (BNL) requires a 150 MeV energy recovery LINAC, whose design includes a new short-pulse stripline kicker. The kicker power system must deliver ±50 kV pulses with pulse widths of less than 38 ns into a 50 Ω load and with low jitter. The kicker power system must be highly reliable and robust to potential faults. Eagle Harbor Technologies (EHT), Inc. is developing a new inductive adder that can meet the needs of the BNL kickers. In this program, EHT designed a single inductive adder stage that was used to demonstrate the pulse characteristics including fast rise and fall times, low jitter, and flat-top stability while operating at the full current (1 kA). EHT will present the development status and output waveforms.

A Bipolar Microsecond Pulser for Electroporation and Cancer Therapies

J. R Prager, A. Henson, K. Muggli, H. Yeager, C. Schmidt

Eagle Harbor Technologies, Inc., United States of America

Emerging biomedical therapies that use electroporation and other electrode-driving techniques require new medical pulsed-power systems. In electroporation, electric fields are applied to cells to increase the permeability of the cell membrane. Chimeric antigen receptors (CAR) T-cell-based therapeutics is a growing electroporation application that requires complex pulse and burst patterns with high-voltage, bipolar pulses.

To address the growing biomedical market demand, Eagle Harbor Technologies, Inc. (EHT) developed a programmable, bipolar microsecond pulse generator. This pulse generator produces ±3 kV pulses with pulses widths from 500 ns to DC at high pulse repetition frequencies up to 100 kHz and precision burst control. An internal microcontroller combined with a graphical user interface allows the user to remotely control the pulse widths, dwell times, and burst patterns. We will present the pulser capabilities including output waveforms.

X-band Relativistic Backward Wave Oscillator with Dynamic Frequency Tunability

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Relativistic tubes are generally used for High Power ElectroMagnetic (HPEM) applications. Most of these tubes radiate high level electromagnetic fields but operate at a fixed frequency. Nevertheless, in most cases, a variable frequency is required. In a previous study, CEA worked on a very compact HPEM source named CLAIRE. The used tube was an optimized X-band sub-gigawatt relativistic resonant Backward Wave Oscillator (BWO) using low-level magnetic field. Based on it, a frequency tunable BWO have been designed last year. Desired tunable frequency range is obtained by changing the distance between the resonant reflector and the Slow Wave Structure (SWS). The first experiments were operated with a fixed frequency. The goal is to obtain a dynamic tunability, which means that the frequency is tuned during a burst. Besides, a gap exists between resonant reflector and tube to facilitate the fast shifting of the reflector. As the electrical contact is not perfect, the impact of a gap on microwave signal was studied in simulation and experimentation. A specific prototype has been realized with an high mechanical accuracy. Two linear stepper motors allow the the resonant reflector motion into the tube. Two bellows maintain good vacuum state while the resonant reflector is mechanically actuated. In the new experiments, the dynamic tunability is validated during a 6s burst. This paper presents the analyzed results, and the comparison with fixed frequency results.

A High-Power Microwave System for Benchmarking the Microwave Dielectric Strength of Carbon Fluoronitriles

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Concerns about sulfur hexafluoride's (SF6) high global warming potential (GWP) have motivated the search for alternative insulating gases. Among the many possible alternatives, carbon fluoronitriles have been demonstrated as a promising alternative to SF6. Gases such as C4F7N (3MTM NovecTM 4710) feature a dielectric strength comparable to that of SF6 while simultaneously offering up to 99% reduction in total GWP. However, prior studies have been largely limited to long-timescale DC and 60 Hz AC conditions. This study details the development of a pulsed, highpower microwave system to experimentally characterize the microwave breakdown strength of C4F7N under microsecond pulsed conditions. This system utilizes a 3 MW S-band (2.85 GHz) high power magnetron and a resonant ring structure to deliver an effective microwave power of 20 MW to a stepped impedance transformer, yielding local electric fields exceeding 150 kV/cm (RMS). Microwave system design, calibration, and absolute field measurement data are reported. Design considerations for the gas mixing, gas isolation, and materials compatibility are reviewed, and initial measurements of dielectric strength are reported.

Investigating the Dynamic Behavior of Copper Foils Driven by a Megaampere Class Capacitor Bank

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We report on the results of an investigation into the dynamic behavior of copper foils when driven at megaampere current amplitudes from a capacitor bank. For these studies, the cross-sectional area and length of the foils was kept constant, while the thicknesses were varied - from a few tens of microns to greater than one hundred microns. The initial mass of the foils was approximately 3 grams. The typical rise-time to peak current in the circuit was in the range of 10-20 microseconds. A diagnostic suite – which included B-dots, D-dots and Faraday rotation sensors – was used to record foil voltage and current time-histories, which in turn were used to calculate the dynamic impedance of the foil circuit. Optical diagnostics, including high speed imaging, were also used to record the dynamic behavior of foils as they were driven through different phase states by the high current discharge. Experiments were conducted in both axisymmetric (cylindrical) and non-axisymmetric (planar) geometries. The media surrounding the foils was also varied to characterize its influence on the dynamic impedance.

Increasing the Hydrophobicity of Silicone Rubber for Electrical Insulators by Rapid Treatment with Pulsed Gliding Arc Plasma in Air

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Hydrophobicity of silicone rubber (SR) is important for the anti-ice and anti-pollution property and flash-over performance of electrical insulators in transmission lines. In this work, gliding arc (GA), as one kind of non-equilibrium plasma, is generated by pulsed high voltage supply with ambient airflow and it is adapted for increasing the hydrophobicity of SR. Kaolin and NaCl solution are used for contaminating suspension and different salt deposit density (SDD, from 0.125 to 1 mg/cm^2) is applied. It is found that with SDD of 0.125 mg/cm^2 and only 30-second treatment with GA, the water contact angle (WCA) of SR increases from ~ 120° to 150°. Even so, with SDD of 1 mg/cm^2, GA treatment of 300 seconds is needed to increase WCA from ~ 10° to 114°. In order to analyze the functional species in GA, optical emission spectroscopy is measured, which illustrates that the O atom has the highest intensity and the energy transfer from excited N_2 to O_2 contributes to a high O_2 dissociation degree. Assisted with Fourier transform infrared analysis of original and treated SR surface, it is demonstrated that high-density O atoms generated by pulsed GA selectively etch the organic matrix of SR and accelerate the accumulation of hydrophobic components in the contaminant. This work proposes a rapid treatment method for increasing SR hydrophobicity, which only consumes electric power and ambient air (without any precursor or rare gas) and has a bright potential for application in the engineering field. [This work is supported by Open Fund of State Key Laboratory of Power Grid Environmental Protection (China Electric Power Research Institute), No. GYW51202101370]

Investigation of sawing Response of PBX 9501 and PBX 9502

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The machining of explosive driven high current devices presents unique challenges in the safety of the operators, integrity of the part, and the timely completion of the operation. Previous works have shown that simple reduction in working speed can be detrimental to the safety of the operation and proper investigation into the machining parameters is needed to avoid dangerous conditions. This work investigates the operating conditions of a band saw in the cutting of polymer-bonded explosives (PBX). Samples of PBX 9501 and PBX 9502 are subject to a range of sawing speeds and feed speeds. Utilizing IR imaging and a force plate the heating of the blade is measured along with the overall forces on the work piece. Further, application of thermocouples in the work piece present more direct access to the conditions of the temperatures in the material of concern. Finite element simulation has been applied to give insight into the internal heat transfer occurring during sawing.

Experiments on a Scaled Rebar Structure to Quantify Lightning Strike Induced Fields on Rebar Reinforced Concrete Structures

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Understanding electric and magnetic fields induced by lighting strike events is crucial to developing efficacious techniques for mitigating the negative effects of lightning strikes. However, experiments investigating the matter are sparse in literature as the prohibitive cost and complexity associated with a full-scale experiment make it impractical to perform. Utilizing electromagnetic scaling relations, scaled experiments allow for the collection of data that may be directly translated to equivalent full-scale quantities. As a second benefit, scaled experiments may also be used to validate computational models that can then be employed for full-scale simulations. Using this scaling principle, a single-layer rebar structure with a 1:4 scale has been constructed consistent with standard construction practices for steel-reinforced concrete structures. Unlike typical rebar structures, this scaled structure features a U-type electrical discontinuity in the roof, which is representative of the full-scale structure of interest to this study. A four-stage Marx generator is used to excite this structure with a peak current of 50 kA. Using a low inductance path, the output of the generator is fed to an attachment point on the structure while maintaining the required scaled rise time of 1.5 µs. Using a Prodyn B-10/20D B-Dot and AD-100R D-Dot probe, the fields produced during the attachment event are investigated. The ground point of the structure is controlled through a single low inductance strap attached to a point on the cage and fed to the building ground. The current passing through the grounding strap is monitored by a Pearson coil (Model #1330), allowing for strike current and waveform shape to be collected. Experimental measurements are compared with the computational model results to verify the computational model.

The characteristic effects of dielectric coatings on electrical exploding film phenomena

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The exploding film phenomenon have a wide a variety of applications in the areas of fast switching, ceramic joining, nano-powder production and exploding bridge wire detonators. Exploding films have many of the same characteristics of exploding wires and foils when they are subjected to high energy densities on the order of magnitude of 10^7-10^8.The metallization layer is heated rapidly up to vaporization where the film explodes and the metal layer is ejected from the substrate. The dielectric coating in the exploding wire phenomena has been previously researched and shown to exhibit a significant increase in energy deposition in the wires core before plasma formation. This work investigates if there is any correlation on how the dielectric coating will affect the exploding film event. Current wave forms of initial strike, dwell time, maximum current of restrike and event duration were analyzed.

Energy dissipation and efficiency of exploding film phenomena at varying stack length and thickness

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Metalized polypropylene films (MPPF) can substitute as an alternate for exploding wires in several applications. MPPF can implemented in several different orientation and shaped for more defined functions and applications. Different metallization and substrate thickness have previously been studied at the Energy System Integration laboratory. This work investigates how the plasma formation and electrical characteristic of the phenomena is affected when the MPPF a stacked in multiple parallel configurations.

Benchmarking the suitability of Novec TM 4710 for application in flux compression generators

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Current data indicates that C_4F_7N (3M, Novec^{TM} 4710) may have many benefits over traditional insulating gases, such as SF_6. For example, data has shown that pure Novec^{TM} surpasses SF_6 electrical insulating properties. However, the data available is primarily for DC or low frequency (i.e. 60 Hz) conditions and at static pressures. For applications such as flux compression generators (FCGs), the operating conditions are significantly different, and we have yet to see any data which is suggestive of Novec^{TM} performance under dynamic stresses similar to those found in FCGs. Here we report a performance comparison of FCGs utilizing air, SF_6, or Novec^{TM} 4710 as the insulating gas. Generators used for this study consist of a single stage, single-pitch helix having an inner diameter of 46 mm (1.8 in), and employing an armature with a diameter of 25 mm (1 in). Direct current seeding is applied to the FCG. In the initial testing, the stator wires are kept bare of insulation to simplify the performance assessment to focus on the different gases. In the experiments, seed current, and load inductance, are explicitly chosen to emphasize the performance differences between Novec^{TM}, air, and SF_6 while avoiding statistical variations in other potential flux loss sources that could mask the gas-specific results. The generator dI/dt is monitored using Rogowski coils and provides the primary indications of gas insulation failure, that being sudden deviations or partial collapses in the waveform during FCG operation. The voltage and electric field distributions within the generator during times of observed indications of breakdown are estimated from modeling and simulation. Other comparisons of FCG performance - namely current gain, energy gain, and output voltage - are provided as well. Future research will address the performance of Novec^{TM} 4710 in more practical FCGs that typically have a stator fitted with solid dielectric insulation. Mixtures may be investigated in the future to evaluate what it would take to match SF_6 performance. In this context, we note that for low-frequency conditions, a mixture of 20% Novec^{TM} 4710 with CO_2 already matches the insulating performance of SF_6.

Impact Low Pressures on Internal Partial Discharge under DC Voltage

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All-electric transportation is targeted as one of the potential pathways to achieving net-zero emission. While electric vehicles are getting close to maturity, the aviation industry is in its infancy for achieving an electrified aircraft that properly operates over commercial missions. Aircraft electrification has given rise to two types of aircraft: more electric aircraft (MEA), all electric aircraft (AEA). A primary goal of this path is to make the power density of the MEA/AEA closer to that of conventional aircraft. To this end, while current commercial aircraft operate at voltages below 1 kV, it is widely accepted that higher operating voltages are necessary for MEA/AEA; and dc is also preferred instead of ac. From an insulation point of view, while our understanding of partial discharges as the main cause of aging and degradation of solid insulation is still immature, a harsh environmental condition, low pressures, is added to the set through the trend mentioned above. This paper aims to develop an algorithm based on finite element analysis (FEA) to model internal PD under dc voltage at low pressures. The entire algorithm is implemented in MATLAB which is interfaced with COMSOL Multiphysics for accurate simulation and calculation of electric stress in the void. The model will be validated through experimental studies. To make internal PDs, testing samples are built through 3D printing with a void inside with known size. To the best of our knowledge, this work has not been done to date. Using the model, the influence of low pressures on internal PD activity is elucidated, and parameters and mechanisms affecting PD under dc at low pressures are identified.

Study of Partial Discharge Inception Characteristics of Aviation Wire Stressed by PWM Voltages under Various Air Pressures

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Partial discharge (PD) is a common and detrimental phenomenon that can cause damage and potential breakdown in insulation systems. According to the Paschen's curve, from sea level to high altitude, the partial discharge inception voltage (PDIV) of the air will decrease with decreasing pressure. So far, there has not been a widely accepted PD testing method for aviation wires in low pressure environment with pulse width modulated (PWM) voltage excitations. There have been studies of the PD behaviors of aviation wires with conventional triangular impulses, ac voltages, and PWM pulses with relatively low dv/dt before. But existing test methods and study results cannot be directly utilized to test and predict PDIV of aviation wires when high dv/dt PWM excitation is applied with wide bandgap (WBG) power devices, such as Silicon Carbide (SiC) Metal Oxide Semiconductor Field Effect Transistors (MOSFET).

Thus, this paper aims to provide more insights on PD behaviors of aviation wires under high dv/dt PWM excitations and possible ways to improve the existing PD test methods. A test setup including an ultra-high dv/dt PWM generator, a test sample fixture, and associated PD sensors including a photomultiplier tube (PMT) and a high frequency current transducer (HFCT), will be introduced. Experimental results and associated analysis for aviation wire test samples at various pressures under high dv/dt PWM excitations will be presented. The effect of the rise time of the PWM will be discussed in detail. Suggestions on how to improve test methods and test standards will be provided.

Optimal Energy and storage abilities of super capacitors

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In terms of energy storage, conventional batteries are the most widely used technology in today's devices and automobiles. However, they lack some qualities that capacitors can provide and are also not as environmentally friendly. Even so, Li-Ion batteries have a much higher energy density of 120-170 Wh/kg compared to capacitors at 5-10 Wh/kg which is a firm requirement for modern electronics. Super capacitors offer traits that normal capacitors cannot in terms of their energy capacity and capacitance. This type of capacitor operates by combining the technology of normal capacitors and batteries. Super capacitors use electrolyte concentrations separated by an insulator similar to a battery. Unlike batteries though, super capacitors utilize the physical movement of ions instead of chemical reactions. For this reason, super capacitors have long life times of over 100,000 cycles which makes them usable for decades without replacement. Additionally, because super capacitors take much less longer to charge and discharge they can deliver larger amounts of instantaneous power. In order to achieve the optimal energy storage device these technologies can be integrated to balance power density with energy density. Using a design composed of a Li-Ion battery in tandem with a super capacitor will be simulated in MULTISIM then built into a circuit to demonstrate the balance of energy and power in an electric motor. The energy and power will be measured using the voltage, current, and time readings provided by the circuit. The results will be compared to each of the technologies individually to emphasize the benefits of the design.

The investigation of dielectric elastomers as non magnetic polymer motor

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Dielectric elastomers (DE) are a subgroup of Electroactive polymers (EAPs) that have the potential of exhibiting large strains in the presence of an electric field. This process produces a compressive and tensile force that causes the film membrane to reduce in its thickness and expand in area which creates linear actuation in response to the application of an electrical stimulus. The actuation of the elastomers is governed by maxwell stress and electrostriction, and this paper will investigate the efficiency and effectiveness of applying and configuring a DE a non-magnetic motor.

Syntherization and characterization of ceramic capacitor based on BZT for use in nonlinear transmission lines

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Nonlinear transmission lines -NLTLs have been investigated as a high-power RF source to apply in radars, battlefield communication disruption, satellites, biomedical instrumentation, and other communication systems [1-2]. Another way to produce the RF signals on NLTL is using nonlinear components such as ceramic capacitors. In this work, we synthesized and characterized a barium zirconium titanate ceramic for use in nonlinear dielectrics. Its application is in NLTLs due to their high permittivity > 5000 in the phase temperature transition with low tangent loss < 0.07. The electrical characterization investigated in this work is in temperature, frequency, and DC voltage sweep, which give the nonlinearity factor of ceramic, a key parameter to produce RF in NLTL, and the dielectric strength to know the breakdown voltage in the pulsed power systems.

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Research on Enabling Process Optimization Methods of Metallized Film Capacitor Elements based on Self-healing Frequency Change Characteristics

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The enabling process is one of the most important manufacturing processes of metallized film capacitors, which has a great effect on the reliability. The electrical weaknesses and defects can be effectively removed by the self-healing during the enabling process. At present, the parameters used in enabling process of metallized film capacitors are empirically determined, and the influence of the parameters on the reliability has not been characterized. In this paper, electro-thermal stress test platform with DC plus harmonic AC voltage will be built. The platform is composed of programmable temperature and humidity test chamber, multi-frequency compound source and self-healing current pulse counter, etc. By changing the operating temperature and the frequency components of the operating voltage, the repetition frequency of self-healing current pulses in continuous periods of time will be recorded under various temperature and voltage frequency. A set of self-healing frequency changing curves will be obtained. Compared with the trend of the infant mortality of the bathtub curve, the most efficient and reliable enabling parameters for metallized film capacitors in different application scenarios will be summarized. This research is of great significance for standardizing and optimizing the enabling process of metallized film capacitors.

Influence of Charge Traps on Flashover Characteristics of Epoxy Resin in Liquefied Natural Gas under DC Voltage

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Liquefied natural gas (LNG) has been widely used as a cooling medium, but its dielectric properties are poorly understood. The use of LNG as the insulating and cooling medium of superconducting energy pipeline is a milestone technology to realize the efficient transmission of power and fuel [1]. The research on insulation characteristics of LNG is related to safe and reliable operation and technological upgrading of superconducting energy pipeline. As one of the main evaluation indexes of insulation system, flashover characteristics of LNG need to be studied in detail from two aspects of experiment and mechanism [2, 3]. In this paper, the solid-liquid interface composed of Glass epoxy laminate sheet (G10) and LNG was taken as the starting point. Firstly, the flashover voltage and current at the solid-liquid interface were measured, and the data were analyzed by using two-parameter Weibull model. Secondly, the surface morphology evolution of G10 before and after flashover was observed. Finally, the flashover mechanism is explained based on the charge trap theory, and the trap energy level and density distribution before and after flashover were measured by isothermal surface potential decay method. This research enriches cryogenic temperature insulation properties of polymer and provides theoretical and experimental support for the development of electrical equipment represented by superconducting energy pipeline.

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Density Functional Theory Calculations of Modified Work Functions for Composite Materials

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Electron emission plays a vital role in numerous applications, including thermionic energy converters, electric propulsion, high-power microwave systems, and ultramicroscopy [1]. Characterizing the electron emission and gas breakdown behavior for these devices is critical for ensuring device reliability and optimum operation. One parameter that may be tuned to adjust electron emission is the work function of the emitting material [1]. Decreasing the work function can enhance emission for high current applications, while increasing the work function can prevent unwanted or damaging electron emission that may lead to gas breakdown in microscale devices. The work function can be modified by surface features on the electrode [2] and by the type of material and surface treatment used [1]. In this work, we assess how using various composites and adjusting surface structure can alter the local work function by using density functional theory (DFT). DFT finds the equilibrium position of atoms within a supercell structure, relaxing the positions to minimize forces. The work function is calculated as the difference between the Fermi and vacuum level energies [3]. We use the Spanish Initiative for Electronic Simulations with Thousands of Atoms (SIESTA) code, an open source code that uses a linear combination of atomic orbitals (LCAO) basis set and pseudopotentials to solve DFT problems [3], to examine the ability to tune work function by adjusting the composites or surface structure. The implications of this work function tunability will be assessed in the context of electron emission and microscale gas breakdown theory to elucidate potential material development for either enhancing or mitigating electron emission. We will summarize the methods and preliminary results, conjecture on potential implications on emission and breakdown performance, and discuss other applications of DFT to composite materials relevant to the power modulator community.

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Protection Assessment of Lightning Strikes on Concrete-Steel Structures simulated at full-scale

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The ability for a structure to provide adequate shielding from the fields induced by lightning attachment is of critical importance. Steel-reinforced concrete structures offer some protection. However, these structures may contain electrical discontinuities in the rebar reinforcement that potentially reduce the structure's shielding capacity.

The induced electric and magnetic fields inside a full-scale model of a steel-reinforced concrete structure with a soil overburden are simulated in electromagnetic software to determine the effective shielding provided by the structure against a lightning protection level (LPL) category one strike. The strike attachment point and strike type (positive/negative) are varied with the fields internal to the structure, evaluated to understand the spatial relation of the strike attachment point on field magnitude. Following NFPA 780, regulation defining lightning protection systems (LPS) for buildings, a model incorporating an overhead catenary wire is analyzed to determine the field mitigation provided by the LPS. The moisture content of the structure’s concrete frame and surrounding soil, as well as soil composition, are investigated to determine their influence on the structure’s internal field levels during attachment. Additionally, the strike rise time is varied to determine the shielding capability of the structure as a function of the strike’s frequency. The simulation models are analyzed to determine a parameter space that promotes an electromagnetically resilient structure against a worst-case attachment scenario.

Multipactor saturation variances due to changes in the SEY curve*

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Multipactor susceptibility regions, when probed through simulations based on a Vlasov-Poisson scheme using finite difference time domain methods (FDTD), show their sensitivity to small changes in the secondary electron yield (SEY) curve. Variations in the 1st SEY crossover points and shape approximations of the SEY curve can result in distinct shifts of the multipactor susceptibility regions. These changes in multipactor susceptibility regions proliferate into changes in multipactor saturation. As multipactor growth occurs, the electron density will eventually achieve saturation due to space charge effects arising from within the electron swarm. In a parallel plate geometric structure, electrons in the center are retarded by electrons near the plates, thus limiting electron growth. Our simulations have shown that variations in the SEY curves can lead to alterations in the rate at which multipactor saturation is reached. The SEY curve also influences the electron density at which multipactor saturation occurs, as well as the peak-to-peak oscillation of the electron density once saturation occurs. As the area of the SEY curve above unity increases, compounding effects are seen in the electron density over time. In this presentation, alterations in the approximate SEY curve shape, 1st crossover point, and maximum SEY are evaluated in detail based on the Vlasov-Poisson scheme to analyze the effects these characteristics can have on multipactor saturation.

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Variation of the Hull Cutoff Magnetic Field with External Resistance and Collisions

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Crossed-field diodes (CFDs), in which a magnetic field is applied orthogonal to the electric field induced by the applied voltage across the anode-cathode gap, are used in multiple high power applications. One of the critical quantities used to characterize a CFD is the Hull cutoff magnetic field (HCMF), which represents the maximum applied magnetic field for which an electron emitted from the cathode still reaches the anode [1]. CFDs with magnetic fields above the Hull cutoff are referred to as magnetically insulated. This Hull cutoff is a critical threshold for characterizing CFD operation since many parameters, such as the maximum stable emission current [1], differ depending on whether or not the CFD is magnetically insulated. However, the traditional Hull cutoff assumes a vacuum planar diode, which may not represent actual operating conditions.

This presentation investigates the implications of adding an external resistor to represent dissipation in the circuit or collisions to represent imperfect vacuum on magnetic insulation. For magnetic fields just below the HCMF, adding an external resistor can cause emitted electrons to return to the cathode. We refer to this condition as "semi-magnetically insulated," since this onset of magnetic insulation is not steady-state. We derive equations for this modified Hull cutoff by accounting for the differences between the applied voltage and potential drop across a CFD in the presence of the resistor. We then use the 1D/3v (one-dimensional in space and three-dimensional in velocity) particle-in-cell software XPDP1 to validate these results. We further assess the modification of the Hull cutoff by incorporating collisions in a CFD. Previous theory and simulations have demonstrated that including ions in the gap could cause a loss of magnetic insulation [2]. By incorporating electron mobility into the electron force law for a CFD, we examine changes in the Hull cutoff as a function of mobility. These results will be compared to XPDP1 simulations, demonstrating changes in magnetic insulation for various pressures. The implications on practical CFDs operating near the Hull cutoff, as studied recently theoretically and experimentally for magnetically insulated line oscillators (MILOs) [3], will be discussed.

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The Pulsed Magnetic Field Diffusion into Moving Metal Body with Pre-Created Gradient of Electrical Conductivity (Numerical Analysis in 2D Model of FlexPDE-6 software)

V. T. Chemerys[1], I. O. Borodiy[2]

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The problem of the pulsed magnetic field diffusion into non-uniform media has been studied in the numerous papers and monographs, which can be called to-day as classical, mainly from the point of view when the media became heterogeneous in result of Joule's heating in the process of intensive interaction with electromagnetic field, or when the medium initially was formatted as the mixture of heterogeneous elements or grains. Beside of such approach, today is of interest to consider the situation of pre-created non-uniform distribution of electrical conductivity coefficient (in more general case [1] – coefficient of magnetic diffusion) as the smooth function along one or two coordinate axes. Similar situation can be created in the process of metal sample manufacturing with a purpose to supply him the special properties. A theoretical background for such approach was prescribed by first author in the paper of 2020 year [2]. There was shown in 2D model how the presence of electrical conductivity gradient had a specific influence on the induced current distribution which can be treated in result as appearance of correction for distribution of pulsed field applied along the normal to the plane of symmetry of model. For the numerical analysis of this process has been chosen a software FlexPDE-6.37 due to principal ability to introduce the gradient of electrical conductivity into system of the field equations as pre-defined smooth function of coordinates, for example, exponential one. The performed numerical experiments provided a demonstration of additional way to control the speed of pulsed field diffusion in the non-uniform sample. Taking into account the velocity of sample movement had allowed to view the process diffusion both for the motion of sample out of applied magnetic field source (a mode of the field decompression) and for the moving to (a mode of the field compression). The results of simulation has been illustrated by the graphics, which represent distribution of electromagnetic quantities along the plane of model at different form pre-defined coefficient of electrical conductivity. The program for the FlexPDE-6.37 which has been used by authors can be included in the appendix of the full description of this work.

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The physical model of explosive ion emission

S. Korenev

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Explosive Ion Emission has been discovered by Dr. Sergey Korenev in 1985 [1]
The explosive ion emission developed the following applications.
Deposition of thin metal films.
Deposition of high temperature super conductor materials.
Formation of high intensity Ion beams.
In spite of such unique applications, physical model of this phenomena has not been created.
Physical model of ion emission is based on the following:
Explosive electron emission from metal mesh cathode with high coefficient of transparency.
Heating of material anode by bombardment high intensity electron beam from metal mesh leads to forming of anode plasma, which is a emitter of ions.
Experimental testing of suggested physical model has been completed on modified Radan [2], which allows to generate positive polarity of voltage using double forming line and charged second coil Tesla transformer.
Experimental study included the measurements of electron and ion current by Rogowski coils and shunt.
The present of electron current allows to acceptable this physical model of Explosive Ion Emission.

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Wavelet Based Feature Extraction From High Voltage Impulse Signal

E. Onal[1], T. C. Akinci[2], A. M. Morales[2]

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WAVELET-BASED PARAMETER ESTIMATION OF

HIGH VOLTAGE IMPULSE SIGNALS

In transmission and distribution systems, electrical equipment is commonly exposed to impulse voltage and currents produced by lightning strikes and switching operations. Transformers, insulators, cables, overhead lines, and other electrical equipment suffer malfunctions and insulation problems leading to short circuits and interruptions in electrical networks.

The parameters of peak value, front time, time to half value, and time to chopping are substantial variables in producing a standard impulse waveform. Nevertheless, disturbances like oscillations and/or overshoots may occur in the impulse signals, preventing accurate and precise testing of high voltage equipment. The frequency range of disturbances varies depending on the source such as the equipment itself, test and measurement systems, and ambient conditions. Eventually, the k-factor filtering approach was suggested in the IEC 60060-1 standard. In this method, the disturbance of oscillations and overshoots are removed from the impulse signal by residual filtering using the k-factor approach.

This study is focused on wavelet-based analysis for the evaluation of impulse signals providing curve fitting and the filtering of disturbances resulted from oscillations and/or overshoots. A wavelet transform has the significant features of presenting time and frequency information at the same time while enabling signal de-noising naturally. Fourier based transforms suffer fixed resolution of window function while wavelet-based approaches provide better time and frequency resolutions. A wavelet-based transform provides sub-band decomposition while presenting curve fitting and de-noising in each level of resolution.

In this context, wavelet based multiresolution analysis was introduced as a suggestion for k-factor filtering. Real time impulse signals are produced and measured using an impulse generator and an oscilloscope. Then, the sampled waveforms were analyzed through k-factor filtering and wavelet based multi-resolution analysis. The mean curves and impulse parameters for each sampled signal are calculated using both methods. Afterwards, the differences in the calculated parameters are analyzed in terms of relative errors. An evaluation of the proposed method in comparison to the IEC approach is provided.

In this study, a comparison of the filtering approaches of k-factor and wavelet-based decomposition is provided. The procedures for each approach are introduced. The steps for optimal wavelet function selection and assessment of sub-band levels are discussed. And the results, obtained by the application of multi-resolution wavelet analysis and the IEC 60060-1 approach are evaluated. The analysis is conducted on several impulse signals produced by the experimental setup. The decomposition level and the wavelet function are determined through the procedures given at last.

In the conclusion, the findings and the contributions of this research are presented. As an alternative solution, the opportunities of multi-resolution wavelet analysis over k-factor filtering are discussed. Based on a numerical analysis, it is found that wavelet-based multi-resolution analysis provides very close results to the k-factor approach. In addition, it is shown that the proposed wavelet-based approach provides a compact solution for curve fitting and filtering while enabling further evaluation of frequency content for each sub-band of high-voltage impulse signals.

Dielectrics I

Time: Monday, 20/June/2022: 3:30pm - 5:30pm · *Location:* Ballroom C
Session Chair: Jennifer Zirnheld

3:30pm - 3:50pm

Effect of Humidity on Electrical Characteristics of an Arc in Air at Normal Flight Altitudes

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[1]Innovative Scientific Solutions, Inc., United States of America; [2]Air Force Research Laboratory/RQQE, United States of America

Although prevention of unwanted electrical arcing is an important goal in the design of aircraft electrical power systems, insulation aging and unexpected damage lead to a need for monitoring of a system for arcing faults in order to maintain reliability. One popular technique for arc detection is current signature analysis which relies upon predictable current/voltage characteristics of electrical breakdown of a gaseous gap. Once initiated, the voltage and current characteristics of an arc are a function of a complicated interaction of numerous collisional processes, creating many challenges in modeling and simulation. A more practical approach is to design an arc-fault detection system based upon consistent laboratory and field measurements.

Because gas constituents are major determinants of arc electrical characteristics, potential errors in design and checkout of an arc-fault-detection scheme can arise if variations in gas pressure and specie concentrations are not considered. Experience has shown that partial-discharge characteristics in air are affected by humidity (water vapor) but it's not clear if there is a similar effect in arcing in an air atmosphere.

Measurements were made of electrical characteristics of arcs in air at various humidity levels at pressures corresponding to sea level and 60,000-Ft (18.3-km) flight altitude. Results show that there is no significant effect resulting from variations in humidity that may be introduced by uncontrolled laboratory air, even when water-vapor levels are well above those expected at temperatures < 0 C.

3:50pm - 4:10pm

A Hydrodynamic Model for Discharge Initiation and Propagation in Air at Low Pressures

M. Hamidieh, M. Ghassemi

Virginia Tech, United States of America

Greenhouse gas (GHG) reduction is UN Sustainable Development Goal 13. Large aircraft, including narrow body and wide body aircraft, are responsible for more than 75% of aviation GHG emissions; considering a historic 4-5% annual growth in air travel, this situation is likely to worsen over time. To take urgent action to combat global challenges by reducing carbon and NOx emissions, aircraft electrification is a promising solution. The thrust power for wide body all electric aircraft (AEA) will be around 25 MW, while the total non-thrust demands are about 1 MW, causing significant challenges to designing optimal electric power systems for wide body AEA. The voltage level increment is the most feasible option to transmit the enormous power level mentioned above. However, designing high-voltage (in a few kV range) and high-power density electrification components capable of working under harsh AEA environments, especially at low pressures, is a big challenge. Although electrical breakdown in air, as an essential insulation medium used in some electrification components or as their interface with ambient, at atmospheric pressure is well understood, this is not the case for low pressures. To address this technical gap, this paper aims to develop a hydrodynamic approach to model discharge initiation and propagation in air for an altitude/pressure of 12.2 km/18.8 kPa, which is the typical cruising altitude for most commercial wide-body airplanes. The model is formulated as a set of partial differential equations (PDEs) describing the transport of charged species coupled to the Poisson equation. The main challenges with this approach are that the problem is strongly nonlinear since the parameters of the drift-diffusion PDEs are field-dependent affected by space charges. In addition, transport is heavily dominated by advection, which leads to the necessity of utilizing special numerical techniques to preserve the positivity of the densities of transported species and to avoid numerical artifacts. These challenges are addressed, and the model will be validated by comparing with experimental results. The model helps understand the impact of low pressures on mechanisms and phenomena behind discharge initiation and propagation in air at low pressures.

4:10pm - 4:30pm

Study of anode-initiated surface flashover in vacuum with spatiotemporally resolved optical emission spectroscopy

R. M. Clark[1], M. P. Mounho[1], W. C. Brooks[1], M. M. Hopkins[2], J. J. Mankowski[1], J. C. Dickens[1], J. C. Stephens[1], A. A. Neuber[1]

[1]Texas Tech University, Lubbock, TX, United States of America; [2]Sandia National Laboratories, Albuquerque, NM, United States of America

Improving the flashover holdoff of electrode-insulator junctions in vacuum systems is a critical step in developing future large-scale pulsed power devices. The insulator stacks in such environments are typically positive 45 degree systems. This configuration exhibits improved voltage holdoff over 90 degree systems due to the suppressed field at the cathode triple junction at the cost of an enhanced field at the anode triple junction. One finds a roughly three times higher field amplitude at the anode, and it is thus argued that the flashover mechanism for these geometries is anode-initiated. To investigate the underlying physical mechanisms of anode-initiated surface flashover, a positive 45-degree flashover fixture has been developed using a hemispherical anode.

The specific geometry localizes the flashover path for improved diagnostic accessibility while maintaining comparable fields to the traditional ring-link insulator stack structure. The source is an eight-stage, 240 kV Marx generator with rise times of a few tens of nanoseconds, resulting in anode triple junction fields in excess of 500 kV/cm for a cross-linked polystyrene (Rexolite) insulator. In addition to electrical diagnostics and imaging, spatially-resolved optical diagnostics are implemented to interrogate the developing plasma light from the UV through the visible. Light emitted from insulator regions near the anode and the cathode is focused into fiber optics by two pairs of rod lenses. The fibers are fed into nanosecond fast photomultiplier tubes for spectrally-integrated light intensity

waveforms, which are compared against voltage waveforms to determine initiation fields. Results have indicated that early anode light precedes early cathode light by several nanoseconds during the early stages of the flashover. Time-resolved anode and cathode spectra are obtained with an Oriel MS-257 spectrograph and accompanying intensified CCD camera. The spatiotemporal development of desorbed gas species, electrode involvement, and bulk insulator involvement in the flashover process are examined.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

4:30pm - 4:50pm

Electrical diagnostics and nanosecond imaging of vacuum surface flashover

M. Mounho[1], J. Young[1], R. Clark[1], W. Brooks[1], M. Hopkins[2], A. Neuber[1], J. Stephens[1]

[1]Texas Tech University, Lubbock, TX; [2]Sandia National Laboratories, Albuquerque, NM

When an insulator in vacuum between an anode and cathode becomes electrically stressed due to the application of a fast high voltage pulse on the anode, the surface of the insulator is typically the first location to breakdown. An experimental apparatus and diagnostics have been designed which localize anode-initiated vacuum surface flashover so that the relationship between voltage, current, and temporally resolved images may be derived to characterize this phenomenon. The high voltage source is an 8 stage Marx generator that stores 20 J of energy and can provide a voltage pulse up to 240 kV. The voltage and current are monitored using a capacitive voltage divider (CVD) and current viewing resistor (CVR). The optical diagnostics include an intensified charge-coupled device (ICCD), with nanosecond resolution allowing for temporally resolved imaging. In addition, time-integrated images are captured using a DSLR which provides the full evolution of the flashover path.

The electrode geometry consists of a hemispherical anode with a 2 cm radius and a planar cathode; the electrodes are separated by 0.6 cm. The insulator geometry under investigation is a positive 45-degree wedge made of cross-linked polystyrene (Rexolite). This geometry aims to pull electrons away from the surface of the insulator, preventing electron multiplication, the driving mechanism of cathode-initiated flashover. The dominant mode of breakdown then becomes anode-initiated vacuum surface flashover; however, little is known about the underlying mechanisms initiating this process. The primary model of anode-initiated flashover was outlined by Anderson [1], who postulated that an initial plasma forms around the anode, with dielectric or gaseous inclusions potentially playing a role. This plasma then creates a cascade of localized bulk-dielectric breakdown propagating toward the cathode due to field enhancement around the edge of the plasma formation. This model and other contributing mechanisms are ultimately what is under investigation, and experimental results are compared to the Anderson-model of anode-initiated flashover where appropriate.

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SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

4:50pm - 5:10pm

Utilization of Additive Manufacturing to Improve the Voltage Distribution Across Inductor’s Turns

F. K. Alsaif, Y. Zhang, R. Borjas, K. Alkhalid, J. Wang

The Ohio State University, United States of America

As a result of prominent developments in power electronics, inductor’s stray capacitances require special attention. Inductor impedance can significantly change at high frequency range due to its stray capacitances. Hence, inductor design for traditional 50-60 Hz alternating current (AC) systems can neglect the effect of these parasitics. However, designing an inductor for an advanced power electronics application, a closer look at these parasitics is needed. Emerging wide bandgap (SiC, GaN) devices in power electronics applications have introduced higher switching frequencies and faster switching speeds (higher dv/dt). Higher switching frequency means that the inductor impedance is dominated by those stray capacitances. Furthermore, higher dv/dt could cause insulation failure in the inductor due to the increased voltage stress. Thus, an understanding of inductor parasitics and voltage distribution across its turns are needed. The parasitic capacitances and voltage distribution across inductor turns were investigated for insulation requirement purposes under high dv/dt [1]. The simulation showed that the voltage was not uniformly distributed across the turns. As the switching speed increases, a higher dv/dt will be observed. Higher dv/dt will result in a higher voltage stress across all the turns and less uniform voltage distribution. Thus, the insulation requirements will be higher which leads to increased volume, cost and decreased power density and reliability. In this paper, an innovative approach is implemented to improve the voltage distribution across an inductor’s turns. Optimization and additive manufacturing are used to harness the inductor’s parasitic capacitances to achieve that goal. Both simulation and experimental validation of the improved voltage distribution will be presented in the final paper. As a result, higher power density, lower cost and more reliable systems can be achieved. Advancements in 3D printing technology were critical to realize the concept proposed here. Precise printing resolution and cheaper costs have helped the 3D printing to emerge in power electronics applications nowadays.

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5:10pm - 5:30pm

Breakdown performance of industry grade Kapton under PWM waveforms

A. Y. Mirza, A. Konstantinou, H. Nguyen, A. Bazzi, Y. Cao

University of Connecticut, Storrs, CT, USA

Conventional insulation systems were designed for sinusoidal excitations at power frequency. With the advent of inverter-fed applications, especially with wide bandgap semiconductors, large voltage transients and fast switching speeds have led to a steep rise in premature insulation failures within inverter-fed machines. About 66% of high-voltage machine failures are due to faults in the stator insulation [1]. This is especially true in transportation electrification applications including marine propulsion, and renewable integration of e.g., wind turbines. To avoid this problem, there is a need to understand the impact of power electronic inverters on conventional insulation systems, advance new materials with better electrical performance, evaluate their safety in medium/high-voltage applications, and develop new standardized testing methodologies. In this study, we attempt to address all the points mentioned above.

To understand the impact of PWM high-voltage and high-frequency emerging power electronic inverters on insulation lifetime, a medium-voltage H-bridge inverter test-bed was built [2] to stress industrially available Kapton (Polyimide) – Kapton HN, Kapton CR, and Kapton MT. Breakdown time of these materials have been compared and the testing methodology has been developed.

Additionally, a novel polymer-based coating with self-assembling, inorganic 2D nano-filler montmorillonite (MMT) was applied on polyimide (Kapton HN film) using a versatile spray coating process. Results of time to breakdown of our nano-coated samples show a 50% increase in the lifetime when compared to the industrially available insulation materials. The most attractive feature about MMT is its anisotropic electrical conductivity which means that it shows insulative character in one direction and conductive character in the other [3]. Our material can find its applications in innumerous industries, like transportation electrification, electric ships, to improve the lifetime under harsh conditions.

This material is based upon work supported by the Office of Naval Research under award numbers N00014-15-1-2413 and N00014-19-1-2306.

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Plasmas, Discharges, and Electromagnetic Phenomena

Time: Tuesday, 21/June/2022: 10:00am - 12:00pm · *Location:* Ballroom C
Session Chair: Mona Ghassemi

10:00am - 10:20am

Computational study of plasma flow in arcing horns during a voltage surge

R. Ranjan[1], A. Karpatne[1], N. Raj[1], S. Thiruppathiraj[1], D. Breden[1], L. Raja[2]

[1]Esgee Technologies Inc., United States of America; [2]The University of Texas at Austin

Arcing horns are used to protect the insulators from high-electric stress conditions. These horns maintain a certain gap between the horn tip such that under excess voltage conditions, the air between the horns breaks down prior to any flashover event across the bushing. Subsequent to the breakdown, a conductive plasma channel forms between the arcing horns. This arc formation leads to the parallel current path which avoids the high voltage build-up across the insulator. In this study, we use VizSpark, a high-fidelity plasma flow solver, to simulate the arcing between the horns under over-voltage conditions. The horn geometry is taken from the previously reported research literature. The build-up of potential in the horns and subsequent arcing in between the electrodes is reported with detailed information on the electric field. The potential and electric field distribution inside the insulator is also reported.

10:20am - 10:40am

Numerical simulation of arcing during contact separation in SF6-filled high voltage circuit breaker

R. Ranjan[1], N. Raj[1], S. Thiruppathiraj[1], A. Karpatne[1], D. Breden[1], L. Raja[2]

[1]Esgee Technologies Inc., United States of America; [2]The University of Texas at Austin

The numerical simulation of thermal arcs in circuit breakers has been challenging, essentially due to the multi-physics involved in the process. In this work, we use VizSpark, a fully-coupled electromagnetic and fluid flow solver to simulate the arcing inside the SF6-filled circuit breaker. The two-dimensional axisymmetric mesh is created for a plug-tulip type SF6 breaker geometry widely reported in the research literature. The moving plug is simulated as an in-motion subdomain, while the tulip, auxiliary nozzle and main nozzle are considered to be static. The sinusoidal current amplitude is varied from 4 to 40 kA to simulate the arcing during the disconnection process. We discuss the temperature, velocity and pressure maps at different time instants to demonstrate the arc evolution process until it quenches.

10:40am - 11:00am

Electron density of pin to plate discharge plasma at different discharge conditions

B. Feng, C. Zhang, T. Shao

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, China, People's Republic of

To investigate the evolution of electron density of pin to plate discharge plasma at atmospheric pressure, the atomic optical emission line is processed by the interpolation to reduce the uncertainties of the Stark broadening method at first. Based

on the Stark broadening method and the imaging method, the electron density of the plasma generated at different pulse frequencies, gap distances and inner diameters of the electrodes is diagnosed. The experimental results indicate that reducing the pulse frequency, shortening the gap distance of the electrodes and using thinner diameter electrode are all in favor to enhance the electron density. With the help of the global model, we perform the numerical simulation to explore the factors that influence the variation of the electron density. According to the simulations results, we find the reduced discharge volume results in the increase of electron density at low pulse frequency. When the gap distance of the electrodes is reduced, although the increased absorbed power and the reduced discharge volume both have an effect on the electron density, the reduced discharge volume plays a decisive role between these two factors. Moreover, using thinner inner diameter electrode can also reduce the discharge volume, which is beneficial to obtain the plasma with high electron density.

11:00am - 11:20am

Pulsed Spark Plasma Cracking Heavy Oil for Hydrogen and Acetylene Production

Z. Fan[1,2], H. Sun[1], C. Zhang[1,2], T. Shao[1,2]

[1]Beijing International S&T Cooperation Base for Plasma Science and Energy Conversion, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China; [2]University of Chinese Academy of Sciences, Beijing 100049, China

Spark discharge plasma is a promising technology for heavy hydrocarbons cracking due to its wide feedstocks adaptability and high conversion rate. Pulsed discharge can improve energy efficiency in energy conversion by its unique low energy compression and high instant power release. A combination of spark plasma and pulsed discharge has a potential for cracking the abundant but low-quality heavy oil efficiently into valuable light chemicals, such as hydrogen and acetylene. In this work, we used microsecond pulse power to crack heavy oil, and the spark discharge and conversion characteristics were studied in a gas-liquid reactor without catalyst at atmosphere pressure and room temperature. Heavy oil was injected into the plasma reaction area by a hollow needle electrode to improve contact with the plasma. Pulse voltage, pulse frequency and carrier gas sorts were evaluated for the improvement of discharge stability and conversion. Hydrogen and acetylene were the main gaseous products, and the gaseous products flow rates increased with discharge proceeding and became stable after 90 s. High voltage and high frequency can improved spark discharge stability, and with the increase of discharge power, the hydrogen and acetylene production flow rates were increased. Gaseous products flow rates were more superior than DBD (dielectric barrier discharge) and corona discharge. Conversion experiments in different carrier gases indicated that methane atmosphere was favorable for heavy oil cracking to produce more gaseous products. The spark discharge emission spectra in heavy oil mainly consisted of C_2 and H_α, and the gas temperature was estimated at about 3000 K by fitting C_2 spectra lines. This work provides a new idea for heavy oil utilization.

11:20am - 11:40am

The effect of Pre-Pulsed-Field on Electric Discharge in Water

T. Sugai[1], A. Tokuchi[2], W. Jiang[1]

[1]Nagaoka University of Technology, Japan; [2]Pulsed Power Japan Laboratory Ltd.

As one of the industrial applications by pulsed power, water purification and sterilization by pulsed electric discharge with water has been investigated. Pulsed power discharge in water produces OH radical and shockwave which decompose harmful substances and kill bacteria. For these applications, it is important to study electric breakdown in water. In a previous study, we confirmed experimentally that a pre-electric field makes a main electric field required for arc-discharge decrease for a few hundred micro-second. From these results, new questions have come up, that is, how the effects of pre-fields on a streamer discharge and production of active species are. Thus, we investigated the effects experimentally. The streamer discharge was generated at a point-to-plate electrode in water, applying a pre-voltage and a main voltage using a pulse transformer source consisting of LTD boards and cores. Characteristics of the streamer discharge with various peaks of the pre-voltage and with various times between the pre-voltage and the main-voltage, were investigated from obtained voltage and current waveforms. Then, the amounts of hydrogen peroxide produced by the electric discharge with and without the pre-electric-field were measured and compared to investigate the effects on active species. In this presentation, these results are detailed, and the effects of the pre-electric field on the generation of streamer discharge and active species are discussed.

11:40am - 12:00pm

Underwater Electric Discharges: Experiment and Modeling

T. Frost[1], B. M. Novac[1], P. Senior[1], L. Pecastaing[2], T. Reess[2]

[1]Loughborough University, United Kingdom; [2]University of Pau, France

At present, underwater electric pulsed discharges are used in a wide range of modern applications. During the development of a system for generating underwater acoustic pressure pulses, a numerical model is an essential tool for guiding the design and interpreting the data. Developing a complex *1-D* numerical code, like those presented in the literature, requires a substantial dedicated effort. Unfortunately, previous work trying to use simple and elegant theoretical models developed many decades ago reported a fundamental issue, apparently related to the input data. The present work performs a detailed analysis of the real meaning of the voltage measured across an underwater discharge and clarifies the correct way the power input to a simple two-phase model should be calculated. Based on accurate measurements, a phenomenological methodology to obtain the input data is demonstrated, with theoretical predictions obtained from the simple two-phase model being successfully compared with the experimental evidence obtained from both the present work as well as from other reliable data presented in the literature.

Solid State Modulators

Time: Tuesday, 21/June/2022: 10:00am - 12:00pm · *Location:* 301B
Session Chair: James Randall Cooper

10:00am - 10:20am

Design and Analysis of a 24 kV PCB-Bus for the Low Impedance Interconnect of a Multiphase PEBB-based Converter

J. Stewart

Virginia Tech - Center for Power Electronics Systems, United States of America

In this work, the design and analysis of a medium voltage (MV) printed circuit board (PCB) -based planar power bus rated for 24 kV with distributed capacitor daughtercards is presented. This bus provides the low impedance interconnect between an external power supply input and two phase legs of a 24 kV/2 MW power electronics building block (PEBB) -based multilevel modular converter (MMC). The bus serves as a motherboard for capacitor daughtercards which are rated for 9 µF 3 kV each. Electric field (E-field) analysis and parasitic extraction was performed via finite element analysis (FEA) using COMSOL Multiphysics and Ansys Electromagnetics for board- and system-level integration. Insulation performance for each component and the assembly was verified through partial discharge (PD) analysis using an Omicron MPD600. The motherboard and capacitor daughtercards partial discharge inception voltage (PDIV) were tested on a layer-to-layer basis, in addition to the full assembly to ensure the system was PD free under normal operation.

A single PEBB is a converter in which the power stage and all ancillary circuitry required to operate independently are contained in a single structure. PEBBs may be stacked in a series and/or parallel fashion to achieve a higher voltage and/or current rating respectively. The 24 kV MMC includes four PEBBs in the upper arm and four PEBBs in the lower arm of each of the two phase legs. Each PEBB also has an independent forced air cooling system which is referenced to earth ground (GND). Due to the system's complexity, the boards layer stackup and connector design were critical when fully integrated into the system.

This 24 kV bus was implemented using a 22-layer stackup with a staggered offset between conductor edges for field grading. A layer of FR4 with a controlled thickness was used between the outermost conductive layer and surface pads. This allowed high fields to be contained with the solid dielectric to avoid corona along the surface of the PCB. Additionally, *guard pads* were implemented to reduce the E-field intensity in air near terminals. These guard pads are placed directly below device terminals and connected to the same potential, at some height within the bus so the field intensity is reduced.

Eight capacitor daughtercards rated at 9 µF 3 kV each were mounted to the motherboard creating a 1.13 µF 24 kV capacitor bank. The daughtercards were constructed using a series-parallel array of 1.5 kV commercial-off-the-shelf (COTS) capacitors. Using this method, the target capacitance for our specific application was achievable. It was beneficial to avoid bulky high voltage can capacitors which require their cans to referenced somewhere near the voltage of their terminals. Additionally, the array of parallel film capacitors provided a much lower impedance which is desirable for such an interconnect.

The final manuscript will provide background on the 24 kV PEBB-based converter at the heart of this work. Detailed analysis for and design of the 24 kV PCB bus and the 3 kV capacitor daughtercards will be presented. Test methods and more extensive results will also be presented.

10:20am - 10:40am

A 30-kV Solid-State Impedance-Matched Marx Generator: Practical Considerations on Impedance Matching

T. Huiskamp, J. van Oorschot, M. Azizi

Eindhoven University of Technology, The Netherlands

Based on the topology of the Impedance-Matched Marx Generator (IMG) presented in 2017 by researchers from Sandia (and others) [1], we created a solid-state IMG using MOSFET switches [2]. The advantage of using the IMG topology is that by using transmission lines to transmit the pulses from the Marx stages the rise time of the pulses can be maintained at the output waveform (when carefully impedance-matched). By designing the Marx stages very compactly and using fast semiconductor components, adjustable pulses with rise times of just several nanoseconds are feasible with this topology. Since we require such fast rising pulses for transient plasma generation, the solid-state IMG is ideally suited for our purpose. In this contribution we present the development of a 30-kV version of the solid-state IMG. It utilizes 12 stages of gate-boosted [3] and series-connected 1200V SiC MOSFETs and achieves several ns rise time at 30-kV output voltage. Specifically, we also focus on the practical considerations on impedance matching with a modified, much longer version of the IMG to investigate practical considerations on impedance matching. We will show that if the matching criteria are not observed, severe distortion of the waveform is possible and that for the fastest pulses we need the best matching possible.

[1] W. A. Stygar *et al*., "Impedance-matched Marx generators," Phys. Rev. Accel. Beams, vol. 20, 040402 (2017)

[2] T. Huiskamp and J. J. van Oorschot, "Fast Pulsed Power Generation with a Solid-State Impedance-Matched Marx Generator: Concept, Design and First Implementation", IEEE T. Plasma Sci., vol. 47, 4350 - 4360 (2019)

[3] M Azizi, J. J. van Oorschot, T Huiskamp, "Ultrafast Switching of SiC MOSFETs for High-Voltage Pulsed-Power Circuits", IEEE Transactions on Plasma Science, vol. 48, 4262 - 4272 (2020)

10:40am - 11:20am

The Stacked Multi-Level Klystron Modulators for the ESS Linac

C. Martins[1], M. Collins[2], M. Kalafatic[1], L. Yury[1]

[1]European Spallation Source ERIC; [2]Lund University Faculty of Engineering - LTH, IEA Division

The European Spallation Source (ESS) Linac will require by its completion a total of 33 klystron modulators. They are based on the novel Stacked Multi-Level topology and are rated at 115kV/4x25A; 3.5ms/14Hz, therefore capable of powering 4 klystrons rated at 1.6MWpk, 704MHz in parallel. Besides complying with the ESS requirements in terms of pulse quality (i.e. rise times$_{0..99\%}$ < 120µs; flat-top droop <1%; ripple <0.2%$_{pk\text{-}pk}$), they also comply with relevant power quality standards on the electrical grid (current THD below 5%, unitary power factor, flicker free operation), thanks to the adoption of Active Front End (AFE) rectifiers in conjunction with constant power regulated DC/DC capacitor chargers. These features allow their direct connection to the AC line without the need for external line compensators or filters.

The topology is modular and based on the association in series of 6 identical HV modules, each rated for 20kV$_{pk}$ and formed by a HVHF transformer, a HV diode rectifier bridge and a HV LC low-pass filter. These modules are placed in an oil tank and are driven by a 1kV/15kHz H-bridge inverter, which in turn is fed from a capacitor bank charged by the aforementioned AFE+DC/DC chargers.

The modulators have a footprint of 1.6m x 4m and a weight of 11.5 ton (including oil). The mechanical layout was designed in order to facilitate access to each component for repairing. In particular, the low voltage and high voltage cabinets can be assembled and repaired independently, with the first one directly pluggable into the top of the second one. The high voltage cabinet comprises the complete oil tank assembly and it can be easily extracted from each side of the modulator by using the built in sliding rail system, facilitating access for maintenance purposes and interchangeability of the HV modules.

In a first part of this contribution, an overview of the different blocks and functionalities of the power conversion structure will be addressed. In a second part, the main lessons learned during the design, construction and validation of both the reduced scale prototype and the full scale series units will be presented, together with the implemented corrective actions and their effectiveness. This will include issues related to the design of the HV modules like field control, effect of stray inductances and parasitic capacitances, integration into the oil tank, the reliability of the insulated oil and the impact of their handling procedures, the common mode noise effects and their mitigation, eddy currents mitigation etc. In the third part, experimental results obtained with the first 660kVA rated series modulator powering a HV resistive dummy load and klystron load will be presented and discussed.

A total of 18 series modulators have been delivered to ESS for the completion of phase I of the Linac construction, allowing an average beam power in the target of 2MW. For future power upgrades of the Linac to 5MW, additional 16 units of similar type will be required.

11:20am - 11:40am

Evaluation of Klystron Modulator Performance in Interleaved Pulsing Schemes for the ESS Neutrino Super Beam Project

M. Collins[1,2], C. Martins[1,2], M. Eshraqi[2], B. Gålnander[2]

[1]Lund University; [2]European Spallation Source ERIC

It has been proposed that the relatively low duty cycle of the European Spallation Source (ESS) linac allows acceleration of additional H- ion pulses interleaved with the baseline proton pulses, representing a unique opportunity to construct a neutrino super beam (ESSnuSB) facility of unparalleled luminosity. Coupled with a distant Cherenkov detector, it is believed that evidence of CP violations in leptons could be obtained, representing a significant step towards understanding the matter/antimatter asymmetry.

In this paper, several such interleaved pulsing schemes are considered from the perspective of the klystron modulators and the RF power system in investigating the possibility to realize the ESSnuSB. Conserving the required output RF energy, these pulsing schemes vary in terms of 1) number of added H- ion pulses per baseline cycle, 2) pulse amplitude and 3) pulse length. Each prospective pulsing scheme offers unique advantages while differently impacting klystron modulator performance. Whereas the ESS linac baseline design requires 33 klystron modulators (rated for pulse amplitude 115kV/4x25A, pulse length 3.5ms and pulse repetition rate 14Hz; each modulator powering 4 parallel klystrons rated 1.6MWpk at 704MHz), the proposed upgrade requires doubling the baseline linac average output power and thus either doubling the capacity of existing modulators or the procurement of additional modulator systems.

In order to evaluate and compare the merit of these solutions from a system perspective, a mathematical framework connecting the attributes of the proposed pulsing schemes to the power transfer curves of the klystrons and subsequently to the performance of the klystron modulators is developed. In particular, the impact on modulator-to-beam efficiency, modulator average input power quality, modulator output pulse flat top ripple, total upgrade cost, total operational cost (assuming a life time of 25 years), and required additional system size is assessed.

Two particularly promising interleaved pulsing schemes are evaluated in circuit simulation. It is demonstrated that an upgrade of the existing modulators utilizing the selected pulsing schemes maintains the baseline modulator-to-beam efficiency (>90%) keeping the input power quality and output pulse quality performance intact while representing a cost-effective solution for the linac upgrade to implement the proposed ESSnuSB project.

11:40am - 12:00pm

Analysis of the Triggering Instants of the Solid-State Switches of the Pulsed Power Sources for Achieving Optimal Projectile Velocity in a Multistage Induction Coilgun

R. Ram, J. T. Meledath

Indian Institute of Science, Bangalore, India

A multistage induction coilgun works on the principle of electromagnetic induction between an array of drive coils, which are wound on a long insulating barrel of appropriate length, and an electrically conducting projectile (or armature) placed inside the barrel. Previously charged high voltage capacitor banks are sequentially discharged into the drive coils through high voltage solid-state switches leading to the generation and flow of high magnitude impulse currents through the drive coils. Time-varying magnetic flux thus produced by the pulsed currents through the drive coils interact with the projectile inside and induce a resultant eddy current in it. The electromagnetic thrust (F) exerted on the projectile is a product of the excitation current through the drive coil (i_c), induced current on the projectile (i_p), and the mutual inductance gradient (dM_{cp}/dx, i.e., the change in mutual inductance between the drive coil and the projectile as the projectile moves along the barrel). The higher the electromagnetic thrust is available from each stage, the higher is the launch velocity (v_p) of the projectile that can be achieved after each stage. A higher dM_{cp}/dx leads to a higher F. Now, dM_{cp}/dx essentially depends on the radii of the drive coil and the projectile, and the distance between the midplanes of the drive coil and the projectile, i.e., the triggering instant of the pulsed power source w.r.t. the position of the projectile inside each drive coil. For a particular multistage induction coilgun design, where the radii of the drive coil and the projectile are fixed, the appropriate instant of synchronization of triggering of the stages, i.e., the optimum triggering instant of the solid-state switch of the pulsed power source w.r.t. the position of the projectile inside each drive coil, plays a vital role in achieving a higher v_p of the projectile. The several stages of a multistage induction coilgun can typically be energized in two ways: (1) positive-positive (PP), where the direction of the excitation current in the subsequent drive coils is kept the same, and (2) positive-negative (PN), where the direction of the excitation current in the subsequent drive coils is reversed alternatively. The optimum triggering instant for the projectile inside each drive coil of the subsequent stages changes accordingly in these two launching configurations. This paper investigates and compares the difference in triggering instants for the projectile inside each drive coil in PP and PN launcher configurations. The analysis is carried out with a four-stage induction coilgun. The input electrical energy to each stage is kept constant. The triggering instant for the projectile inside each drive coil is then set such that the projectile position is anywhere from 0 mm to 18 mm with a linear step of 1.6 mm. The triggering position inside each drive coil is measured w.r.t. the rear end of the corresponding drive coil. The analysis presented in this paper will help better understand the operation of a multistage induction coilgun.

Poster 2: Posters: Solid State, Power Electronics, High Voltage, Biomedical

Time: Tuesday, 21/June/2022: 1:30pm - 3:00pm · *Location:* Exhibition Hall D / Henley Concourse
Session Chair: Xiu Yao

Design and Implementation of the SML Modulators for the ESS Linac

M. Collins[1,2], C. Martins[1,2]

[1]Lund University, Sweden; [2]European Spallation Source ERIC

The European Spallation Source (Lund, Sweden) is an under construction multi-disciplinary research facility to be based around a Linear Particle Accelerator which is to provide 2.86 ms long proton pulses at 2 GeV at a pulse repetition rate of 14 Hz, representing an average beam power of 5 MW. To accommodate the requirements of the proton linac, a large number of klystrons driven by solid state modulators rated for pulse amplitude 115 kV/100 A, pulse length 3.5 ms, pulse repetition rate 14 Hz, and pulse rise time on the order of 120 µs are required. These klystron modulators implement the novel Stacked Multi-Level (SML) modulator topology.

In the SML topology, the input stage capacitor chargers are based on an AC/DC Active Front End (AFE) rectifier and DC/DC buck converter chain. The AFE generates a stable dc-link voltage while shaping the line current to be sinusoidal and in phase with the line voltage, effectively eliminating line current harmonics and reducing reactive power to a minimum. The DC/DC converter connects the dc-link to the main capacitor bank energy storage via an inductive link, controlling the charging current to exhibit inverse waveform with respect to the capacitor bank voltage such that the required energy is replenished just in time for the following pulse, yielding constant power charging and thus flicker mitigation despite the high power pulsed load. Pulse generation is achieved in a pulse modulation/demodulation scheme as follows. First, a DC/AC inverter (H-bridge) generates an AC square voltage waveform fed to a high voltage high frequency (HVHF) transformer providing voltage amplification. Then, the amplified voltage waveform is rectified in an AC/DC high voltage diode rectifier stage and subsequently filtered, re-creating the fundamental shape of the output pulse. The topology is modular, with the implemented modulators for the ESS Linac utilizing three parallel connected input capacitor chargers and six series connected high voltage modules, increasing system power density and facilitating maintenance.

This paper presents key points, the working principle as well as the design and control of these modulators while highlighting the details of their practical implementation. Issues related to optimization, high voltage design (e.g. field control and details on the use of 3D finite element electromagnetic analysis in design), modeling and mitigation of circulating currents due to parasitic capacitive elements, and thermal management/lifetime considerations of IGBTs in high power pulsed applications are treated. Experimental results and efficiency measurements obtained in full power testing of the implemented modulators are presented.

Triggered Spark Gap Evaluation and Optimization for Low Jitter, High Reliability Applications

J. L. Contovasilis, A. J. Young, A. M. Pearson, R. D. Speer

Lawrence Livermore National Laboratory, United States of America

This paper discusses the evaluation and performance of three-electrode triggered spark gap switches for use in a low turn-on jitter, low pre-fire probability tolerant application. Turn-on jitter, turn-on delay time, pre-fire/no-fire occurrence, and shot life were recorded using an automated testbed for High Energy Devices TA5.0 and Excelitas GP489 spark gaps. The spark gaps were tested at 3.5kV with 1.2kA of peak current and 10mC of charge transferred per shot. The testbed apparatus and data results are shown for trigger modes A, B, and C using manufacturer-recommended triggering circuitry. Spark gap failure modes and optimum trigger modes are identified. A method for minimizing turn-on jitter using a nanosecond rise time trigger circuit with optimized trigger pulse energy for the TA5.0 spark gap is shown which achieves turn-on jitter less than 2ns.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Pulsed Power Supply for Magnet Quench Training

M. T Davidson, C. C Jensen, M. R Kufer, H. Pfeffer, S. Stoynev

Fermi National Accelerator Laboratory

Superconducting magnets typically go through a series of spontaneous “training” quenches as their current is increased towards its design value. A device has been designed and built to boost the magnet current at the moment a quench has been detected to possibly decrease the number of these quenches. The aim of the boost is to drive the magnet coil further along towards its maximum current with each training quench, and hence reduce the number of quenches required.

The current boost is accomplished by diverting the current in the magnet circuit from a diode in series with the load to a charged capacitor (400 mF charged to 1 kV) connected across the diode. The output terminal of the capacitor is connected to the cathode of the diode by closing IGBT switches. The connection initially adds 1 kV to the magnet voltage and drives its current up rapidly. The voltage on the capacitor bank discharges to zero as its stored energy transfers into an increase in magnet current above the quench level. The energy transfer time is some tens of milliseconds, after which the magnet protection is initiated.

The circuit has been built and is being commissioned. The design, protection systems and tradeoffs will be discussed.

A 300 kA Pulsed Power Supply for LBNF

C. C Jensen[1], J. Hugyik[2], B. Morris[2], T. Omark[1], H. Pfeffer[1], K. Roon[1]

[1]Fermi National Accelerator Laboratory; [2]SLAC National Laboratory

The Long Baseline Neutrino Facility (LBNF) will produce the world’s most intense neutrino beam. Three series connected magnetic horns will require 5 kV, 300 kA, 800 µs pulses at a rate of 0.7Hz to focus the beam. Fermilab has designed and built pulsed high current supplies for horns in the past. Pulsed currents of 205 kA for Neutrinos at Main Injector (NuMI / NOvA), focusing a 120 GeV beam, and 170 kA for Booster Neutrino Bean (BNB / MiniBooNE) for focusing an 8 GeV beam have been operational for about 18 years. It is required that the LBNF horn power supply last the lifetime of the project, 30 years.

A resonant, half sine wave pulser was used for NuMI and BNB and has many practical advantages. The system has impedance limited fault currents by design, albeit large ones. The pulse length of 800 µs is needed to meet the required flatness of the focussing field. The resonant behavior means that thyristor switches are well suited for this application. The design will continue the use of many pulser circuits in parallel to provide the high current. Only 30% of the initial energy stored in the capacitors is lost, based on load estimates, so an energy recovery system that is also resonant will be used to reduce charging supply size. Many fault modes of the system have also been calculated. Several circuit changes were incorporated so that a single fault can be tolerated. The supply must also be reversable to enable both neutrinos and anti-neutrinos to be produced. The reversal requirement required a significant amount of mechanical design features as the first horn must always be at the lowest potential. This requires the output polarity to change and reversal of all the semiconductors. Further design considerations will be discussed, and prototyping has begun.

High-Speed Imaging of Exploding Detonators

H. J. Gaus[1], J. J Mankowski[2], A. Neuber[2], D. H. Barnett[3]

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An experiment for imaging detonators used in explosively driven pulsed power applications with high-speed, short exposure time cameras will be described in the work to follow. Three, commercially available, high intensity, pulsed xenon light sources (> 107 candela intensity) yielded unsatisfactory image quality with a minimum exposure rate (~320 k frames per second). Above 320 k frames per second, the combined output intensity of the light sources were too dim. Due to this, a lamp system was designed that would be capable of delivering higher light intensity to the target.

Two types of lamp arrays were designed and tested. The first was a large lamp array comprised of a couple high energy flash lamps, while the second was a small lamp array comprised of many low-energy flash lamps. The large lamp array was intended for multiple shot use, and was placed behind a protective sheet of polycarbonate to separate the bulbs from the detonator. The second small lamp array with low-cost flash lamps was intended for one time use and will be placed closer to the detonator. Multiple five stage, Rayleigh Pulse Forming Networks (PFNs) were developed to find the optimal energy for the flash lamp array. Each PFN was modeled using LTSpice circuit simulator to verify proper operation, and help with optimization. Experimental measurements were taken of the PFN’s voltage and current outputs and compared to simulated values. A photodiode was used to measure relative light intensity from the different lamp arrays.

The next step progress for a skin effect opening switch construction (the resistive version)

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free, Russian Federation

The next step progress for a skin effect opening switch construction

(the resistive version)

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A skin effect opening switch based on a transformer inductive energy storage (L_{SEOS}) was offered for consideration in [1-2] and its resistive version (R_{SEOS}) was offered in [3] too. The latter possesses some properties of contactors. For example, it is able to carry kiloamperes current during one second and more with minimal losses. Combined with auxiliary elements (an opening switch, a capacity bank and others) the version R_{SEOS} is converted to an opening switch configuration, where the version R_{SEOS} gets dynamic properties. Embedded in pulsed power generator based on inductive storage as a component, the received configuration of R_{SEOS}

requires the generator adaptation to a load. There are many different loads: -inductive, resistive, nonlinear and others kind of one. Each of them claims itself approach to solve a problem of adaptation. Realized by a developing technology, an engineered impulse device is able to generate nanosecond high-voltage pulses. It lets to solve some pulsed power tasks effectively, for example, a pulse train generation of a terawatt level using direct current. Besides energy storage and its output to a load is concurrent activities [3].

There are many parameters of pulsed power generator exerting influence on a pulse form in a load. Some of them are the parameters of a high-ohm layer R_{SEOS}, such as depth, d, and conductivity, ρ. A time current diffusion in a solid-state conductor is $t_{dif} = (d^2\mu_0/4\rho)$, where $\mu_0=4\pi\cdot10^{-7}$ H/m. It is obviously that changing conductivity ρ, the time characteristics of the pulse changes, especially its the trailing edge too. Influence of heating and melting of the high-ohm layer on a pulse form during pulse generation for different amount of current density is discussed in this presentation. All computations were performed for a resistive load. The offered construction of R_{SEOS} is reusable. It lets to expand a field of application.

References

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2. O.G. Egorov, Patent No.2680343 “The method of energy output form transformer inductive storage to a load.” Patent of Russian Federation, 02.11.2017.

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SLAC LINAC Sub-booster Modulator Upgrading with Solid State Switch

X. Chen, J. de Lamare

SLAC National Accelerator Lab, United States of America

The LINAC sub-booster modulator was designed in last 60s decade and have serviced SLAC LINAC about 60 years without primary upgrading. The primary switch for high power pulse is vacuum tetrode switch. Recently the vacuum switch price has surged, probably because many customers of the vacuum switches has shifted to solid state switches. With the foresight of the vacuum switch will finally become obsolete in market, the solid-state switch has been tested in SLAC LINAC sub-booster modulator and the performance is evaluated. The design and performance will be reported.

X-Band TWT Transmitter

M. Kempkes, R. Simpson, M. Gaudreau, L. Jashari, J. Kinross-Wright, B. Lindsay, K. Vaughan, T. Hawkey

Diversified Technologies, Inc., United States of America

In 2021 Diversified Technologies, Inc. (DTI) developed and installed a high power X-band transmitter into a new radar. The transmitter’s design is closely based on several high power traveling-wave tube (TWT) transmitters previously delivered by DTI. This X-band transmitter employs the Communications and Power Industries’ (CPI) TWT, model VTX-5681B3, to deliver a peak power of 130 kW at 35% duty. DTI built the modulator and other electronics subsystems, purchasing and integrating the RF systems for the transmitter, as well as providing cooling on a dish antenna. This on-mount arrangement gives the most direct waveguide run from the TWT to the antenna feed network, resulting in the lowest microwave losses and maximum transmitted power. The remainder of the transmitter electronics are mounted on the ground near the antenna pedestal in a DTI-supplied shelter. A single DTI-supplied cooling skid provides system cooling for both transmitters delivered.

DTI’s X-band transmitter consists of state-of-the-art, solid state, high-voltage subsystems. The speed, precision, and reliability of solid state devices offer a level of performance unattainable in conventional transmitter designs. The only vacuum electron device (VED) in the transmitter is the CPI VTX-5681 very high power coupled-cavity TWT.

High Stability Klystron Modulator for Commercial Accelerator Application

M. Kempkes, C. Chipman, A. Heindel, M. Benjnane, H. von Kelsch, Z. Ruan, M. Gaudreau, R. Simpson

Diversified Technologies, Inc., United States of America

Diversified Technologies, Inc. (DTI) designed and developed a high stability modulator system for a commercial linear accelerator application. The DTI modulator delivers significant advantages in klystron performance through highly reliable functionality as well as flicker- and droop-free operation from 50-500 µs up to 400 Hz (duty limited). The main assemblies on the DTI system consist of a controls rack, high voltage power supply (HVPS), modulator, and cooling manifolds for the modulator, high voltage power supply and klystron tube. Two HVPS (upgradeable to four) provide stable and accurate DC voltage which is used to drive a CPI VKP-8352C UHF-band pulsed klystron for the linear accelerator. A solid state series switch, based on DTI’s patented design, provides both pulse control and arc protection to the klystron. Operating with four HVPS, the DTI modulator is able to operate at a maximum average power of ~750 kW at 105 kV, 47 A nominal. At the end of the initial contract, DTI provided two systems and a total of four HVPS (two of which are used with each system).

Aluminum electrolytic capacitor vulnerability evaluation in DC power supplies at the Spallation Neutron Source

S. T. Harave

Oak Ridge National Laboratory, United States of America

The service life of electrolytic capacitors is a concern for long-term reliable operation of power supplies. The Power Conversion Group at the Spallation Neutron Source (SNS) facility of Oak Ridge National Laboratory is responsible for more than 500 power supplies with over 1000 electrolytic capacitors installed in these power supplies. Most of the electrolytic capacitors are in operation since 2007 and are either well over or close to the manufacturer provided lifetime. This paper addresses this vulnerability to ensure continued reliable operation of the SNS. The power supply circuit will be simulated in a MATLAB/Simulink environment to quantify the capacitor ripple current and operating voltage. Combined with manufacturer data, this information will be used to estimate capacitor lifetime. Utilizing the simulation results and lifetime projections of the capacitors, capacitor replacements for the power supplies will be prioritized. To assess end-of-life, the ambient temperature and ripple current of the capacitor is used. Based on the manufacturer's data and scientific literature review, capacitor end-of-life will be established. The results of the simulations and analysis will be presented. Data on the highest priority supplies will also be presented, and statistics on the capacitor performance, reliability and remaining lifetime will be shown.

Duty Cycle Adjustable High-Voltage AC Power Supply with High Repetition Rate

Y. Feng[1], Y. Gao[1], C. Zhang[1,2], T. Shao[1,2]

[1]INSTITUTE OF ELECTRICAL ENGINEERING,CHINESE ACADEMY OF SCIENCES, China, People's Republic of; [2]University of Chinese Academy of Sciences

Low-temperature plasma has a wide range of applications and unique superiority in environmental pollution improvement, biomedicine, materials modification and energy conversion due to its electrical and physical properties. For industrial applications, adopting AC power supply for generating plasma is also a most common method due to high stability of system. However, the application of ac mode also brings forward the demand of more efficient operation modes which include alterable duty cycle , adjustable amplitude of output voltage and repetition rate. To decreasing the dimension of whole systems, we sacrificed some adjustable range of variable parameters. The main circuit of presented power supply utilize push-pull circuit since no need for considering potential problems of gate drive for switches, and the auxiliary circuit consists of dual channel output gate driving circuit with adjustable duty cycle and step-down circuit. As a result, the AC power supply can generate output voltage~6 kV, peak repetition rate ~20kHz, which is expected to be applied in DBD load in the future for demonstration of generating plasma.

A high-power pulse resistor with nonlinear low inductance

Z. Duan[1], G. Sun[1,2], X. Si[2], Y. Huang[2]

[1]Hefei University of Technology, China, People's Republic of; [2]Hefei Hangtai Electrophysics Co. Ltd

High-power pulse resistor used in surge current Marx generator shall adjust the current waveform with desired inductance. However, the demand of low inductance is always conflicted to the size of resistor for its low resistance with surge current lager than 10kA. To break through the limited application, here, a high-power pulse resistor of multi-conductor coaxial structure, made out of ferromagnetic material ($OCr_{25}Al_5$), that works in magnetic saturation is designed. Our test results showed that the resistor is about 400mΩ, the inductance decreases nonlinearly with current amplitude and could be much small as 1.7μH in 30kA. This inductance allows the resistor meets lots of surge current generator requirements, especially in lightning current waveform generation. More importantly, the resistor size compared to general pulse resistors decreased vastly. Our study illustrates that that resistor design could be well used in supporting generation of high-amplitude pulse current waveform.

A low cost, fast rise time, 120 kV multiple use Pulsed Power trigger generator

M. Woodyard, B. Novac, P. Senior

Loughborough University, United Kingdom

A pulsed power trigger generator is introduced, having a simple design based on ceramic capacitor stacks having a total capacitance of 5.3 nF, mounted inside an oil-filled cylindrical-coaxial transmission line. After being charged to 120 kV, the unit is discharged by a self-breakdown spark-gap switch, generating an output voltage impulse with a rise time of only a few ns. Experimental data is provided for the pulsed generator operated with various loads.

An Experimental Apparatus for Novec 4710 for Pulsed Power Applications

J. A. Matthies[1], L. Silvestre[1], J. Stephens[1], J. Dickens[1], J. Mankowski[1], A. Young[2], A. Neuber[1]

[1]Texas Tech University, United States of America; [2]Lawrence Livermore National Laboratory

Sulphur hexafluoride (SF_6) is a prevalent insulating gas in high voltage environments. However, the high global warming potential of SF_6 has motivated a search for an alternative, more environmentally friendly insulating gas. Novec 4710 (C_4F_7N) is a primary candidate due to potentially having nearly twice the voltage hold-off of SF_6, significantly lower atmospheric lifetime, and a greatly reduced greenhouse effect.

While prior work has focused chiefly on DC and AC (power utility) frequencies, an experimental apparatus was developed to assess the pulsed power performance characteristics of Novec 4710 in mixtures with CO_2 and N_2 at pressures of up to three atmospheres. The pressure chamber has interchangeable anode and cathode connections to facilitate the testing of multiple breakdown geometries such as plane-to-plane, rod-to-plane, et cetera. The electrode design permits the study of various electric field gradients on the hold-off voltage of Novec 4710. Within the chamber, the electrodes are integrated as center conductors in a 50 Ohm coaxial transmission line geometry. Thus, the system maintains 50 Ohm impedance throughout the geometry, thereby minimizing reflections and allowing for voltage and current diagnostics with fast, nanosecond resolution.

Development of a Magnetron based S-band High Power Microwave Test Bed

G. Gomez, J. Mankowski, J. Dickens, A. Neuber, J. Stephens

Texas Tech University Center for Pulsed Power and Power Electronics

This poster reviews a magnetron based high power microwave (HPM) system and subcomponents for producing ~2.5 MW HPM pulses with ~ 3.6 µs pulse duration. This system utilizes a 5-stage, 25 Ohm, Guillemin quasi-type-E pulse forming network (PFN), initially charged to 24 kV. The PFN delivers 12 kV to a matched load, which consists of a 1:4 transformer to drive a high power magnetron (EEV M5193) with up to 48 kV and 110 A (~400 Ohm effective impedance). The electrical performance characteristics of the PFN with resistive load terminations are reported and compared with circuit simulation. Preliminary HPM performance characteristics are reported.

Design Challenges in High Current Pulsed Striplines

H. Pfeffer, M. Davidson, N. Curfman, T. Omark

Fermilab, United States of America

The Long Baseline Neutrino Facility (LBNF) will produce the world's most intense neutrino beam. Three series connected magnetic horns will require 5kV, 300kA, 800µs pulses at a rate of 0.7Hz to focus the beam. Connecting a single power supply to these focusing horns will require a low impedance connection measuring over 60 meters in length. In order to meet the challenging requirements of connecting the horns to the power supply, this connection is engineered as a nine-conductor, high-current pulsed stripline. It must pass through a harsh radiation environment, be passively cooled, and have an operational lifetime of at least 30 years. This paper discusses mechanical and electrical considerations such as high-voltage holdoff, clamped joint performance, and Lorentz force mitigations in order to meet the specified requirements. The results of tests and experiments on several prototypes of key design features will be presented and discussed.

The Recent Improvements of the SNS Extraction Kicker Power Supplies

Y. Tan, R. Saethre

Oak Ridge National Laboratory, United States of America

A total of 14 extraction kickers, with one as the hot spare, are in service to extract protons out of the storage ring at SNS. The jitter issue and the short lifetime of the switches were resolved after the thyratrons were replaced with solid state switches in 2018. This paper discusses the recent improvements. Two thyristor switches suffered overheating damage in separate incidents. One was due to the oil pump failure and the other was the result of a disconnected oil hose. An ultrasonic flow meter and fiber optic temperature monitors have been installed for each extraction kicker power supply. The flow meter continuously monitors the entire tank oil flow. The temperature monitors detect the thyristor switch real-time temperatures in three locations. Fault thresholds are selected so that the thyristor switches are protected from overheating damage. Alarms are configured to alert staff to take actions before faults occurs. In addition, the cause of an intermittent mis-fire issue was identified, and the solution was implemented. Lastly, a future oscilloscope upgrade is discussed.

Los Alamos National Laboratory Fast Kicker Upgrade 2022

H. J. Gaus III, L. Merrill, R. McCrady, J. T. Bradley III, J. B. Sandoval, W. T. Roybal, G. V. Cordero-Rivera

Los Alamos National Laboratory, United States of America

LA-UR-22-21024

The Los Alamos Neutron Science Center's proton storage ring (PSR) extraction kicker systems consist of two thyratron switched blumlein modulators. The operating parameters of the PSR have changed over the years and the flattop voltage of the modulator outputs has become a limiting factor in the length of the beam pulse able to be extracted from the ring. The extraction voltage pulse travels upstream relative to the beam and thus needs to be longer than the beam pulse. A reanalysis of the voltage waveforms and the beam propagation times revealed that a longer pulse could reduce beam spill levels that have been seen during past run cycles. Reduced spill will allow operation at higher beam currents and thus increase the amount of beam current available for experimenters. We have upgraded the blumlein cables in both extraction kicker modulators with longer cables. We present test results of the modulator outputs and correlate their improvement with reduced beam losses at the PSR exit septum and improved beam delivery.

Simple Method of Core Loss Measurements

C. F. Strowitzki

MLase AG, Germany

For applications in pulsed power nanocrystalline cores are very common. They show very good performance by moderate costs. A critical point is the insulation of the ribbons. The cores are made of amorphous material, which has to be annealed after winding. Nano crystalline ribbons are too brittle to wind a core. The insulation is made with ceramic powder. The coating of the ribbon has to be done very constant to prevent short circuits between the layers. Such short circuits cause excessive core losses due to eddy currents. This core losses have to be measured at magnetization speed close to the later application. The current method is quite laborious and needs a high-speed oscilloscope with calculation function. It is not suited for incoming inspection in production. In this paper we present a method for measuring the core losses close to the application without the needs of an advanced oscilloscope. The core is magnetized by a high voltage H -bridge (3 kV) switch. Due to the efficiency of modern SiC semiconductor the power draw of the bridge is direct related to the core losses. The power draw could be measured by simple current meter. With this method incoming inspection and selection is possible.

Fast Measurements with Modified HVD Series of High Voltage Dividers

A. Pokryvailo
Spellman High Voltage Electronics Corp., United States of America

HVD Series of precision high voltage dividers manufactured by Spellman [1] are specified for DC measurements only. As such, they possess very high input impedance (1 GOhm and higher) and are corona-free.

We modified 100-kV and 200-kV models for time-domain measurements, extending the range of HVD100 to 140 kV. These models are dubbed HVD100C, HVd140C, and HVD200C (C stands for "compensated"). The last two models have also modified corona suppression electrodes, and E-field analysis is described showing that the field is below corona inception. Typical usable risetime is 2 us for 100-kV and 140-kV models, and 10 us for the 200-kV kV model. Settling time to 0.2 % is less than 2 ms.

HVDs are calibrated for fast response both at low and high voltage by step response method; calibration results are provided. The modified, compensated, versions retain the same DC accuracy as their original DC counterparts.

The modified HVDs are useful for laboratory and manufacturing practices when HV time domain measurements are necessary in combination with high DC accuracy and high input impedance.

[1] Resistive Voltage Dividers, https://www.spellmanhv.com/en/high-voltage-power-supplies/HVD

A Multi-Hundred kW HV Power Supply Platform with Low Stored Energy for Industrial Applications

I. Erakovic, D. Green, A. Pokryvailo
Spellman High Voltage Electronics Corp., United States of America

A modular concept and industrialized demonstration of a 200kW, 45kV power supply possessing high dynamic characteristics is described. The system is comprised of eight 25kW, 45kV chassis connected in parallel and a control unit. Owing to the phase shift within and between the modules, high conversion frequency, and straight rectification schemes, the output capacitance is extremely low, which facilitates fast dynamic response, e.g., fast recovery after load sparking; stored energy is <10J, and ripple is <1% at full load.

The system is housed in three cabinets. Each chassis is packaged in a 19" 6U rack and weighs 45kg. Solid insulation and air cooling were adopted. Mechanical and electrical designs were assisted by circuit and FEA analyses. Particular attention, in view of high-power density, was paid to heat transfer, which was analyzed from the component level up to CFD modeling at the chassis and cabinet levels.

A variable parameter PID regulator achieves 300us rise time for a full range of loads without over/undershoots.

Electric Field Driven Ionization Waves in Nanosecond-pulse Discharge

C. Zhang[1,2], H. Bangdou[1], T. Shao[1,2]
[1]Institute of Electrical Engineering, Chinese Academy of Sciences, China, People's Republic of; [2]University of Chinese Academy of Sciences

Electric field is an extremely important microscopic parameter in the subject of high voltage (HV) and gas discharge. In this paper, electric field induced second harmonic (E-FISH), as a non-intrusive diagnostic method for electric field, is developed with good temporal and spatial evolution. This method is adopted to measure the spatial-temporal distribution of electric field in nanosecond pulsed discharges, including surface dielectric barrier discharge (SDBD) [1] and atmospheric pressure plasma jet (APPJ) [2], which verifies its reliability and feasibility. It is found that ionization waves (IWs) exist universally in nanosecond-pulse discharges with different geometries, which are driven by the intensified electric field at the wave front region. The weak electric field in the plasma channel is also very important for sustaining the IW propagation. Both space charges in surface and volume charges on dielectric will contribute to the measured electric field, the former of which generate a retarding electric field when IW propagates driven by unipolar HV pulses. To summery, the E-FISH diagnostic is a promising method to measure the space electric field and to retrace the behavior of space charges in a wider field of applications.

Calculations of pulsed magnetic Field Interactions with Neurons using Sim4Life

E. F. Downing[1], R. R. Ramos[1], A. M. Loveless[1], H. A. Ryan[2], K. M. Virgilio[3], A. L. Garner[1]
[1]Purdue University, United States of America; [2]Veritas Alchemy LLC; [3]Luna Innovations

As medical applications of electromagnetic radiation transition from in vitro tests to the clinic, understanding multiscale behavior from the molecular to organism level becomes critical. This necessitates accurately modeling the interaction of electric fields at not only the cellular level, but at the tissue level. While many studies have investigated mechanisms at the cellular level, modeling in vivo effects requires determining the interaction of an applied electric field with the tissue before predicting cellular behavior [1]. However, it can be difficult to ascertain how the different components in these systems will interact as they are vastly complicated compared to the single cell models explored already. This is even the case when considering something as apparently simple as dielectric properties, which will vary with tissue type and location throughout the body. Sim4Life (https://zmt.swiss/sim4life) is a multiphysics software that was specifically developed to perform these calculations from the electromagnetic source to the tissue level by considering the physical and dielectric properties of phantoms for an organism of interest. Furthermore, Sim4Life contains the functionality of integrating NEURON, which is an open source software that specifically assess the effect of an electric stimulus on neurons [2]. This integrated software provides the user the flexibility to characterize changes in neuron behavior, such as action potentials, from an electromagnetic stimulus.

As a first step in this process, we are modeling the interaction of a pulsed magnetic field (PMF) applied to a rat model using Sim4Life. We will specifically consider the effects of pulse duration, rise- and fall-times, and repetition rates of the current source used to generate the PMF under the idea that the magnetic field will induce an electric field that will change the transmembrane potential of the exposed cells [2]. Whether permeabilization is induced, we will be able to use the integrated Sim4Life and NEURON software to explore changes in the action potential for various PMF exposures, delivery mechanisms, and positions along the rat. Modifications of this model to assess ex vivo proof of principle experiments to benchmark the model prior to using it to guide in vivo tests on rats will be discussed.

This research was funded by the Defense Health Agency under contract #W81XWH-20-C-0094.

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Comput., vol. 9, pp. 1179-1209, 1997.

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time-varying magnetic fields," IEEE Trans. Plasma Sci., vol. 48, pp. 1088-1095, 2020.

Modeling Plasma Membrane Pore Dynamics During Exposure to Electric Pulses Delivered by a Mismatched Blumlein Transmission Line

S. J. Wyss[1], A. M. Loveless[1], W. Milestone[2], R. P. Joshi[2], A. L. Garner[1]

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Electroporation occurs in cells when an applied electric pulse (EP) induces a transmembrane potential above a threshold to cause an increase in the plasma membrane conductivity. Many experiments, mathematical models based on the Smoluchowski equation (SME), and molecular dynamics simulations have examined the phenomena responsible for this behavior for standard rectangular or trapezoidal waveforms. In practical experiments, the applied waveforms differ from these idealized shapes, particularly when applying multiple EPs that permeabilize the cells and cause ion transport between the cytoplasm and extracellular fluid that causes a mismatch between the impedance of the cell suspension and the pulse generator. For the Blumlein generators often used for nanosecond EP delivery, these mismatches can create fluctuations in the pulse waveforms, including periodic waves after the main rectangular EP [1]. While important for applications involving multiple EP delivery, pore dynamics for a sinusoidal electric field after a rectangular EP have not been commonly studied. One study used the asymptotic SME to show that applying an AC field immediately after a square pulse could extend pore lifetime if it induced a sufficient amplitude of the transmembrane potential [2]. This then raises the question about the implications of mismatch-induced sinusoidal electric field following the applied rectangular pulse on membrane pore dynamics, particularly depending on the frequency and intensity of this sinusoidal component. This presentation examines this behavior by applying an asymptotic Smoluchowski equation (SME) [3] to model membrane pore dynamics for a cell exposed to EP waveforms characteristic of these mismatches. We will examine the effects of the frequency and amplitude of the secondary sinusoidal electric fields on membrane pore dynamics for main EPs of various rise- and fall-times, pulse durations, and electric field. We will also compare the results from this model to a simplified electroporation model based on transmembrane potential and assess potential intracellular effects that may arise due to these more realistic pulse waveforms.

[1] J.F. Kolb, S. Kono, and K. H. Schoenbach, "Nanosecond pulsed electric field generators for the study of subcellular effects," Bioelectromagnetics, vol. 27, pp. 172-187, 2006.

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This research was funded by the Office of Naval Research under grant #N00014-21-1-2055 and the Defense Health Agency under contract #W81XWH-20-C-0094.

Dielectrics II

Time: Tuesday, 21/June/2022: 3:30pm - 5:30pm · *Location:* Ballroom C
Session Chair: Kevin Burke

3:30pm - 3:50pm

Electrostatic Surface Charge Decay of Floating Dielectrics

Z. Cardenas[1], B. Esser[1], I. Aponte[1], M. LaPointe[1], J. Dickens[1], J. Mankowski[1], J. Stephens[1], D. Friesen[2], D. Hattz[2], N. Koone[2], C. Nelson[2], A. Neuber[1]

[1]Texas Tech University, United States of America; [2]Pantex, Amarillo Tx. United States of America

Electrostatic surface charge accumulation on dielectric materials, followed by surface charge decay, is investigated. This work focuses on charging floating dielectric surfaces to the limit of electric breakdown in atmospheric air in humid and dry conditions, succeeded by the slow charge decay on the timescale of minutes to hours. The mechanisms leading to reducing the surface charge density include surface charge cancellation from ions attracted from the surrounding gas medium as well as charge migration along the dielectric. A 100 mm diameter sphere of varying materials (Teflon, Acrylic, and metal as a reference) was triboelectrically charged to tens of kilovolts and allowed to decay uninterrupted in relative humidities of 40% and 12%.

While the metal sphere charge decay was largely unaffected by the humidity, the dielectrics exhibited a much faster surface charge density decay in humid conditions, particularly when the surface charge initially covered only a fraction ~ 10 to 25% of the sphere. That is, the humid conditions cause moisture layers to form on the dielectric's surface, impacting the surface conductivity of the material and allowing charge to redistribute along the surface. For instance, one finds an exponential dependence of the conductivity on the number of adsorbed water layers for Teflon and quartz reported in the literature.

For acrylic, in humid air, an initial drop in voltage upwards of 30% of the initial charging voltage was observed over 5 seconds. This rapid voltage drop is attributed to charge redistribution occurring on a much faster time scale than the air-ion to surface charge recombination. Further experimentation on decay behavior from uniformly charged dielectric spheres and partially charged spheres was conducted. This work provides details on the nonlinear surface conductivity, which is found to be electric field dependent.

3:50pm - 4:10pm

Characterization and Modeling of electrostatic Discharges on floating dielectric Materials

B. Esser[1], I. A. Aponte[1], J. C. Stephens[1], J. C. Dickens[1], J. J. Mankowski[1], D. Friesen[2], D. Hattz[3], N. Koone[3], C. Nelson[3], A. A. Neuber[1]

[1]P3E Center, Texas Tech University; [2]Mission Engineering Development Group, CNS Pantex; [3]Facility Engineering Electromagnetics Group, CNS Pantex

Electrostatic Discharge (ESD) waveforms are measured for polymeric materials – PTFE, PMMA, PA6 – with high-speed (sub-nanosecond) current viewing resistors (CVR). These waveforms are used to create lumped element models which capture the behavior in addition to a comparison to a drift-diffusion numerical simulation. Cylindrical dielectric samples without a well-defined ground (i.e. samples are 'floating') are of particular interest in this study. The ~100 mm diameter samples are charged primarily via triboelectric means to high voltage – greater than 20 kV. The surface charge distribution is mapped before and after a discharge to determine energy lost to establishing the spark, conduction to ground, and radiation – captured with a B-Dot probe. A three-axis – R, Z, and rotational Phi – movement system was created to perform the mapping of charges and control the approach speed of the discharging electrode. Discharge electrodes consisting of spheres of 5-20 mm diameter and pointed electrodes with tip radii ranging from 0.1 to 1 mm are used with approach speed ranging from 10 to 150 mm/s. The radiated field from the B-dot probe exhibits a sharp peak at ~1.5 GHz, temporally coinciding with peak current. Discharge waveforms are similar in shape between materials and charging polarities; however, peak current and length change. For instance, PTFE charged negatively creates a spark 150-200 ns in length, whereas positively charged PMMA creates a spark 100-150 ns in duration. Peak currents, on average, are similar between materials and polarity, ~0.2 A, and peak dI/dt range from 0.3 to 0.57 A/ns for PTFE and PMMA, respectively.

Through pre- and post-mapping of the surface charge, the discharged area of the charged dielectric is captured. The discharged areas range from 4 to 8 cm^2, with the charge maps revealing extended surface tracking mainly parallel to the symmetry axis of the cylinder.

With the spark length mainly dependent upon the approach speed for the same voltage, namely that faster approach speeds result in shorter sparks, one may expect lower speeds to exhibit lower peak current – that is, a longer spark would be suspect of losing more energy in establishing the spark. However, in experimental studies, this doesn't always occur. While a Rompe & Weizel spark model with an RC object model captures the basic behavior of the discharges, the drift-diffusion model reveals the fundamental physics at play. The numerical simulation captures the electron and ion motion/generation/loss and includes modeling the emission process of charges from the dielectric surface.

4:10pm - 4:30pm

A Finite Element Analysis Model for Internal Partial Discharges under DC Voltages

M. Saghafi, M. Ghassemi

Virginia Tech, United States of America

To achieve net-zero emission, all-electric transportation and moving towards 100% renewable power have been targeted. Due to the nature of load and generation in these two targeted areas, dc systems are preferred to achieve higher power densities and more efficient and optimal architectures than ac systems. From the insulation aspect, partial discharge (PD) is widely regarded as one of the best "early warning" indicators of component failure. However, while the PD topic is booming for ac systems, it is immature for dc systems. Also, although much work has been done and significant progress has been made on PD measurement and detection techniques, this is not the case for PD modeling. To address these technical gaps, a finite element analysis (FEA) model for internal PD under dc is, for the first time, developed to help understand the mechanisms behind PD under dc voltages. The model is validated through experimental studies where testing samples are built using 3D printing. Each sample has a void inside, which will cause internal PD. Through experiments, parameters necessary for calculating inception and extinction fields are obtained. Using the model, we also compare the magnitude and duration of charge and the frequency of PD signals under dc and ac.

4:30pm - 4:50pm

Monitoring of Polymeric Insulators by Infrared Thermography in HVAC and HVDC Systems

A. F. Leite Neto, E. G. Costa, P. B. Vilar, I. B. Oliveira, J. V. J. Melo

Federal University of Campina Grande, Brazil

The transmission of electrical energy in the world is predominantly provided by High Voltage Alternating Current (HVAC) lines. However, High Voltage Direct Current (HVDC) lines have gained space in power transmission over long distances. As the transmission lines, both in HVDC and HVAC, are susceptible to efforts from the environment and from the action of electromagnetic fields in transmission energy process. Such efforts wear out the materials that make up the system, especially the insulators, which can lead to failures and interruptions in the electricity supply. One of the main causes of interruptions, whether scheduled or unscheduled, is associated with the performance of electrical system insulation. In the case of electrical transmission and distribution systems, the insulation between the conductors and the towers is carried out by atmospheric air and by components called electrical insulators. Among electrical insulators, polymeric insulators have a prominent role due to their comparative advantages to ceramic insulators. To mitigate insulation failures that are related to polymeric insulators, it is recommended the use of predictive techniques to identify damages that could compromise the system. A prominent technique in the electrical system is infrared thermography. It suggests that the presence of defects in the polymeric insulators causes an increase in the local leakage current, which generates abnormal heating of the component. In AC, the technique is used by power utilities due to its electrical efficiency and usability in other equipment. In DC, operational experience using thermography to identify defective individuals has not been documented. This work presents a comparative analysis of the techniques for the application of infrared thermography in polymeric insulators in research on alternate (AC) and direct (DC) voltages. Therefore, electrical tests in AC and DC were carried out on polymeric insulators with different operating states. It was observed that polymeric insulators with degradations around the core, associated or not with fiberglass exposure, cause localized heating in the AC test. The generated heat identifies faulty regions in the insulators and allows effective monitoring of the evolution of damage to the polymeric coating. On the other hand, the results obtained from the insulators in DC did not identify a significant increase in temperature in any region of the insulator. The low value of the leakage current was the cause indicated for the thermal profiles obtained in the DC test. The results indicate that, in general, they use as monitoring techniques what is not possible to identify an isolated condition directly, except in cases where the defect is quite severe.

4:50pm - 5:10pm

Effect of Titania Nanofiller on Electrical Tree of Silicone Gel

<u>K. Nishikawa</u>[1], M. Kurimoto[1], T. Kawashima[2], H. Muto[1]

[1]Nagoya University, Japan; [2]Toyohashi University of Technology

In recent years, to reduce the size and increase the power density of power modules, the inside of the module is exposed to high electrical fields. The high electric fields may cause electrical tree in the silicone gel used as an encapsulant inside the module. As a result, the electrical insulation strength and the insulation life of the silicone gel deteriorate. Therefore, it is very important to suppress the generation and development of electrical tree to extend the service life of the material. The addition of nanofillers to silicone gels has been found to be effective to suppress the generation and propagation of electrical tree. In a previous study, it was confirmed that the addition of titania had a significant effect on the suppression of electrical tree. However, the data showed some variability. Therefore, to increase the reliability of the verification of the suppression effect, we refined the evaluation conditions for the electrical tree. The breakdown experiments were conducted by setting several patterns of voltage increase speed, and it was confirmed that the higher the voltage speed increase, the higher the breakdown voltage. In addition, titania was added to the silicone gel to investigate the difference in the effect of improving dielectric strength depending on the amount of titania added. The samples were subjected to ultrasonic treatment to disperse the titania particles. As a result of the experiment, the sample with 0.1 vol% titania showed the highest breakdown voltage when the voltage was applied at 10 kVrms/sec. Further, we observed the progress of the electrical tree. The samples were centrifuged to remove micro-sized agglomerates. The filling rate after centrifugation was as small as 0.05 vol% or less, so it could not be measured, but since the sample itself was cloudy, it is considered that agglomerates or nanoparticles of a size that cannot be observed with an optical microscope remain. The AC voltage of 50 Hz was applied to the needle electrode at 0.14 kVrms/5 sec, 8.5 kVrms was continuously applied, and the progress of the electrical tree was observed using an optical microscope. As a result, the outline of the electrical tree observed in the nanocomposite gel was not significantly different from that of the unfilled silicone gel. We obtained, in addition, the electrical tree of neat gel stretched to 2 mm within 500 seconds. On the other hand, the electrical tree of NC gel stretched at the same speed as neat gel to 0.5 mm, and grew more slower than neat gel from 1 mm or more. Some trees did not extend to 2 mm. From these results, it is considered that the nanoparticles in the gel suppressed the progress of the electrical tree. In the future, we will continue our research on the mechanism of electrical tree propagation in silicone gel and nanofillers that can further suppress electrical tree.

5:10pm - 5:30pm

Research on Influence of Harmonic Frequencies on the Growth Characteristics of Electrical Tree in Epoxy Resin

<u>Y. Shao</u>, X. Liu, G. Shang, M. Chen

State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, People's Republic of China

Cast epoxy insulation has the advantages of flame retarding, good electrical and mechanical properties, so it is widely used in the main insulation of converter transformer dry bushings. However, the converter transformer dry-type bushing generally operates under quasi-DC conditions, and its withstand voltage contains more high-order harmonic components. Higher harmonics will accelerate the deterioration of polymer insulation, which is generally considered to develop in the form of electrical trees. Due to the damaging effect of electrical trees, the life and insulation properties of insulation is significantly reduced, and breakdown may even occur. Therefore, the impact of harmonic frequencies on electrical tree characteristics of epoxy resin needs further investigation. This paper considers the influence of harmonic frequencies on the growth characteristics of electrical tree in epoxy resin between 50Hz to 350Hz. Under certain temperature, with the increase of the voltage frequency, the initiation voltage of the electrical tree in epoxy resin decreases, and the development speed of the electrical tree is accelerated after the initiation of the electrical tree. However, it does not mean that the breakdown time decreases as the frequency increases, which is related to the release of charge after the electrical tree penetrates.

High Power Microwaves

Time: Tuesday, 21/June/2022: 3:30pm - 5:30pm · *Location:* 301B
Session Chair: Jon Cameron Pouncey

3:30pm - 4:10pm

High Power Microwave and Pulsed Power Development at the University of Michigan

N. M. Jordan, D. A. Packard, B. J. Sporer, A. P. Shah, G. V. Dowhan, S. C. Exelby, P. C. Campbell, T. J. Smith, C. J. Swenson, R. A. Revolinsky, E. N. Guerin, L. I. Welch, S. V. Langellotti, Y. Lau, R. D. McBride, R. M. Gilgenbach
University of Michigan, United States of America

The Plasma, Pulsed Power, and Microwave Laboratory (PPPML) at the University of Michigan (UM) is home to three large pulsed-power drivers: the Michigan Electron Long Beam Accelerator (MELBA), the Michigan Accelerator for Inductive Z-pinch Experiments (MAIZE), and the Bestowed LTD from Ursa Minor Experiment (BLUE). MELBA is a 7-switch Marx generator with an Abramyan circuit and is capable of generating a 10 kA electron beam at -1 MV for up to 1 µs; this accelerator is currently configured to produce -300 kV and is used for high-power microwave (HPM) research. MAIZE is a 3-m-diameter, single-cavity Linear Transformer Driver (LTD) that supplies a 1 MA, 200 ns pulse for high energy-density physics (HEDP) research. BLUE is the most recent addition to the PPPML, consisting of four 1.25 m diameter LTD cavities which were previously part of Sandia's 21-cavity Ursa Minor facility. A single cavity of BLUE produces an estimated 150 kA at 100 kV in ~100 ns into a load matched to the driver's 0.5 Ω impedance. The 4 cavities can be stacked for a total driver impedance of ~ 2 Ω and correspondingly increased matched-load voltage of 400 kV.

Recent HPM developments will be presented, including: a multi-frequency Harmonic Recirculating Planar Magnetron (HRPM) utilizing a dual-frequency (L-band and S-band) slow-wave structure to enable low-Q operation at the MW level; a 5 MW Recirculating Planar Crossed-Field Amplifier (RPCFA) with ~ 9 dB gain at 3 GHz; experimental demonstration of the Recirculating Planar Magnetron with Coaxial-All-Cavity Extraction (RPM-CACE); a moderate current (< 10 kA) Magnetically Insulated Line Oscillator (MILO) operating in L- and S-band; and the implementation of a GW-class MILO on the BLUE LTD.

Pulsed power developments will also be highlighted, particularly the recent improvements to spark-gap switch reliability in MAIZE. UM has tested 3 spark-gap switch designs on MAIZE, and uncovered a number of operating modes that result in inconsistent breakdown and triggering. The lessons learned from these undesirable operating conditions, and the subsequent methods to achieve reliable operation, should benefit the growing population of researchers using and designing LTDs.

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4:10pm - 4:30pm

Modeling Composite Nonlinear Transmission Lines as High-power Microwave Sources

X. Zhu, A. J. Fairbanks, T. D. Crawford, A. L. Garner
Purdue University, United States of America

Nonlinear transmission lines (NLTLs) can sharpen input pulses and induce output oscillations as high-power microwave (HPM) sources with high pulse repetition rates, frequency agility, durability, and reliability, leading to compact devices with inexpensive construction costs and reduced power consumption [1]. In general, NLTLs use ferroelectric and/or ferromagnetic materials with field-dependent permittivity and/or permeability, respectively; implementing ferromagnetic materials produces microwave oscillations through gyromagnetic precession when biased under an external magnetic field [1].

In this work, we use COMSOL Multiphysics to model NLTLs containing ferroelectric and/or ferromagnetic composites and compare to experimental results. We have previously measured and simulated the linear effective electromagnetic properties of composites containing various volume loadings of barium strontium titanate (BST) and/or nickel zinc ferrite (NZF), which are nonlinear dielectric and magnetic materials, respectively [2]. We have also measured the nonlinear permeability and nonlinear permittivity of various volume loadings of these materials. These studies demonstrate the tunability of the electromagnetic properties of the composites, which may be used to adjust the RF output from a NLTL.

To reduce computational expense, we model the composite regions in the NLTLs as homogeneous domains. To model the gyromagnetic NLTLs with ferrite composites, we solve the Landau-Lifshitz equation [3] and treat the gyromagnetic ratio and damping factor as fitting parameters determined by comparison to experiments. The center frequency of the output pulses primarily varies with the gyromagnetic ratio when the bias field, the incident field, saturation magnetization of the applied ferrites, and ferrite filling ratio are fixed [3]. We compare the resulting models to experiments using NLTLs with different compositions of BST and/or NZF driven by different pulse forming lines. We then use the benchmarked model to predict performance with different materials and volume loadings to assess potential future designs. Implications for a complete HPM system design integrating an antenna and pulse forming network will be discussed.

We gratefully acknowledge funding from the Office of Naval Research (Grant No. N00014-18-1-2341).

[1] A. J. Fairbanks, A. M. Darr, and A. L. Garner, "A review of nonlinear transmission line system design," *IEEE Access*, vol. 8, pp. 148606 – 148621, 2020.

[2] 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," *Compos. Sci. Technol*., vol. 214, 2021, Art. No. 108978.

[3] I. V. Romanchenko, V. V. Rostov, A. V. Gunin, and V. Y. Konev, "High power microwave beam steering based on gyromagnetic nonlinear transmission lines," *J. Appl. Phys*., vol. 117, 2015, Art. no 214907.

4:30pm - 4:50pm

System Design Considerations for a Nonlinear Transmission Line Used Simultaneously as a Pulse Forming Line and High-Power Microwave Source

T. D Crawford, X. Zhu, A. J Fairbanks, A. L Garner

Purdue University, United States of America

Nonlinear transmission lines (NLTLs) have been of increasing interest for pulse sharpening and high-power microwave (HPM) generation. Their compact form factor coupled with their inexpensive and rigid design makes them ideal for field implementation where system survivability is a concern.

NLTLs are just one subcomponent in the overall HPM systems structure. Recent efforts have examined using the NLTL simultaneously as both the pulse source and HPM generator by biasing the lines with a DC charging voltage [1]. While this further reduces the spatial footprint of the system, such a design has inherent complications associated with extracting the signal it generates.

This work focuses on full system design considerations when using a NLTL in the PFL format. We manufactured 10-ohm composite based NLTLs that utilize a combination of barium strontium titanate and nickel zinc ferrite encapsulated in PDMS. The output of the NLTL was coupled to a pressurized spark gap switch that closed upon reaching a sufficient charging voltage. An impedance transformer was then designed to taper the impedance to a 50-ohm standard. We demonstrate that the RF output of the NLTL is a strong function of impedance with the RF signal becoming weaker with increasing impedance. This provides additional motivation for the NLTL in the PFL format since the impedance is readily flexible since it does not need to be directly matched to a Pule Forming Network. The ability to enhance RF generation with a lower impedance may permit further reduction in device size by eliminating the need for additional systems, such as a bias magnetic field. Overall implications on system development will be discussed.

1. A. J. Fairbanks, T. D. Crawford, and A. L. Garner, “Nonlinear transmission line implemented as a combined pulsed forming line and high-power microwave source,” Rev. Sci. Instrum., vol. 92, 2021, Art. no. 104702.

4:50pm - 5:10pm

RF Output Power Detection of the RADAN MG-4 Microwave Generator

N. C. Harrison, K. Allen, J. C. Dickens, A. A. Neuber, J. Mankowski

Texas Tech University, United States of America

The RADAN series-based MG-4 Microwave Generator is a compact, high power microwave system developed by the Institute of Electrophysics in Ekaterinburg. The system features the RADAN high voltage generator which is a SINUS-series device featuring a Tesla transformer charger and a Blumlein pulse forming line. The MG-4 microwave head is a mm-band relativistic backward wave oscillator (BWO) that operates at 35 GHz with a 5 to 10 MW peak output power and a pulsewidth of 3 nsec. The typical method of output power measurement is done with a cryogenic detector supplied with the system which utilizes a germanium crystal that changes resistivity as microwave radiation is absorbed.

In order to confirm the rf output power level of the MG-4, and because the germanium crystal rf detector was unavailable, a commercially available rf envelope detector was employed. Analog Devices ADL6012 is a broadband envelope detector that operates from 2 GHz to 67 GHz at input powers up to +15 dBm. It also features a 500 MHz envelope bandwidth and 0.6 nsec output risetime capability.

The diagnostic setup features the ADL6012-EVALZ, an evaluation board with the ADL6012 offered by Analog Devices, shielded in a fitted brass box located in the far field (~60 cm) from the microwave output horn. The output mode of the MG-4 is nominally TM_{01} but a mode convertor allows for a TE_{11} output mode as well. The surrounding surfaces close to the detector are covered with attenuation foam to limit reflections that could possibly be detected and interfere with measurements. A 20 dBi receiving antenna and four high frequency attenuators are used to reduce the input power to the acceptable input range of the detector. Two equal length coax cables connect the differential outputs from the detector to two channels of a high-speed 1.5 GHz oscilloscope where the positive and negative envelopes of the pulse are captured separately. Based on the peak differential output voltage of the positive and negative signal, the input power of the detector can be determined by the typical performance characteristics curves in the ADL6012 data sheet. Lastly, accounting for the attenuators, antennas, and free space path loss, the peak output power of the MG-4 can be accurately determined. At 60 cm centered from the MG-4, the ADL6012 output a 660 mV differential voltage. Using the typical application curves in the data sheet, this corresponds to a 4.4 dBm input power into the ADL6012. Accounting for the attenuators, receiving antenna, and free space path loss, the transmitted peak power of the MG-4 is 98.17 dBm (6.56 MW). This is in the expected output power range of the MG-4.

5:10pm - 5:30pm

Compact 60kV High Voltage Capacitor Charger for UWB Electromagnetic Pulse Generator

W. C. Jeong, H. J. Ryoo

Chung-Ang University, Korea, Republic of (South Korea)

In this paper, a portable 60kV high-voltage capacitor charger for ultra-wideband electromagnetic pulse generator based on a 24V battery was described. The HVCC should charge storage capacitors up to breakdown voltage(about 55kV) of spark gap switch inside Marx generator of the ultra-wideband electromagnetic pulse generator at 100Hz repetition rate. It should be considered not only the operation specification, but also size and weight for portability, nonetheless current burden on the used components is relatively large because of low input voltage. In addition, there are other difficulties such as the voltage stress of each components and isolation from other parts like grounded case. To satisfy the requirements, a parallel loaded resonant converter which operates as high-efficiency and high-frequency and an output rectifier designed by modifying the basic Cockcroft-Walton voltage multiplier(CWVM) were applied. The parallel loaded resonant converter operating at above resonant frequency was designed with a small value of parallel resonant capacitor to reduce reactive power, crest factor of the resonant current, and conduction loss. Also, proper snubber capacitor design is applied to reduce turn off switching loss. The modified CWVM is composed of two symmetrical CWVMs charged in parallel by a center-tapped transformer and storage capacitors inside the CWVMs are connected in series to the load. With this structure, it can be alleviated the voltage stress and maximum voltage potential. Therefore, it significantly reduces the difficulty of selecting components, design of the high voltage transformer and considering insulation when manufacturing actual system. In addition, it can be operated through very simple sensorless control method, only needs the information of the time to charge the load capacitor once and repetition rate, due to the characteristics of the designed resonant converter, such as a current source characteristic and inherent maximum voltage limit. Between the HVCC and Marx generator, the conductorless high voltage cable is connected to replace the isolation resistor to block a noise generated by UWB EMP, and to limit the excessive charging speed. Finally, the HVCC was actually implemented as small(120*120*245mm) and lightweight(4kg). Various experiments with 3.2nF and 8.4nF load capacitors equivalent to the sum of storage capacitors in the Marx generator were conducted. Also, it is verified that the HVCC can charge to 62kV and be inherently limited due to the characteristic of the designed converter without any control. Finally, it was verified by the experimental result with the actual Marx generator load that the HVCC repeatedly charge over 50kV at 100Hz repetition rate.

Repetitive Pulsed Power

Time: Wednesday, 22/June/2022: 10:00am - 12:00pm · *Location:* Ballroom C
Session Chair: Jacob Stephens

10:00am - 10:20am

Spark Gap with integrated triggering Laser

J. C. Pouncey

Naval Surface Warfare Center Dahlgren Division, United States of America

The use of pulsed lasers to trigger the operation of spark gap switches has a long history in pulsed power applications [1]. However, the application of this technology to compact low-energy modulators has been hampered by the size and complexity of the typical laser and optical systems. In previous work [2], the author described early experiments using a commercial diode-pumped solid state micro-laser to trigger pressurized spark gap switches. The small size of this laser made it feasible to integrate the laser directly into the body of the spark gap switch, thus reducing the complexity and providing improved ruggedness. However, the laser used in the initial experiments featured an integrated pump diode, which requires driving from a low-voltage electronic circuit. Integrating this laser directly into the spark gap would negate the principal benefit of laser triggering: the galvanic isolation of the triggering system from the high voltage circuitry of the modulator. This challenge has been addressed through a configuration in which the pump laser is fed to the solid-state laser resonator via an optical fiber. Since the pump is several orders of magnitude lower in power than the pulse from the resonator, efficient coupling through a fiber is greatly simplified compared to attempting to deliver the high-power trigger pulse through it. This configuration retains the close coupling of the laser resonator with the switch, while enabling the remote location of the low-voltage pump laser diode. An experimental switch has been constructed according to this configuration, and preliminary test results have validated the usefulness of this concept for the triggering of switches in compact modulators.

[1] A. H. Guenther and J. R. Bettis, "A review of laser-triggered switching," *Proc. IEEE*, vol. 59, no. 4, pp. 689-697, 1971.

[2] J. C. Pouncey and J. M. Lehr, "Triggering of Pressurized Gas Switches With a Class I Laser," in *IEEE Transactions on Plasma Science*, vol. 48, no. 7, pp. 2531-2537, July 2020

10:20am - 10:40am

COBRA DANE Radar Transmitter Group Replacement

M. Kempkes, T. Hawkey, L. Jashari, K. Vaughan, Y. Francis, M. Gaudreau, R. Simpson

Diversified Technologies, Inc., United States of America

In 2019, Diversified Technologies, Inc. (DTI) delivered a transmitter group replacement (TGR) for the COBRA DANE ground-based radar facility at Eareckson Air Station, Shemya Island, Alaska. This individual L-Band transmitter group is part of the twelve transmitter groups housed at the facility. Each transmitter group energizes, controls, and protects eight high-power, ring-bar type traveling wave tubes (TWTs). Individual RF outputs from each tube are input to a space-fed phased array antenna. At the system core is the modulator which manages the operation of high-speed solid-state opening switches, tube filament/grid supplies, and grid switch for each of the eight TWTs in the group; minimizing the impact of any single TWT failure on the group's performance.

The Group Controls Cabinet houses the Programmable Logic Controller (PLC) with graphical interfaces provides enhanced control, fault handling and diagnostic capabilities thereby increasing overall system sustainability and maintainability. A Power Distribution Unit feeds the group's two high voltage power supplies (HVPSs) which power the Capacitor Bank. The Capacitor Bank feeds the modulator opening switches to provide the full beam current for the group of 8 TWTs.

The Cobra Dane TGR effort was built for the USAF under subcontract to Raytheon Intelligence and Information Systems. This unit is the first group upgrade for the replacement of all 12 TWT groups in the radar (96 TWTs total). The contract for the remaining 11 Groups was awarded directly to DTI by the USAF in September, 2020.

10:40am - 11:00am

Microscale Gas Breakdown for Microwave Fields: Theory and Simulation

S. Mahajan[1], A. M. Loveless[1], A. Semnani[2], A. Venkattraman[3], A. L. Garner[1]

[1]Purdue University, West Lafayette, IN 47906 USA; [2]The University of Toledo, Toledo, OH 43606 USA; [3]University of California, Merced, Merced, CA 95343 USA

Several studies have utilized theory and particle-in-cell (PIC) simulations to examine the unification of field emission and Townsend avalanche for DC gas breakdown in microscale gaps [1]. While similar techniques have been used to study field emission driven microscale gas breakdown for radiofrequency (RF) and microwave (MW) fields [2,3], these studies have not applied the asymptotic approaches used to derive closed form solutions for DC microscale gas breakdown [1] to obtain scaling relationships between pressure, frequency, and gap distances for AC fields.

This study will use PIC and theory to characterize breakdown conditions for RF and MW conditions for various pressures, frequencies, and gap distances. Following previous studies [2,3], we incorporate field emission and collisional effects into the force law for the theory. We perform PIC simulations using the code XPDP1, which is one-dimensional in space and three-dimensional in velocity and modified to incorporate field emission [1], to determine breakdown voltages under various conditions to benchmark the theory and to elucidate particle behavior, most notably charge density and ion drift velocity, for incorporation into the theory. Specifically, we use theory and simulation to characterize critical scalings, most notably pd and f/p, where p is the pressure, d is the gap distance, and f is the frequency, for gap distances from 100 nm to 10 µm and frequencies from 0.1 to 10 GHz. Modifying the integration of field emission into the MW breakdown theory [2,3] by using approach developed previously for DC [1] enables us to perform asymptotic analyses in the limits of low (i.e., field emission) and high ionization (i.e., Townsend avalanche) to determine the implication of the dominant breakdown mechanism on the scalings mentioned above. Implications on device operation, plasma parameters, and extensions to larger devices will be discussed.

1. A. L. Garner, A. M. Loveless, J. N. Dahal, and A. Venkattraman, “A tutorial on theoretical and computational techniques for gas breakdown in microscale gaps,” *IEEE Trans. Plasma Sci*., vol. 48, pp. 808-824, 2020.

2. M. U. Lee, J. Lee, J. K. Lee, and G. S. Yun, “Extended scaling and Paschen law for micro-sized radiofrequency plasma breakdown,” *Plasma Sources Sci. Technol*., vol. 26, 2017, Art. no. 034003.

3. A. Semnani, A. Vankattraman. A. A. Alexeenko, and D. Peroulis, “Frequency response of atmospheric pressure gas breakdown in micro/nanogaps,” *Appl. Phys. Lett*., vol. 103, 2013 Art. no. 063102.

11:00am - 11:20am

Synthesis of Pulsed Forming Systems for Electromagnetic Manufacturing Process

D. Kaushik, J. T. Meledath

Indian Institute of Science Bangalore, India

Electromagnetic(EM) manufacturing systems utilize an intense transient current pulse generated by discharging of a pulsed power source into the tooling coil (actuator coil) through a suitable closing switch. This induces strong eddy currents in the workpiece and their interaction with the current flowing through the tooling coil produces the necessary force required for the workpiece deformation. Electromagnetic manufacturing has wide range of applications for processes ranging from electromagnetic forming, magnetic pulse welding, electromagnetic crimping, embossing, deep metal drawing, sheet metal sheering etc. to name a few.

The essential components of a manufacturing system consist of a suitable pulsed power source, tooling coil, die and the workpiece. The essential figure of merit that affects the deformation in the workpiece is the embedded features of the magnetic pressure waveform. The tooling coil produces the necessary magnetic pressure on the workpiece and its geometrical configuration is responsible for the spatial distribution of the magnetic pressure on the workpiece. The parameter of the pulsed power source controls the temporal behavior of the magnetic pressure on the workpiece. Finally, the die design determines the final shape of the deformed workpiece. Therefore, there exists a limiting approach for the design of the pulsed electromagnetic forming system for the workpiece depending on the final objective of the process. If the goal is to form shallow features on the workpiece such as free forming process etc., the essential figure of merit is the temporal variation of pressure profile and the maximum pressure on the workpiece. However, if significant deformation is required where the workpiece is made to impact a die in processes like embossing or magnetic pulse welding, which produces substantial impact pressures, the essential figure of merit in this case is the maximum velocity or the impact velocity of the workpiece. Nonetheless, the determination of the temporal behavior of magnetic pressure profile on the workpiece becomes the starting point.

The spatial features of the magnetic pressure on the workpiece are fixed once the geometrical assembly has been finalized. However, the pulsed electromagnetic manufacturing methods provide a high degree of flexibility for the control of temporal features of the magnetic pressure acting on the workpiece. The paper describes a novel approach to design and synthesize the pulsed power systems starting from either the target pressure profile or the velocity profile of the workpiece, and then presents a suitable methodology for synthesizing the pulsed power circuit. A suitable topology of circuit elements is first defined, and then important design parameters are identified for the synthesis of the pulsed circuit. Curve fitting methods along with unconstrained optimization techniques are used to find the optimized values of design parameters. The deformation in the workpiece is also simulated for the target and computed profiles and the designed pulsed power system is experimentally validated for the given tooling coil and workpiece system under consideration. The results obtained are found to be in good agreement for the designed parameters.

11:20am - 11:40am

Acoustic energy from exploding wire generated chemical reaction

T. Frost, B. M. Novac, P. Senior

Loughborough University, United Kingdom

The exothermic chemical reaction between aluminium and water is well known for a long time. However, this presentation will focus on a study representing the first stage of development of a repetitive exploding wire-based pressure source for industrial applications.

The practical arrangement and the diagnostic tools will both be presented, together with data showing amount of chemical energy transferred to the acoustic pressure wave.

11:40am - 12:00pm

Explosive Pulsed Power: Milling operation limits of PBX 9501 and PBX 9502

E. Weeks[1], J. Williams[1], R. Clark[1], S. Watkins[1], R. Albin[1], J. Dickens[1], J. Mankowski[1], J. Brikman[2], A. Neuber[1]

[1]Texas Tech University, Lubbock, TX; [2]CNS Pantex, FM2373 and HWY 60

Explosive-driven pulsed power performance benefits from modern polymer-bonded explosives. Owing to the explosives' fast reaction, high voltage pulses with microsecond to nanosecond duration may be produced. In the fabrication of explosively driven devices, high precision in the dimensional shape is required in practical application, and high machining speeds are desired. The range of allowable machining speeds is dictated by the US DOE-STD-1212-2019 with general coverage of all explosive materials. As previously demonstrated for lathing, the machining of the new polymer-bonded explosives may be safely exceeded. To establish new, safe boundaries, the thermalresponse of PBX 9501/9502 under conventional milling methods is studied. The presented work focuses on face milling performed with dry machining on a CNC, remote-controlled milling machine. Spindle RPM, feed rate, step size, and depth of cut were chosen as the primary parameters of interest. While pushing some parameters a factor 4 higher than presently allowed in the standard, the temperature was monitored via high-speed IR videography and with a K-type thermocouple inserted into the endmill's through coolant holes. A 6-axis force sensor mounted beneath the HE samples records operational forces and torques. Force and temperature curves are examined as a function of time, revealing behavioral differences for each material. Overall, milling regimes exist outside of DOE-STD-1212-2019 for which milling temperatures remain well below the HE critical temperatures. Characterization by the material removal rate allows for the generalization of the temperature trends and, more significantly, identification of milling regimes that maintain low temperatures and low cutting forces while allowing for relatively quick milling cycles. The analysis of empirical equations enables assessing the theoretical limits of the different parameters.

Biomedical and Applications

Time: Wednesday, 22/June/2022: 10:00am - 12:00pm · *Location:* 301B
Session Chair: Ram Anand Vadlamani

10:00am - 10:20am

Pulsed Electric Field Activation of Platelet Rich Plasmas with Different Levels of Platelet Enrichment and Red Blood Cell Content

B. Neculaes[1], A. Garner[2], E. Longman[2]

[1]GE Research, Niskayuna, NY, United States of America; [2]Purdue University, West Lafayette, IN, United States of America

Ex vivo platelet activation is being explored for a variety of regenerative medicine and wound healing applications. Activating the platelets releases multiple proteins and growth factors with key roles in the wound healing cascade. Platelet rich plasma (PRP) is typically obtained by centrifugation from the whole blood drawn from the patient. Bovine thrombin, a biochemical agent derived from animal sources, is then used in the clinic as the state of art platelet activator. The activated PRP, called platelet gel, is applied topically on the wound to be treated. Several studies have examined pulsed electric fields as a physically based method for platelet activation with several key advantages over bovine thrombin, including an easier workflow, the ability to standardize the method, reduced cost, enhanced tunability, and independence from animal sources that may cause immune response. Pulsed electric fields of various pulse durations [1] and delivery modality (capacitive or conductive coupling; various concentrations of extracellular calcium) [2] have been successfully used for ex vivo platelet activation in several biological matrices, including whole blood [3] and platelet rich plasma with red blood cell (RBC) content. This study presents the first results of pulsed electric field activation using three types of platelet rich plasmas from four human donors – one with RBC content and two others with minimal RBC content. Two types of microsecond pulsed electric fields have been used in this study, along with negative (no activation) and positive (activation using bovine thrombin) controls. Experimental results confirm growth factor release with pulsed electric fields for all three types of PRP – opening the door for wide clinical adoption of this novel pulsed power based biomedical approach.

[1] A. L. Garner, A. S. Torres, S. Klopman, and B. Neculaes, "Electrical stimulation of whole blood for growth factor release and potential clinical implications," *Med. Hypotheses*, vol. 143, 2020, Art. no. 110105.

[2] A. L. Garner, A. L. Frelinger III, A. J. Gerrits, T. Gremmel, E. E. Forde, S. L. Carmichael, A. D. Michelson, and V. B. Neculaes, "Using extracellular calcium concentration and electric pulse conditions to tune platelet-rich plasma growth factor release and clotting," *Med. Hypotheses*, vol. 125, pp. 100-105, 2019.

[3] B. Neculaes, A. L. Garner, S. Klopman, C. Morton, and A. S. Torres, "A multi-donor ex vivo platelet activation and growth factor release study using electric pulses with durations up to 100 microseconds," *IEEE Access*, vol. 9, pp. 31340 – 31349, 2021.

10:20am - 10:40am

Analysis of the Role of Cellular Heating in Microsecond Irreversible Electroporation

W. J. Milestone[1], Q. Hu[2], A. M. Loveless[3], A. L. Garner[3], R. P. Joshi[1]

[1]Texas Tech University, Lubbock, TX 79409, USA; [2]Eastern Michigan University, Ypsilanti, MI 48197, USA; [3]Purdue University, West Lafayette, IN 47906, USA.

Irreversible electroporation (IRE) involving tumor ablation presents a minimally invasive treatment and has found a niche in oncological applications. It has proven to be a safe and effective procedure for treating many unresectable tumors. However, the use of a series of high frequency sinusoidal bipolar electric pulses, in the context of cellular drug delivery and/or irreversible electroporation, has not been studied to the best of our knowledge. This scheme, similar to the High Frequency Irreversible Electroporation (HFIRE) protocol, could prove to be of utility and synergistic effects of local membrane heating might well be beneficial in the context of this long wavetrain. In the present simulation study, two aspects of interest will be probed: (i) the role of cell heating in possibly promoting the successful uptake of drugs for treatment, and (ii) the possible synergistic interplay between the electric field and local membrane heating in reducing the required electroporation threshold.

In this work, membrane electroporation will be simulated based on a Smoluchowski continuum analysis discussed elsewhere by our group, together with spatio-temporal heating due to the power dissipation from the external bi-phasic source. We will consider two-dimensional transient heat flow with azimuthal symmetry in a single spherical cell. The following aspects will be analyzed and discussed in this presentation: (i) Changes induced by including heating, especially effects on pore formation dynamics. (ii) Quantitative assessment of the magnitude of heating caused by the applied electric fields and its dependence on wavetrain and field characteristics. This could define safe-operating limits and/or provide guidance towards optimum parameter space. Given that the vast parameter space depends on multiple factors, including cell size, pulse characteristics, electrical and thermal parameters of the biological system, applied waveforms, and number of pulses, only a few test cases will be probed. (iii) The present simulations will allow predictions and mechanistic insights into the level of electric field threshold reductions possible due to synergistic heating. (iv) And finally, the possibility of establishing large thermal gradients at the membrane for thermo-diffusive transport will also be quantitatively assessed.

10:40am - 11:20am

Enhanced inactivation of Gram-negative bacteria using Gram-positive antibiotics and nanosecond electric pulses

R. A. Vadlamani[1], A. Dhanabal[2], D. A Detwiler[3], R. Pal[1,2], J. McCarthy[3], M. N Seleem[1,2], A. L Garner[2]

[1]Virginia Tech; [2]Purdue University; [3]Nanovis

Physically disrupting microorganism membranes with electric pulses renders the resistance mechanisms that inhibit or excrete antibiotics inert, reducing the antibiotic dosages required and making ineffective antibiotics effective. The growing threat of antibiotic resistant infections combined with a lack of drugs in the discovery pipeline necessitates novel ways for enhancing existing antibiotic effectiveness [1]. Nanosecond electric pulses (NSEPs) can make Gram-positive antibiotics, which are abundant, effective against Gram-negative resistant strains of bacteria, for which new and effective medicines are sorely lacking, on a sufficiently short timeframe to prevent resistance mechanisms from developing. We demonstrate the synergistic inactivation of a Gram-positive (*Staphylococcus aureus*) and two Gram-negative (*Escherichia coli,* and *Pseudomonas aeruginosa*) bacteria by combining various antibiotics with different mechanisms of action with 222 30 kV/cm or 500 20 kV/cm, 300 ns duration electric pulses (EPs) [2], energy matched [3] but selected such that the lower electric fields had minimal impact on viability, but reacted synergistically in combination with antibiotics. Combining NSEPs with antibiotics induced several log-reduction of colony forming units for antibiotics that induced no inactivation following 10 minutes of exposure in solution without NSEPs. *Staphylococcus aureus* inactivation improved compared to EPs alone when we combined 2 mg/L or 20 mg/mL of rifampicin with the 30 kV/cm EPs; however, only a few of the other combinations enhanced inactivation. *E. coli* inactivation improved compared to EPs alone by combining either EP pulse train with 2 mg/L or 20 mg/mL of mupirocin or rifampicin or by combining the 30 kV/cm EPs with either 2 mg/L or 20 mg/mL of erythromycin or vancomycin. These results indicate that EPs can make Gram-positive antibiotics efficient for inactivating Gram-negative bacteria.

[1] D. S. Davies and E. S. Verde, "Antimicrobial resistance," *Search Collab. Solut. World Innov. Summit Health Doha*, pp. 1–36, 2013.

[2] A. Vadlamani, D. A. Detwiler, A. Dhanabal, and A. L. Garner, "Synergistic bacterial inactivation by combining antibiotics with nanosecond electric pulses," *Appl. Microbiol. Biotechnol.*, vol. 102, no. 17, pp. 7589–7596, 2018.

[3] K. Schoenbach, R. Joshi, S. Beebe, and C. Baum, "A scaling law for membrane permeabilization with nanopulses," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 16, no. 5, pp. 1224–1235, Oct. 2009.

11:20am - 11:40am

Using intense pulsed electric fields for the sterilization of solid pre-packed food – the design and preliminary testing of a practical MV-class system

M. Woodyard, B. Novac, P. Senior, J. Stobbs

Loughborough University, United Kingdom

A pulsed power MV-class system for generating intense pulsed electric fields in a very large volume of water was designed, manufactured and tested. This is a first and essential step towards the proof-of-principle demonstration of a novel technique for the non-invasive sterilisation of pre-packed food. The pulsed power system, based on MV Tesla transformer technology, is capable of producing pulsed electric fields in excess of 100 kV/cm in a massive volume (≈1 L) of water. The electric field distribution in the processing volume is obtained using a commercially available electrostatic solver, benchmarked using an electro-optic Kerr-effect assembly. The paper presents a detailed analysis of the unique processing unit and theoretically explores a possible scenario related to processing pre-packed food.

11:40am - 12:00pm

Resonant Charging Circuit for a Semiconductor-based Marx Generator for an Electropoation Device

M. Sack, D. Herzog, J. Ruf, G. Mueller

Karlsruhe Institute of Technology, Germany

Electroporation devices for the treatment of plant material in a continuous flow may employ a Marx circuit featuring parallel charging and a complete discharge of the capacitors during each pulse. Thereby, the use of semiconductor switches rather than spark gap switches allows for a modern design without the need of recurring maintenance of the spark gap switches. However, the use of semiconductor switches demands for an adaptation of the circuit to the properties of these switches being able to operate at lower voltage and current but higher pulse repetition rate compared to spark gap switches. For such a design, resonant charging turned out to be of advantage because it combines a fast energy transfer from a DC-link capacitor as part of the power supply to the stage capacitors of a Marx generator with a charging circuit having no active switches. Moreover, it enables an increase in the charging voltage by a factor of approximately two with respect to the DC-link voltage.
An 8-stage Marx circuit with a stage voltage of 1 kV has been set up to study resonant charging. Its charging path has been equipped with current-compensated chokes having a low inductance during charging and a high inductance for transient insulation of the stages during the pulse generation. The charging circuit has been designed for a peak current of 70 A and a charging time of 800 µs. A separate inductance between the DC-link capacitor of the power supply and the generator serves as the inductive component for the resonance circuit. As pulse switches IGBTs have been employed. In the course of the charging process, they serve as opening switches allowing for fine tuning of the charging voltage in repetitive operation. The generator has been operated either with a ground connection at its negative output terminal or grounded at its center to deliver a ground-symmetric output voltage. In both cases the magnetic energy stored inside the current-compensated chokes has been either degraded or recycled to prevent the cores from saturation. In the latter case, measurements revealed oscillations in a resonant circuit comprising the stray capacitance of the current-compensated chokes. A series diode avoids these oscillations. The paper describes selected details of the circuit design and presents measurements of the charging process.

IPMHVC Plenary Lecture - R. Joshi

Time: Wednesday, 22/June/2022: 1:30pm - 3:00pm · *Location:* Ballroom EF

1:30pm - 2:30pm Warning: The presentations finish prior to the end of the session!

Modeling electric-field driven nonequilibrium phenomena for applications to pulsed power, electron beam generation, transport in materials, and electromanipulation for biomedicine

R. P. Joshi, M. Brown, W. Milestone, M. Sanati, J. Mankowski, J. Dickens, A. Neuber
Texas Tech University, United States of America

This talk will briefly touch upon the many innovative applications involving nonequilibrium and ultrafast processes in areas of pulsed power and high power microwaves driven by high electric fields. Many applications either involve the use of high electric fields to help enhance system currents or power generation (as in high power microwave systems), or to take advantage of non- equilibrium transient phenomena which can produce larger responses (e.g., the transient drift velocity overshoots in photoconductive switches), or be used to curtail the role of slower processes (such as dynamic shielding based on charge transport that typically require longer times), or help attain high internal electric fields in a targeted manner through robust displacement currents (e.g., the field penetration into sub-cellular organelles in biomedical applications). It is, therefore, possible that somewhat different system responses and outcomes can be achieved due to the ultrashort temporal regimes, or under the influence of high local electric fields. This operating domain can often trigger novel physics, or lead to effects dominated by nonequilibrium processes, or simply bring certain mechanisms to the forefront that might otherwise have remained negligible under near-equilibrium conditions.

This presentation will focus on our efforts at modeling and simulations of phenomena dominated by high electric fields, with inclusion of the transient processes. The goal is towards a better understanding for successful and more efficient applications to pulsed power, high power microwave generation, and biomedicine. The talk would include aspects of electron emission, outgassing in high power machines, operation of ultrafast photoconductive switches, materials engineering to curtail deleterious effects, electrochemotherapy and possible nerve stimulation, etc. The connection between engineering and the underlying science will also be discussed that can then lead to optimization.

High Voltage

Time: Wednesday, 22/June/2022: 3:30pm - 5:30pm · *Location:* Ballroom C
Session Chair: Howard Sanders

3:30pm - 3:50pm

Influence of Low Pressure on Thermal Limit of MVDC Power Cables Used in All Electric Aircraft

A. Azizi[1], M. Ghassemi[1], J. Lehr[2]
[1]Virginia Tech, United States of America; [2]University of New Mexico, United States of America

An electric power system (EPS) with high power delivery and low system mass is required for wide-body all-electric aircraft (AEA). Cables are an essential component of this future EPS. The pressure at the cruising height of a wide-body aircraft is around 18.8 kPa. At that pressure, heat transfer to the ambient air by convection is strongly limited, so the temperature field distribution across the aircraft cables is expected to be different from atmospheric pressure. The temperature field across the cable depends on the velocity field of the ambient air, which is a function of pressure and temperature. Also, to obtain the electric field of the DC cables in the electric aircraft power system, the conductivity of the insulation, a function of temperature and electric field, should be calculated. Therefore, a coupled multi-physics study should be conducted to calculate the temperature field and electric field across the cable. In this paper, a 5 kV DC cable is studied at 18.8 kPa pressure to compare the cable's temperature field and electric field at low pressure to the atmospheric pressure. The voltage level considered was resulted from our previous studies where we proposed new EPS

architectures for a wide-body AEA. Moreover, the maximum permissible flowing current of the cable is investigated at the pressure of 18.8 kPa regarding the thermal limits of the cable. It is shown that at low pressures the temperature of the cable is highly increased compared to atmospheric pressure, so the maximum permissible flowing current is lower than the rated current.

3:50pm - 4:10pm

An innovative approach to the design of medium voltage power electronics printed circuit-boards

Q. Yang, C. Diendorfer, D. Nath, M. Steurer, G. C. Montanari

Center for Advanced Power Systems, Florida State University, United States of America

Going towards maximization of power density and dynamics, the supply of electrical and electronics components in industrial, electrified transportation and renewable electrical assets is shifting from sinusoidal AC to modulated AC and DC, involving voltage and load transients.

Voltage is increasing to the MV range so that power electronics boards must be designed to withstand, for the specified operation life, high electric fields and temperatures. Very fast switching time and high modulation and carrier frequencies have to be also managed.

This determines electrical, thermal and mechanical stress profiles which can change significantly with supply voltage and time. They can affect (increasing) electrothermal and mechanical aging rate regarding both intrinsic and extrinsic aging factors.

As an example, the electric field in bulk insulation defects or on the PCB surface can incept partial discharges, PD, for some stress conditions, with different PD amplitude and repetition rate from AC to DC. This impacts on extrinsic aging rate, so that life reduction can be dramatic even if PD activity would be discontinuous.

This paper introduces an innovative approach to power electronic board design which should allow an optimized design of PCB insulation systems as regards their reliability, life, shape and dimensions/weight, taking into account the risk of generating extrinsic aging phenomena. The so called “three-leg approach” is based on the comparison and match of results coming from electric stress profile simulation, discharge modelling and partial discharge, PD, measurements under the type of waveform that a PCB can experience, specifically modulated AC and DC. It consists of extracting the information of maximum bulk and surface (tangential) electrical stress (field) at operating temperatures, comparing them with models for partial discharge inception that associated the stress to PD likelihood and linking such results with PD measurements (particularly the partial discharge inception voltage, PDIV). This would provide a PD-free design allowing inference on connector technology and shape, as well as quantities as creepage and clearance. The focus in this paper is describing how to deal with the first leg approach on a 5 kV PCB, showing electric field simulation results and explaining how discharge modelling and PD measurement will complete the whole optimized design.

4:10pm - 4:30pm

Breakdown Characteristics of Printed Circuit Board Based Transformer Windings

R. E. P. Frost[1], P. L. Lewin[2]

[1]QinetiQ, United Kingdom; [2]University of Southampton, United Kingdom

Further to work presented at IPMHVC 2018 [1], this paper examines printed circuit board (PCB) based transformer winding technology that can be used in a new generation of UHV power supply. Transformer windings printed on PCBs have several advantages over conventional windings. In addition to being robust and convenient to handle, they are easy, and relatively cheap, to manufacture. For these reasons they have enjoyed limited use in low voltage applications.
In the last few decades, PCB windings have begun to be used in HV applications. James Cross took advantage of their compact size, and ease with which power electronics could be mounted to them, when designing his 750 kV insulated core transformer [2]. However, despite their increasing use in HV applications, until now there has not yet been a comprehensive investigation into the voltage handling limits of PCB windings. This paper seeks to redress this shortage.
To do this an investigation was carried out, which began by dividing any potential winding into separate areas in which breakdown may occur, and then simulating the electric field around each one in order to identify areas of increased electrical stress. Possible breakdown mechanisms are discussed based on these results.
Practical experiments were then undertaken to verify the results of these simulations. Experiments were also carried out after the initial breakdown occurred, in order to determine the effect that the solder mask has on breakdown voltage. It was shown by simulation and experimental results that adjacent tracks, separated by 0.5 mm, could withstand a voltage potential of several kilovolts. This research suggests that PCBs are an ideal technology for constructing transformer windings, and provides an insight into a possible future of HV power supply design. Future publications concerning this project will focus on the effects that the distance between tracks, operating frequency, and environmental factors have on the breakdown voltage between windings.

[1] R. E. P Frost, J. A. Pilgrim, P. L. Lewin, M. Spong, "An Investigation into the Next Generation of High Density Ultra High Voltage Power Supplies", *Int. Power Modulators and High Voltage Conference (IPMHVC)*, 2018.
[2] J. D. Cross, Modular High Voltage Power Supply with Integral Flux Leakage Compensation, US6026004A, 1998.

4:30pm - 4:50pm

Reliable, Low-Jitter 100-kV Trigger Generator

R. E. Beverly III

R. E. Beverly III and Associates, United States of America

Large pulsed power systems require multiple trigger generators that are synchronous and accurate. Spark gaps having up to 200 kV across the electrodes are often utilized. Precise system triggering requires a comparable open-circuit peak voltage for low jitter operation and high certainty of gap commutation. "Low jitter" is typically σ ≤ 3 ns relative to a fast rise, 5-V command signal. One standard deviation σ is calculated using sampled delay-time measurements, where t_d is defined as the time between the leading edges of the input command and generator output signals.

The trigger generator must be highly reliable. Large systems carry enough energy to damage the load or other components even if one sub-module unintentionally pre-fires. Large systems are also degraded by misfires because most experiments have specific requirements for amplitude and temporal shape of the load current. Collectively these constraints place severe demands on trigger generators.

In simplest terms, the problem is one of amplification of the command pulse with a power gain of ~85 db. In practice, this must be done in multiple steps. In our approach, the command pulse is amplified to ~1 kV using a proprietary solid-state driver. Voltage multiplication is accomplished by a four-stage inductive adder that provides a fast-rise (17 ns) trigger pulse for a highly-compact (21 kg), 3-stage Marx generator with 19 J of stored energy. The first stage is configured as a trigatron with a surface discharge trigger.

The load (field-distortion switch, railgap, etc.) is connected through either a 6-m RG-220/U or 21-m RG-218/U coaxial cable. When driving a cable matched load (50 Ω), the peak voltage is ≈100 kV with a rise time <5 ns and e-folding time ≈150 ns. A peak voltage of 180 kV, rise time of <3 ns, and e-folding time of 190 ns are observed with a higher-impedance load (190 Ω). The self-break fraction (f) is defined as the ratio of Marx generator operating voltage (V_{op}) and median self-breakdown voltage (V_{sb}), where V_{sb} is a function of the internal gas pressure. t_d decreases rapidly to a lower asymptote as $f \to 1$ and $\sigma < 4$ ns when $f \geq 0.83$. The probability of a pre-fire is extremely low as long as $f \leq 0.90$, therefore the trigger generator affords both low jitter and high reliability when operating within the recommended range $0.85 \leq f \leq 0.89$.

Compared with other commercially-available trigger generators, our design does not rely upon bulky and difficult-to-obtain thermionic devices (e.g. thyratrons). The design is fully scalable to higher voltages by incorporation of additional Marx stages and scalable to higher energies by increasing the number of capacitors per stage. The output polarity may be changed by the user. The control console accepts both fiber-optic and electrical command inputs. The trigger generator is largely impervious to load faults when properly coupled. The system is designed for long life with minimal maintenance.

4:50pm - 5:10pm

Custom electrostatic probe diagnostics

M. LaPointe[1], B. Esser[1], I. Aponte[1], Z. Cardenas[1], J. Dickens[1], J. Mankowski[1], J. Stephens[1], D. Friesen[2], N. Koone[2], D. Hattz[2], C. Nelson[2], A. Neuber[1]

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A custom electrostatic probe design for the mapping of surface charge is presented. The coaxial geometry capitalizes on capacitive voltage division, allowing for a simple design and rapid prototyping abilities. Previously a coaxial probe was designed with a 9.4 mm diameter inner conductor to reduce field enhancements to surpass commercially available probe thresholds of +/- 20 kV. Designing the inner conductor to reduce field enhancements that could reach +/- 30 kV at 1 cm distances in air resulted in a reduced resolution compared to commercially available probes when compared directly without post-processing. This work focuses on an updated design where the inner conductor diameter was reduced to 1.6 mm, yielding an improved resolution by a factor of approximately six. The outer conductor was wrapped around the center conductor to keep the field enhancement low, leaving only an ~ 0.5 mm insulating gap between the outer, grounded conductor and the center. This effectively created a hemispherical ending with a 9.4 mm diameter since the potential difference between inner and outer conductors is only on the order of a few volts.

A post-processing procedure using an Inverse Wiener filter, often used in image processing, deconvolves the custom probe's response and regains some of the resolution lost through the necessarily large distance from the charged surface. A COMSOL finite element simulation was used to find the spatial transfer function needed for the post-processing correction. Surface charge mapping was performed for both PTFE and Acrylic, focusing on how charging polarities and different humidities affect charge distribution to determine a relationship between charge decay and unique charge distributions. For instance, using the same triboelectric charging technique for PTFE and Acrylic resulted in negative and positive surface charging, respectively, as expected from the triboelectric series. Across the measured RH humidity range, ~ 10 to 60%, Acrylic had a slower decay rate than PTFE, which may be primarily driven by the initially higher surface potential magnitude observed for PTFE under triboelectric charging.

5:10pm - 5:30pm

Improved Manufacturing Process for High Voltage Pulsed Diodes

A. Usenko[1], A. Caruso[1], S. Bellinger[2]

[1]University of Missouri-Kansas City, United States of America; [2]Semiconductor Power Technologies, Manhattan, KS, USA

DSRDs - Drift Step Recovery Diodes are used as opening switches for pulse generators since 1960s. Deep diffusion into a thinned wafer have been mostly used for the DSRD fabrication. The diffusion-based process has limitations in: (1) doping profile optimization, (2) diode side surface termination, (3) diode side surface passivation, (4) stacking on wafer level. These features limit final diode performance. (1) long voltage rise time, (2) and (3) low diode breakdown voltage, (4) heavy labor at die assembly into stacks.

We have suggested and tested new DSRD fabrication scheme where (1) deep diffusion replaced by epitaxy with desired doping profile, (2) diode side termination done by anisotropic etch instead on mechanical sawing, (3) diode side passivation by silicon dioxide instead on polyimide, (4) stacking on wafer level.

TCAD simulation predicted an optimal DSRD doping profile to reach the shortest rise time on a load. The predicted profile is different from profile obtained by diffusion (complementary error function). The predicted profile can be copied into silicon by controlling dopant flow during epitaxy. We have modified epitaxy tool to achieve desired profile and successfully grown near 200-micron thick epitaxial layer. This is drastically different from known attempts to fabricate DSRD using non-controlled (flat) epitaxial doping profile.

In traditional DSRD technology, wafers are cut into diode dies mechanically - by sawing, waterjet, laser cut, etc. This result in termination of diodes by surface that is perpendicular to wafer surface (vertical wall). While beveled wall is preferable – it gives higher breakdown voltage. Thus, traditional DSRD has breakdown along the vertical wall - diode termination surface. Also, mechanical cutting inevitably produces cracks, up to 50 microns deep into silicon. These additionally lower the breakdown voltage. And requires chemical etching, typically in HNA – to dissolve the damaged silicon.

We have replaced mechanical cutting step by anisotropic etching of v-grooves through lithography mask. Advantages are beveled diode side termination wall and no cracks. These result in higher breakdown voltages of the diodes. Another advantage is – v-groves go only below the epitaxial p-n junction layers, but not to the bottom of silicon substrate. Therefore, wafer integrity is preserved. This gives us an opportunity to stack wafers, not individual dies. Finally, we get more then hundred times smaller number of stacking operations, i.e., better manufacturability.

Passivation in the traditional DSRD process is heavily restricted. Say, oxidation cannot be used as top, and bottom of diode dies are already covered with metal layers for Ohmic contacts. Therefore, polymer coating – polyimide or silicone used. Our v-groove diode die separation does not pose this limitation. We have option to deposit metals later in process flow. Therefore, we use thermal oxidation to passivate side surfaces of individual diodes. The silicon dioxide passivation is preferable compared to polymer coating in both, breakdown voltage and long-term device stability considerations.

DSRDs manufactured with our novel process are sent for measurement of their pulsed performance. Separate presentation will report comparison of pulsed performance between traditional and our DSRDs.

Analytical Methods

Time: Wednesday, 22/June/2022: 3:30pm - 5:30pm · *Location:* 301B
Session Chair: Amanda M. Loveless

3:30pm - 3:50pm

Comparison of Particle-in-Cell and Continuum Simulations for RF Microscale Gas Breakdown

A. M. Loveless[1], V. Ayyaswamy[2], S. Mahajan[1], A. Semnani[3], A. L. Garner[1]

[1]Purdue University, United States of America; [2]University of California Merced, United States of America; [3]University of Toledo, United States of America

Understanding and accurately characterizing electron emission and gas breakdown is necessary with increasing device miniaturization. For DC voltages, Paschen's law, which is based on the Townsend avalanche criterion, is commonly used to predict gas breakdown; however, for microscale gaps, the resulting strong electric fields at breakdown induce the release of additional electrons by field emission (FE), which considers the enhanced surface electric field due to the decreased potential barrier at the cathode [1]. Accurately predicting breakdown under these conditions requires combining field emission and Townsend avalanche. Similarly, field emission also contributes to breakdown for microscale gaps under RF and microwave fields, motivating theoretical studies and particle-in-cell (PIC) simulations [2] to account for this behavior. While effective for gaps below ~10 microns at atmospheric pressure, PIC is not computationally efficient for larger gaps due to the computational expense encountered with additional particles. Thus, this study compares RF breakdown simulations using PDP1, a 1D/3v (one-dimensional in space, three-dimensional in velocity) PIC code, to continuum simulations using SOMAFOAM [3], a finite volume framework to simulate low-temperature plasmas. The results between PDP1 and SOMAFOAM will be compared to each other and theory for various frequencies, pressures, and gap distances, particularly to assess scaling laws between these parameters in different operational regimes. The computational efficiency of the two methods and assessment to theory and experiment will be discussed.

[1] A. L. Garner, A. M. Loveless, J. N. Dahal, and A. Venkattraman, "A tutorial on theoretical and computational techniques for gas breakdown in microscale gaps," *IEEE Trans. Plasma Sci.*, vol. 48, pp. 808-824, 2020.

[2] M. U. Lee, J. Lee, J. K. Lee, and G. S. Yun, "Extended scaling and Paschen law for micro-sized radiofrequency plasma breakdown," *Plasma Sources Sci. Technol.*, vol. 26, art. no. 034003, 2017.

[3] A. K. Verma and A. Venkattraman, "SOMAFOAM: An OpenFOAM based solver for continuum simulations of low-temperature plasmas," *Comp. Phys. Comm.*, vol. 263, art. no. 107855, 2021.

Work supported by the Office of Naval Research under Grant Number N00014-21-1-2441.

3:50pm - 4:30pm

Crossed-Field Nexus Theory: Incorporating Collisions, Field Emission, Thermionic Emission, and Space-Charge

L. I. Breen[1], A. M. Loveless[1], A. M. Darr[1], K. L. Cartwright[2], A. L. Garner[1]

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Understanding electron emission is vital for characterizing diode performance for numerous applications, including directed energy systems, thermionic converters, time-resolved electron microscopy, and x-ray systems. The "nexus theory" formulation may be used to predict the physical conditions where multiple electron emission mechanisms, such as thermionic, field, and space-charge limited emission, may need to be solved jointly [1]. Once nexus theory identifies such a regime, one can derive exact equations from first principles that couple the relevant physics to assess behavior. The exact model should recover the standard equations for the individual emission mechanisms under appropriate asymptotic limits [1]. Operating conditions near where these asymptotic solutions match require more complicated equations coupling the relevant mechanisms; regimes farther away from these intersections may use the simpler, well-known solutions.

A common diode design in high power applications incorporates an external magnetic field perpendicular to the electric field induced by the applied voltage. Electron trajectories in these crossed-field diodes may either cross the gap if the magnetic field is below a limiting value known as the Hull cutoff or be turned back to the cathode for magnetic fields exceeding the Hull cutoff. Above the Hull cutoff, the diode is magnetically insulated. Much as the Child-Langmuir equation characterizes planar space-charge limited current (SCLC), similar equations may be derived for the limiting current in crossed-field diodes under non-magnetically insulated [2] and magnetically insulated conditions [3]. These conditions do not strongly depend on the specific electron emission mechanism, but rather define the maximum current that may be emitted into the gap based on geometry and boundary conditions.

This presentation highlights our application of nexus theory to crossed-field diodes. We unify thermionic and field emission with the limiting current in a crossed-field diode by introducing the generalized thermal-field emission current density equation, as was previously derived for non-magnetic diodes [1]. We will next introduce collisions into the derivation of the limiting current of crossed-field diodes [2,3] to derive a collision limiting current for a crossed-field diode, equivalent to a Mott-Gurney law for non-magnetic SCLC with collisions. The implications of the transitions between these mechanisms under various conditions and the respective limits on device operation will be discussed.

1. A. M. Darr, C. R. Darr, and A. L. Garner, "Theoretical assessment of transitions across thermionic, field, and space-charge-limited emission," Phys. Rev. Res., vol. 2, 2020, Art. no. 033137.

2. Y. Y. Lau, P. J. Christenson, and D. Chernin, "Limiting current in a crossed-field gap," Phys. Plasmas, vol. 5, pp. 4486-4489, 1993.

3. P. J. Christenson and Y. Y. Lau, "Transition to turbulence in a crossed-field gap," Phys. Plasmas, vol. 12, pp. 3725-3727, 1994.

4:30pm - 4:50pm

Novel techniques for deriving the space-charge limited current for nonplanar diodes

N. R. Sree Harsha, A. M. Darr, J. M. Halpern, A. L. Garner

Purdue University, United States of America

Space-charge-limited current (SCLC) is the maximum current that can flow in the steady-state operation of the diode. Characterizing SCLC is critical for understanding the behavior of various devices, including high-power vacuum devices, organic field-effect transistors, quantum diodes, *n-i-n* or *p-i-p* diodes, and photovoltaic devices [1]. The SCLC in a one-dimensional (1-D) planar diode was derived independently by Child and Langmuir over a century ago [1]. Recently, we applied variational calculus (VC) and conformal mapping (CM) to derive analytic solutions to SCLC for nonplanar diode geometries [2].

In this presentation, we review the application of VC and CM to obtain analytic solutions for SCLC for nonplanar diodes. The analytic solutions for SCLC in any orthogonal coordinate system can be obtained using VC by extremizing the total current in the gap [2]. While VC is a powerful technique to solve for SCLC, the calculations become tedious for diodes exhibiting curvilinear flow. For such geometries, we have applied CM to transform the curvilinear flow into a rectilinear flow, thereby obtaining analytic SCLC solutions [2]. We extend VC to obtain a mathematical relationship between vacuum potential and space-charge-limited potential in any orthogonal geometry [3]. The exact solutions for SCLC in two-dimensional and three-dimensional planar diodes with finite emitters are presented [3]. We also apply Lie point symmetries to derive SCLC with nonzero injection velocity in nonplanar diode geometries and describe how similar solutions may be obtained using VC. The practical importance of this flexibility and a comparison between these mathematically powerful techniques will be discussed.

[1] 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," J. Appl. Phys., vol. 129, no. 10, Mar. 2021, Art. no. 100902.

[2] A. L. Garner, A. M. Darr, and N. R. Sree Harsha, "Calculating space-charge limited current density for general geometries and multiple dimensions," IEEE Trans. Plasma Sci., submitted.

[3] N. R. S. Harsha, M. Pearlman, J. Browning, and A. L. Garner, "A multi-dimensional Child–Langmuir law for any diode geometry," Phys. Plasmas, vol. 28, no.12, Dec. 2021, Art. no. 122103.

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4:50pm - 5:10pm

Assessment of Techniques for Determining Space-Charge Limited Current for Non-planar Crossed-field Diodes

H. Wang, N. R. Sree Harsha, A. M. Darr, A. L. Garner

Purdue University

The maximum stable current that can flow in a diode, known as the space-charge limited current (SCLC), is essential for numerous applications, including nano vacuum transistors, electric thrusters, and time-resolved electron microscopy. Recently, several general approaches for deriving analytic solutions for non-planar and multidimensional diodes have been developed [1]. Crossed-field diodes (CFDs), where an external magnetic field B is applied perpendicular to the electric field, may also be characterized by a maximum current that depends on whether an emitted electron crosses the gap or turns back to the cathode [2]. Unlike non-magnetic SCLC, the space-charge limit does not characterize the maximum current in a CFD, which is instead determined by electron flow stability [2]. These initial studies derived solutions for the limiting current that were only valid for planar diodes [2], which are not representative of typical crossed-field devices.

This presentation assesses various approaches to derive the limiting current for non-planar diodes. We first describe the derivation of the SCLC in both magnetically insulated and non-insulated CFDs by using the Euler-Lagrange equation for planar and concentric cylinder diodes [3]. While this approach may, in principle, be extended to any general geometry, the actual mathematical application is daunting. Thus, we also apply conformal mapping, which was used to derive the mapping of the space-charge limited potential from a given geometry to the standard planar geometry, to obtain SCLC for concentric cylinders [1]. We next apply Lie point symmetries, which may be considered as a generalization of conformal mapping, to derive SCLC in other complicated geometries, including concentric spheres, which are not amenable to conformal mapping [1]. An overall assessment and comparison of the SCLC using these different techniques will be discussed, as will the extension of conformal mapping and Lie point symmetries to more complicated geometries.

[1] A. L. Garner, A. M. Darr, and N. R. Sree Harsha, “Calculating space-charge limited current density for general geometries and multiple dimensions,” IEEE Trans. Plasma Sci., submitted.
[2] P. J. Christenson, “Equilibrium, stability, and turbulence in cycloidal electron flows in crossed electric and magnetic fields,” Ph.D. dissertation, Department of Nuclear Engineering and Radiological Sciences, University of Michigan, 1996.
[3] A. M. Darr, R. Bhattacharya, J. Browning, and A. L. Garner, “Space-charge limited current in planar and cylindrical crossed-field diodes using variational calculus,” Phys. Plasmas, vol. 28, no. 8, 2021, Art. No. 082110.

5:10pm - 5:30pm

Optimization of a Set of Electron-Neutral Collision Cross Sections in Fluorinated Nitrile (C4F7N)

M. Flynn, A. Neuber, J. Stephens

Texas Tech University, United States of America

Plasma fluid models for high-voltage gaseous discharges rely on transport coefficients which are often calculated with an electron swarm kinetic model (e.g. Monte Carlo, Boltzmann equation). These calculations, however, require the input of a set of electron-neutral cross sections which are not well known for many gases. C_4F_7N (i.e. 3M™ Novec™ 4710) is one such gas. Owing to its short atmospheric lifespan and large dielectric strength, C_4F_7N has received recent attention as an insulating gas with significantly reduced global warming potential, when compared to SF_6.

This report details the progress made in the development of a complete and self-consistent set of cross sections for electron swarms in C_4F_7N. MultiBolt, a multi-term Boltzmann equation solver, is utilized to optimize elastic and inelastic cross sections for the calculation of swarm parameters, which are compared with available literature. The cross section optimization procedure and considerations for the Boltzmann model will be discussed.

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