IVEC EVENTS OCTOBER 20, 2020

- **Opening Remarks**
- **Plenary Session I**

  Joan Yater: Opportunities in Cathode Research Enabled by Advanced Nanoscale Material Control and Understanding

  Bogdan Neculaes: Industrial Charged Particle Beam Applications in Medical Imaging, Electron Beam Additive Manufacturing and Circuit Breakers

- **Technical Sessions**

Session 1:
Microfabrication & THz I

Chair: Jennifer Hwu, Innosys

1.1 - High Power Pulsed 263 GHz Extended Interaction Amplifier

- *Mark Hyttinen*
  Cpi Canada Inc
- *Albert Roitman, Peter Horoyski, Henry Deng*
  CPI Canada Inc

A new model of a pulsed EIK amplifier operating at 263 GHz with an output power greater than 70 watts, gain of over 30dB and a -3dB bandwidth greater than 1000 MHz has been developed. This model targets advanced weather radar, visual imaging for homeland security and DNP enhancement of NMR systems.

1.2 - TWTs for Point-to-Point D-Band Wireless Links

- *Rupa Basu, Laxma R. Billa, Jeevan M. Rao, Rosa Letizia, Claudio Paoloni*
  Lancaster University

A new project to realize a point to point wireless system above 150 GHz with multigigabit per second data rate is in progress. The upper side of the D-band (151 -174 GHz) offers about 20 GHz with 3 GHz forbidden band for full duplex transmission. The aims it to enable fiber on air capacity with more than 1 km range to provide up to 45 Gb/s data rate. The wireless system works in Frequency Division Duplexing and consists of two front-ends, each of them with a transmitter powered by novel traveling wave tubes (TWT) fed by a directly modulated Resonant

Tunnelling Diode (RTD) oscillator. Two TWTs are designed using the double corrugated waveguide at 151 – 161.5 GHz and 161.5 – 174.8 GHz.

1.3 - On a D-Band Traveling-Wave Tube for Wireless Links

- *Rupa Basu, Laxma R. Billa, Jeevan M. Rao, Nicholas Renninson, Benjamin Rodgers, Rosa Letizia, Claudio Paoloni*
  Lancaster University
- *Quang Trung Le*
  HF Systems Engineering GmbH

The D-band (141 - 178 GHz), due to relatively low attenuation and about 27 GHz available, is attractive for point to multipoint backhaul. However, solid state power amplifiers at this frequency have no sufficient power to assure needed propagation range with 99.99% availability. This paper will describe the design and fabrication of a novel D-band traveling wave tube power amplifier to enable first point to multipoint system at D-band. The design approach is for large scale production. For the first time a new topology of double corrugated waveguide, used as slow wave structure, has been fabricated and measured at D-band. The D-band TWT provides about 35 dB gain and more than 12 W output power.

1.4 - Gated Silicon Field Emitter Array Characterization

- *Ranajoy Bhattacharya, Jim Browning*
  Boise State University
- *Nedeljko Karaulac, Winston Chern, Akintunde I. Akinwande*
  Massachusetts Institute of Technology

Arrays of silicon field emitter tips are being studied for use as vacuum nano-transistors. These arrays are analyzed using the CST particle tracking solver and via experiment. The simulations are used to study the potential transfer characteristics and performance for use as transistors for the vertical emitter structures. An experimental system has been developed to test the arrays under high temperature (400C) and for various gases to study the noise characteristics and the effects of adsorption and desorption on performance.

Session 2:
Power Supplies

Chair: Yehuda Goren, Teledyne Electronic Technologies

2.1 - AN/TPQ-18 Radar Transmitter

- *Michael Kempkes, Christopher Chipman, Philip Gordon, Luan Jashari, John Kinross-Wright, Marcel P.J. Gaudreau, Rebecca Simpson*
  Diversified Technologies, Inc.

  Diversified Technologies, Inc. (DTI) is building a new transmitter for the U.S. Air Force (USAF) Western Range AN/TPQ-18 radar facility. This 3 MW C-Band radar transmitter energizes, controls, and protects a CPI VKC- 8313A (5.4 GHz to 5.9 GHz) Extended Interaction Klystron (EIK).

2.2 - Gyrotron Pulse Modulator Test Stand

- *Michael Kempkes, Marcel P.J. Gaudreau, Craig Conecoff, Nigel Stuart, Luan Jashari, Rebecca Simpson, Tuan Nguyen*
  Diversified Technologies, Inc.

  Diversified Technologies, Inc. (DTI) has delivered a new 70 kV pulse modulator test stand to the Ulsan National Institute of Science and Technology (UNIST) in Ulsan, South Korea for full power testing of gyrotron tubes. The output is flat to less than 1% over 100 µs.

2.3 - Integrated System of a Mini-Marx Generator Charged by a Cockcroft-Walton Voltage Multiplier

- *Zhaofeng Zhang, Kaviya Arangandin, Ming-Chieh Lin*
  Multidisciplinary Computational Laboratory, Department of Electrical and Biomedical Engineering, Hanyang University
- *Hua-Yi Hsu*
  Department of Mechanical Engineering National Taipei University of Technology
- *Po-Yu Chang*
  Insitute of Space and Plasma Sciences National Cheng Kung University

  A Marx generator generates a high-voltage pulse by charging lots of capacitors in parallel, then suddenly connecting them in series. In principles, a comparatively lower voltage DC power supply can be used for the charging to achieve the desired high voltage. However, a moderate DC high-voltage power supply is still quite expensive and bulky but not in full-time charging. In this work, a mini-Marx generator powered by a Cockcroft-Walton (CW) voltage multiplier has been proposed to form a more efficient but affordable choice of pulsed high-voltage power sources. For generating a high voltage in a range of 70-100 kV, the mini-Marx generator consists of 8 stages. Therefore, a CW multiplier operating up to 10-15 kV is required. For demonstration, a 22-stage CW multiplier with an AC supply voltage of 220V at 60 Hz is chosen so that it can be driven by household electricity to generate a DC voltage of over 13 kV to charge the mini-Marx generator. Numerical simulations using PSpice have been performed for validating the concept. A prototype is developed. After setting a suitable time-controlled switch for releasing CW multiplier and a trigger for the spark gaps of the mini-Marx generator, the preliminary simulation results predicting a pulsed open-circuit voltage up to 85 kV from the mini-Marx

generator can be achieved while being charged by the CW generator operating at 11 kV. Detailed simulation and experimental results will be presented.

2.4 - High Power Density Electronic Power Conditioner for Airborne Transmitter

- *Neeraj Kumar, A. J. Zabiulla, Pradheep H. N., P. Sidharthan*
  Micowave Tube Research and Development Organisation, (Defence in Reasearch and Development Organisation)

The modern airborne transmitters for RF imaging, demand compact size and high RF output power. Miniature Klystrons offer higher efficiency, low voltage operation and compact size as compared to Traveling Wave Tubes (TWT) delivering similar output power within narrow bandwidth. Development of a high power density Electronic Power Conditioner (EPC) described in this paper complements a miniature klystron for delivering low phase-noise in the RF output, achieved with stringent control over the regulation, stability and ripple in the high voltage output for the anode voltage. High efficiency of the EPC allows operation of the transmitter for limited time without cooling.

2.5 - Development of a Power Supply Unit for a 10-kW Pulsed TWT

- *Daniel T Lopes*
  Fundacao PATRIA
- *Claudio C Motta*
  University of Sao Paulo

In this paper we present the development steps and early experimental performance results of a power supply unit being developed for a 10kW pulsed traveling wave tube. Our requirements demand a 14kV cathode voltage with a grid swing voltage pulses from -300V to an adjustable and regulated +250V. The common place 6.3Vdc for the filament and a depressed collector voltage of 11kV are used as well. The specified maximum duty cycle is 2% @ 50?s maximum pulse width and average prime power is around 600W. A power conditioner stage converts that voltage in 192VDC, which feeds the power inverter stage. The power inverter is composed of a usual power Mosfet H-bridge driven by a controlled PWM circuit. The step-up transformer has 2 primary and 6 secondary windings in order to assuage the voltage stress over rectifiers and filters. The grid modulator has followed a standard design with high and low voltage stages are isolated by means of optical fiber and optical Tx-Rx pairs. We expect to present the details of the design and experimental results in the final form of the paper.

Session 3:
Cold Cathodes

Chair: Joan Yater, Naval Research Laboratory

3.1 - Diamond p-i-n-nanoC Diodes for Electron Emitters

- *Franz A. Koeck, Harshad Surdi, Robert J. Nemanich*
  Arizona State University
- *Manpuneet Benipal*
  Advent Diamond

Electron emitters are widely deployed in traveling wavetubes (TWT's) for telecommunications, radar applications, and scientific apparatus like free electron lasers. These instruments typically utilize cathodes that release an electron current through application of thermal energy or high electric fields. A novel electron emitter approach exploits the negative electron affinity surface of diamond in a modified semiconductor p-i-n diode. Under a forward bias electrons are injected into the conduction band of the diamond diode and a fraction are emitted into vacuum. Electron emission occurs at room temperature and low electric fields. We have prepared a modified diamond p-i-n diode that included a highly conducting nanostructured carbon (nanoC) contact layer utilizing plasma-enhanced chemical vapor deposition (PECVD) on a single crystal boron doped substrate. Emitter devices with various geometries were then fabricated using photo-lithography. After a hydrogen passivation step individual devices were characterized in vacuum. Under a forward bias the p-i-n-nanoC diodes displayed light emission indicative of bipolar transport. With a typical diode current of 0.1 A an electron emission current approaching 0.4 mA was measured from a single device sized 1.2 mm x 0.2 mm.

3.2 - Field Emission Cathodes Fabricated from Bulk Carbon Nanotube Fibers and Films

- *Steven B. Fairchild, Paul T. Murray*
  Air Force Research Laboratory, Materials & Manufacturing Directorate
- *Salvador Portillo*
  University of New Mexico
- *Genevieve Dion*
  Drexel University

Carbon Nanotube (CNT) fibers and films have demonstrated excellent field emission (FE) properties and thus hold significant potential for use as electron sources for vacuum electronic devices (VEDs). FE cathodes made from 100µm diameter CNT fibers were fabricated on an industrial grade 3D knitting machine. A 1" diameter cathode was tested using 30kV, 30A power supply with a 300ns pulse width. An applied field strength of 3V/µm produced a measured current level of approximately 15A. A CNT film cathode was fabricated from a 20mm wide film arranged in a corrugated geometry. This cathode was tested in a low impedance linear transformer driver (LTD) system operating at 30kV with a 200ns pulse width. The measured current level was approximately 2kA for an applied field strength of 6V/µm.

3.3 - Observing Performance of Individual Metal-Coated Silicon Field Emitters in an X-Ray Generator

- *Gil Travish, Aquila Mavalankar, Jamie Cameron, Manuel Fohler, Isabel Gomes, Silvia Sottini, Nivedita Yumnam*
  Adaptix Ltd

The performance of a field-enhanced emitter (FEE) array in an enclosed and field-operated device has long been known to deviate from the ideal characteristics observed in laboratory settings. Here we report on the performance and failure mechanisms measured in FEE arrays operating in high-voltage sealed x-ray generators. The emitters are fabricated from etched silicon pyramids and coated with metal. Unlike many previously reported arrays, here the pitch is large (1cm) and affords easy measurement and diagnosis of individual emitters. We report on emitter performance and likely causes of deviations from ideal, including the impact of anode treatment, emitter geometry and catastrophic failure mechanisms.

3.4 - Graphene Hot Electron Photoemitters: Theoretical Performance Limits

- *Ragib Ahsan, Mashnoon Alam Sakib, Hyun Uk Chae, Rehan Kapadia*
  University of Southern California

Electron emission devices play a vital role in different applications ranging from electron microscopy to free electron lasers. Recently, it has been experimentally demonstrated that photoexcited hot electrons in graphene can be extracted using a dc electric field with orders of magnitude higher quantum efficiency (QE) compared to the cold electrons. The 2D nature of graphene allows the hot electrons to be emitted without any need to be transported to the emitting surface allowing high QE of the device. We have conducted a theoretical investigation on the performance limits of graphene photoemitter using a quantum mechanical model of electron emission with coupled Monte Carlo Boltzmann Transport Equation (MCBTE) solving technique. We have showed that our theoretical model can quantitatively reproduce the experimental results with reasonable accuracy. Our model predicts two different regimes of operation for the photoemitter: (1) single hot electron emission at relatively lower optical power density (<10^9 W/m2) and (2) ensemble hot electron emission at higher optical power density (>10^9 W/m2). In the ensemble hot electron emission regime, it is possible to achieve a quantum efficiency >100% with a subpicosecond response time. This theoretical result sets up an experimental roadmap to build new photoemission devices that produce high optical power density featuring integrated photonic components allowing ultrahigh and ultrafast photoemission current.

3.5 - Two-Color Laser Induced Electron Emission from Biased Metal Surface

- *Yi Luo, Peng Zhang*
  Michigan State University

By solving the time-dependent Schrödinger equation, we construct an exact analytical solution for nonlinear ultrafast electron emission from a dc-biased metal surface illuminated by two-

color laser fields. Our results show a large dc bias can significantly increase the photoemission current, while maintaining a strong current modulation with respect to the phase delay of the two-color lasers. Application of our model to time-resolved photoelectron spectroscopy shows the dynamics of n-photon exited states depends strongly on the dc field.

Session 4:
MMW TWTs

Chair: Mark Basten, Northrop Grumman

4.1 - Demonstration of a W-band TWT with 10 GHz Bandwidth - keynote

- *Alan Cook, Colin Joye, Reginald Jaynes, John Rodgers, Igor Chernyavskiy, Frank Wood*
  U.S. Naval Research Laboratory
- *Edward Wright, Khanh Nguyen*
  Beam-Wave Research, Inc.
- *Takuji Kimura, John Atkinson, Galen Aymar*
  CPI, LLC

We present testing of a W-band traveling-wave tube (TWT) based on a serpentine waveguide circuit, powered by a 20 kV, 130 mA electron gun. We measure peak output power of 215 ± 2 W at 93 GHz with 20.1 ± 0.15 dB saturated gain, and >100 W from 88-98 GHz, pulsed at 0.1% duty. Operating at 20.8 kV, the TWT produces 285 ± 3 W at 91 GHz with 22.4 ± 0.15 dB gain.

4.2 - A 50 Watt W-band MPM

- *Ji Chen, Jialu Li, Chang Gao, Zhangxiong Zi, Jun Cai*
  National Key Laboratory of Science and Technology on Vacuum Electronics and Beijing Vacuum Electronics Research Institute
- *Fengyan Wang, Zhiwei Zhang*
  Southwest China Research Institute of Electronic Equipment
- *Zhigang Wang*
  University of Electronic Science and Technology of China

BVERI has developed a broad band microwave power module (MPM) providing over 50W RF power from 91GHz to 97GHz. The MPM includes a folded waveguide CW TWT with a gain equalizer, a modular electronic power conditioner (EPC) and a solid state amplifier(SSA).

4.3 - W-Band 30W Continuous-Wave Wide-Band Folded Waveguide TWT

- *Li Fei*
  Aerospace Information Research Institute, Chinese Academy of Sciences

A W-band 30W wideband continuous wave folded waveguide TWT (CW FWTWT) with 15kV operation voltage was designed and fabricated. The measured results showed that beam transmission was over 98.5% at dc and better than 97% at the highest peak RF power. Measured saturated output powers were higher than 31W within frequency range of 90-99GHz. The maximum output power was 58.1W and the maximum saturated gain was 37.7dB at center frequency point of 94GHz.

4.4 - Design of a Multi-kW Ka-Band Elliptical Beam Amplifier with PPM Focusing

- *John Pasour, Frank Wood, Spence Albright*
  NRL
- *Khanh Nguyen, Edward Wright*
  Beam Wave Research

To achieve higher output power while maintaining the compact size and weight of typical PPM-focused TWTs, we have explored options for incorporating a sheet or elliptical cross section electron beam in a coupled cavity or folded waveguide circuit. This approach allows significantly higher beam current to be propagated at a given voltage and magnetic field amplitude than is possible in a round beam. However, there are fundamental design constraints that limit the aspect ratio of the beam and the corresponding circuit designs that can be utilized. Here, some of these constraints will be discussed and designs presented for elliptical beam Ka-band TWTs that are capable of >2 kW output power with a 20 kV, 1A electron beam.

4.5 - 3D Meander Line Slow Wave Structure for W-band TWT

- *Juan M. Socuéllamos, Rosa Letizia, Claudio Paoloni*
  Lancaster University
- *Roberto Dionisio*
  European Space Technology and Research Centre

Planar meander lines have been recently studied in detail due to their favorable properties as slow wave structures for traveling wave tubes. However, the interaction of a cylindrical electron beam with this kind of structures is not efficient enough in order to achieve the output power levels required for space applications at W-band. A new design, suitable and optimized for the cylindrical beam geometry, is introduced in this work. Cold and large signal results are presented in the paper.

Session 5: Multipactor

Chair: John Verboncoeur, Michigan State University

5.1 - Multipactor Thresholds in a Planar Test Cell

- *Zachary C Shaw, Benedikt Esser, James C Dickens, John J Mankowski, Andreas A Neuber*
  Center for Pulsed Power and Power Electronics

A planar test cell was designed and implemented to observe the multipactor effect in waveguide structures. This plug and play device allows for multiple geometries to be machined and easily replaced within the test structure. A direct detection method was used to observe the multipactor effect while the upper and lower thresholds were measured for a 2.1 mm gap at 2.85 GHz. While there is an obvious lower limit to multipactor (~2 kW), there was no observable upper limit even at powers over 200 kW. This is attributed to the transverse electric field distribution in the dominant TE10 mode which is not taken into account in most multipactor theoretical models.

5.2 - Multipactor Effects on Signal Quality in Transmission Lines with Impedance Mismatches

- *Patrick Wong*
  University of Michigan & Michigan State University
- *Y. Y. Lau, Nicholas Jordan, Ronald Gilgenbach*
  University of Michigan
- *Peng Zhang, John Verboncoeur*
  Michigan State University

Multipactor is a resonant AC discharge of secondary electrons driven by RF signals and has been a center point of current interest because of its detrimental effects in space satellite communications. Much effort has been placed in mitigating/suppressing or determining the onset of multipactor. However, not much attention has been directed to the effects of multipactor, should it occur, on the quality of the original signal. In this paper, we will look at different types of multipactor (single-surface and two-surface) and how they may affect a signal (single-tone and dual-tone) in planar and coaxial transmission line systems with impedance mismatches. I-Q plots that characterize the multipactor effects will also be presented.

5.3 - Secondary Electron Yield Measurements on Materials of Interest to Vacuum Electron Communication Devices

- *Talal Malik, Mark Gilmore, Salvador Portillo, Edl Schamiloglu*
  University of New Mexico

Vacuum electron devices (VEDs) can experience degraded performance, including complete failure, due to multipactor breakdown (MPB). This effect is tied to the production and acceleration of secondary electrons due to electron impact and coupling to the RF fields. In order to better understand the initiation of MPB with materials of interest, researchers at the University of New Mexico (UNM) are carrying out a study of the secondary electron yield (SEY) contribution from various materials used in high power VEDs. This work describes SEY data from electron bombardment in the low energy regime, from 10 eV to 1 keV, on Cu as a baseline material, - stainless steel, aluminum 6061 (Al) and Invar (Fe64/Ni36). SEY data for Cu as a

function of incident beam angle is also presented. In addition, different surface cleaning treatment protocols employed in this study will be described.

5.4 - Analysis of Single-Surface Multipactor Discharge in the Frequency Domain

- *Asif Iqbal, Patrick Wong, John Verboncoeur, Peng Zhang*
  Michigan State University

This work presents the frequency domain analysis of multipactor discharge on a dielectric surface with rf electric fields of single or two carrier frequencies, by using a one-dimensional multiparticle Monte Carlo (MC) simulator with adaptive time steps. The study shows that the single tone rf operation produces a normal electric field to the dielectric surface consisting of pronounced even harmonics of the driving rf frequency. The strength of a harmonic component is a function of the incident rf amplitude. For dual tone operation, the amplitude spectrum of the normal electric field reveals spectral peaks at various frequencies of intermodulation products of the rf carrier frequencies. Empirical equations are proposed to approximate the temporal profiles of the normal electric field in terms of its frequency components, for rf operation with either single or two carrier frequencies.

5.5 - A General Empirical Model of Secondary Electron Yield and Its Application in Monte Carlo Simulation of a Microporous Gold Surface

- *Asif Iqbal, Peng Zhang*
  Michigan State University
- *Jonathan Ludwick, Marc Cahay*
  University of Cincinnati
- *Steven Fairchild, Tyson C. Back*
  Air Force Research Laboratory
- *Daniel Gortat, Martin Sparkes, William O'Neill*
  University of Cambridge

We present a general empirical model of secondary electron yield (SEY), which successfully fits the experimentally measured SEY of a flat gold surface for both normal and oblique incidence of primary electrons. This empirical model is applied in a two-dimensional Monte Carlo (MC) simulation to estimate the effective SEY reduction of a microporous surface. The simulation results are in very good agreement with the experimental data.

5.6 - Design, Simulation, and Testing of an S-Band Coaxial Multipactor Test-Cell

- *Stephen V. Langellotti, Nicholas M. Jordan, Y. Y. Lau, Ronald M. Gilgenbach*
  University of Michigan

In satellite communication systems, multipactor discharges have the potential to disrupt signal transmission and damage hardware. This paper discusses the design, simulation, and testing of a

coaxial multipactor test-cell that will be operated at GHz frequencies. The experiment's design has been guided by CST Particle Studio PIC simulations to predict multipactor breakdown. A number of diagnostic instruments will be used to detect and characterize the discharge. This experiment will ultimately be used to study the multipactor phenomenon and explore mitigation strategies.

Session 6:
Klystron Manufacturing

Chair: Ed Eisen, CPI Microwave Power Products Division

6.1 - Miniature Klystron for CubeSats - keynote

- *Bernard Vancil, Jereme Shaver, Forrest Bishop*
  e beam, inc.
- *Malcolm Caplan, Danilo Radovich*
  Consultant

We report results of a 3-year study to build a very small 35 GHz klystron for use in a cloud-imaging radar and deployed on a 1U (10 cm x 10 cm x 10 cm) CubeSat. Three klystrons and four beam testers were constructed. One device achieved 22 watts of saturated output power. DC beam transmission was 99 percent. The devices employed many innovative features, including glass rod fastening of gun, collectors, and circuit elements, a glass vacuum envelope for easy removal of heat by radiation, a novel permanent magnet focusing system and gun construction, a four-stage depressed collector of unprecedented compactness and simplicity, and a half-watt miniature scandate cathode. The paper describes the modeling tools used and compares their predictions to measured results.

6.2 - Noble Gas Retention Effect on Klystron High Voltage Stability

- *Andrew Cripps, Mark Hyttinen, Doug Yake, Anna Moskvicheva*
  Communications and Power Industries

Several fielded klystrons experienced operational interruption due to sporadic arc events. Root cause analysis at CPI Canada revealed that VacIon pumps used to process these klystrons were saturated with nobble gases. Pressure bursts in pumping process indicated spontaneous release of gases back into the system. This process resulted in residual pressure of noble gases in the klystron. The cycle of adsorption and spontaneous release continued in the operating klystron resulting in sporadic high voltage arcing. This paper describes the details of root cause analysis and preventive actions.

6.3 - Reliability Optimization Techniques in High Power, High Duty Factor Klystrons

- *John Moss, George Toby, Timothy Miner, Charles Peters*
  Oak Ridge National Laboratory

  The Spallation Neutron Source Radiofrequency Systems have enjoyed high reliability (> 97.7 percent) over the past five years due in large part to the techniques used to optimize the operation of the klystron amplifiers. SNS klystrons operate at up to an 8 percent duty factor with a peak RF output power up to 5 MW. Reliable operation starts with the process used to characterize each klystron and adjust its operational parameters in situ for best performance. Techniques are described here with examples.

6.4 - Multiple Beam Power Grid Tubes for High Frequency and High-Power Operation

- *Robert Lawrence Ives, Thuc Bui, David Marsden, George Collins*
  Calabazas Creek Research, Inc.
- *Ricky Ho, Leroy Higgins, Christopher McVey, Nileshwar Chaudar*
  Communications & Power Industries, LLC
- *James Potter*
  JP Accelerator Works

  High power, high efficiency RF sources are required at frequencies below 700 MHz for ion and proton accelerators. These sources are also used for high energy accelerators, such as the Advanced Photon Source, which is seeking 350 MHz RF sources producing more than 200 kW of continuous power. The program is developing multiple beam triodes capable of providing this RF power at efficiencies exceeding 80%. The sources would be extremely compact and low cost. Both the triodes and the associated RF cavities are being developed.

6.5 - Modular High-Power RF Sources for Compact Linear Accelerator Systems

- *Brandon Weatherford, Mark Kemp, Xueying Lu, Julian Merrick, Emilio Nanni, Jeffrey Neilson, Ann Sy, Sami Tantawi*
  SLAC National Accelerator Laboratory

  SLAC is pursuing high efficiency, low cost RF source designs that are suitable for mass production, in order to enable the next generation of linear accelerators. These efforts have driven the development of compact linac systems with integrated modulators, klystrons, and accelerator structures, based on a modular, low voltage klystron topology. There is substantial demand for compact linacs for X-ray radiography with security applications, and for new radiation therapy machines that reduce treatment times by orders of magnitude and may yield beneficial biological effects. In this presentation, details and challenges for these new compact accelerator systems and the corresponding RF sources are discussed.

6.6 - Manufacture of CEPC 650-MHz 800-kW CW Klystron

- *Yunfeng Liao, Rui Zhang, Xiudong Yang, Zhihui Geng*
  Aerospace Information Research Institute, Chinese Academy of Sciences

This paper describes the manufacture process of CEPC 650MHz 800kW continuous wave klystron. Klystron mainly includes electron gun, high frequency cavities, output window, collector, etc. Aerospace Information Research Institute, Chinese Academy of Sciences (AIR) has completed the design review of klystron, structural optimization, machining, cavity cold test, component welding, electron gun degassing, and klystron assembling. Now the first klystron has been manufactured.

Session 7:
Modeling: Guns & Collectors

Chair: Eric Nelson, Los Alamos National Laboratory

7.1 - Development of the Compass Framework for Multi-Disciplinary System Design Optimization - keynote

- *Aaron Jensen, Alex Burke, Serguei Ovtchinnikov, John Petillo*
  Leidos
- *Alexander N Vlasov*
  Naval Research Laboratory

Compass is a new framework for rapid prototyping and design optimization. The pilot framework was developed to leverage SolidWorks as the front end for simulation using SolidWorks' ability to rapidly generate well defined geometries in a natural way, and with constraints. Boundary and meshing constraints are defined in SolidWorks using the Compass interface. This approach greatly increases designer efficiency by eliminating the need for geometry scripting and meshing which are both done "under the hood" by the Leidos Compass tool in conjunction with SolidWorks. The effort to develop Compass is ongoing. A modular approach is being used to develop a multi-disciplinary system design optimization (MSDO) framework and infrastructure that supports potentially any simulation software in a general way. Compass modules can be connected to form simulation pipelines. The geometries and simulation pipeline can be optimized using Dakota or Galaxy Simulation Builder (GSB). Here we employ Compass for the design of vacuum electronic amplifier components.

7.2 - Recent Advances in Beam Optics Analyzer

- *Thuc Bui, R. Lawrence Ives*
  Calabazas Creek Research Inc.
- *Chris McKenzie*
  Oxford Instruments X-ray Technology, Inc.

Recent advances in Beam Optics Analyzer include anisotropic materials implemented within the finite element framework, higher order interpolation for thermal and stress analyses, and smoother, more efficient shapelets method to construct current density on 3D surfaces

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7.3 - A 2-1/2 Dimensional Model of Miram Curves

- *Abhijit Jassem, Yue Ying Lau*
  University of Michigan
- *David P. Chernin, Serguei Ovtchinnikov, John J. Petillo*
  Leidos, Inc.

The physical reasons behind the shape of Miram (and I-V) curves for a thermionic cathode have been a mystery for decades, despite significant efforts to analyze them, both in experiments and in modeling. This is an important matter because a thermionic cathode is almost always operated in the vicinity of the "knee" of the Miram curves for TWTs and klystrons, due to considerations of thermal stability and long cathode life. This paper presents a novel analytic model, which solves the Poisson equation in 3D exactly, including an arbitrary distribution function of work function on the cathode surface. An earlier version of this model (in press) solves the Poisson equation in 2D, and it yields excellent agreement with the corresponding MICHELLE code results. Our close examination of the emission patterns at the boundaries of patchy emission led to unprecedented insights into the physics of Miram curves. The 3D extension of this analytic model, and its tests against MICHELLE, will be presented in IVEC 2020. The flexibility of this 3D analytic model would allow for ready prediction of the Miram curves for a realistic cathode that includes patchy, nonuniform emission of electrons from the cathode surface.

7.4 - Nexuses between Field, Thermionic, and Space-Charge Limited-Emission Theories

- *Adam M Darr, Caleb R Darr, Allen L Garner*
  Purdue University

Electronic device design requires increasingly extreme operating conditions such as temperature, gap miniaturization, voltage, and pressure. Transitions between electron emission physics have been studied, and transitions between pairs of regimes are increasingly well understood. This paper derives equations that give exact solutions over a wide range of gap distance, temperature, and voltage and asymptotic solutions for field, thermionic, and space-charge limited emission in appropriate limits. The matching of two or more asymptotic solutions yields nexuses that elucidate the device parameter regimes requiring solving the exact equations. As an example, a nexus between Fowler-Nordheim, Mott-Gurney, and Richardson-Laue-Dushman occurs at a temperature of 3056 K, bias voltage of 717 MV, and gap distance of 0.18 m, and pressure of 15.4 atm.

7.5 - Transitions in Electron Emission and Gas Breakdown from Nanoscale to Microscale

- *Amanda M. Loveless, Adam M. Darr, Allen L. Garner*
  Purdue University

The miniaturization of electronic devices requires a deeper understanding of electron emission and gas breakdown dynamics at nano- and microscales. Micro- and nanoelectromechanical systems (MEMS and NEMS, respectively) for sensing and scanning, microplasma applications, and directed energy devices require an accurate characterization of electron emission behavior for accurate predictions of device behavior. While breakdown has historically been predicted by Paschen's law—driven by Townsend avalanche processes—this fails as gap distance decreases to the point where field emission (FE) become relevant. Further decreasing gap distance makes electron emission space-charge-limited as defined by the Child-Langmuir law (CSCL) at vacuum, the Mott-Gurney law (MG) if collisions contribute, or quantum space charge behavior (QSCL) at nanoscales when Schrodinger's wave equation must be used to consider single particle effects. This study nondimensionalizes the governing equations defining these underlying phenomena to identify transition points between them and understand the underlying physics dominating the emission behavior in these regimes to aid device design and experimental setup. A sample case theorizes a nexus occurring between all emission mechanisms at a pressure of approximately 1780 Torr, a gap distance of 62 nm, and an applied voltage of 6 V. Additionally, we discuss the implications of work function and surface roughness on these behaviors.

7.6 - MICHELLE 2020 Beam Optics Simulation Code: Bringing Ease of Use to Complex Simulations

- *John J. Petillo, Serguei Ovtchinnikov, Aaron J. Jensen, Alex T. Burke , Eric Nelson*
  Leidos
- *George Stantchev, Simon Cooke*
  US Naval Research Laboratory
- *Ben Held, Alan Nichols*
  AWR

The MICHELLE Beam Optics code continues to grow and evolve with new capability. With the demand for more complexity of applications – from multi-beam structures to field emission arrays – and yet higher accuracy as a predictive tool, there has been an emphasis on ease of use without detracting from the ability to build complex simulations. As such, much of the new capability is in the area of the user interaction, consideration of other tools standards used in the process of device design, like CAD, streamlining the process of optimization, and a seamless transition from rapid scoping of new concepts on local machines to performing complex multidimensional optimization on supercomputers when needed, and identifying/quantifying sensitivity of design to manufacturing variations. MICHELLE is a core module of our new COMPASS tool, which enables much of this functionality and methodology. Additionally, much progress has been made with regard to mesoscale simulations that captures first principles thermionic emission physics on a microscopic level, as well as improved thermal-field emission for application to finite and large-scale arrays. To support such disparate spatial scales, effort has been put into disparate meshing capabilities. The presentation provides an overview of the new capability that has been achieved

Session 8:
High Power Microwaves I

Chair: David Abe, DARPA

8.1 - Simulations and Experiments on Magnetically Insulated Line Oscillators

- *Drew Anthony Packard, Christopher J Swenson, Anna Cooleybeck, Brendan J Sporer, Alexander E Mazarakis, Nicholas M Jordan, Y.Y. Lau, Ryan D McBride, Ronald M Gilgenbach*
  University of Michigan

The magnetically insulated line oscillator (MILO) is a compact source of high power microwaves (HPM) that creates a self-generated magnetic field for crossed field interaction. At the University of Michigan, multiple efforts in simulation and experiment are underway to improve MILO operation in different ways. A new pulsed power test bed BLUE (Bestowed LTD from the Ursa-Minor Experiment) is under development, capable of generating different output voltages (100-800 kV). BLUE will be used to drive a GW-class MILO, testing operation at various injected voltages. Simulations of the MILO in CST-Particle Studio have demonstrated accurate predictions of output power and current across a range of input voltages that BLUE is projected to generate. Investigations in simulation and experiment of a planar MILO with external magnetic field are also underway. A planar, applied-B MILO could potentially operate at higher efficiencies than the conventional cylindrical geometry.

8.2 - Backward-Wave Oscillator with Distributed Power Extraction Operating at an Exceptional Point of Degeneracy

- *Tarek Mealy, Ahmed F. Abdelshafy, Filippo Capolino*
  University of California, Irvine

We propose a new and efficient degenerate synchronous regime for backward wave oscillators (BWO) based on an exceptional point of degeneracy (EPD) in the RF-electron beam interactive system. Compared to conventional BWOs, we introduce distributed power extraction all the way along the BWO structure. The EPD is obtained in the interactive RF-beam system by the simultaneous presence of distributed gain (due to the electron beam) and power extraction. Current PIC simulation results show that at a guiding magnetic field of 2.6 T, electron beam of 600 kV and 1740 A, an output power of 0.5 GW is extracted with power conversion efficiency of 47% and oscillation frequency of 9.7 GHz. This paper shows the feasibility of this new concept, and performance could be further improved.

8.3 - Experiments on the Recirculating Planar Magnetron with Coaxial All-Cavity Extraction

- *Nicholas M Jordan, Drew A Packard, Christopher J Swenson, Sunkeerth Tummala, YY Lau, Ronald M Gilgenbach*
  University of Michigan
- *Matthew A Franzi, Brad W Hoff*
  Air Force Research Laboratory

Calibrated microwave power measurements are presented for the Recirculating Planar Magnetron with Coaxial-All-Cavity Extraction (RPM-CACE). Experimental results are compared with computational predictions using the particle-in-cell code ICEPIC. The RPM-CACE was

designed using extensive simulation and optimization to demonstrate the RPM concept, and was simulated to operate at 1.89 GHz and produce peak powers of ~400 MW at 50-70% efficiency. The experiment utilizes a novel coaxial extraction system to minimize the total diameter of the device.

8.4 - Controlled Harmonic Frequency Locking in the Harmonic Recirculating Planar Magnetron

- *Drew A. Packard, Nicholas M. Jordan, Y.Y. Lau, Ronald M. Gilgenbach*
  University of Michigan
- *Brad W. Hoff*
  Air Force Research Laboratory

The Harmonic Recirculating Planar Magnetron (HRPM) is a novel, tunable, multi-spectral source of high power microwaves (HPM). Consisting of an L-Band Oscillator (LBO, near 1 GHz) and S-Band Oscillator (SBO, near 2 GHz), the HRPM can generate HPM at multiple frequencies simultaneously by exploiting harmonic frequency locking. In the locked state, the SBO frequency locks to the LBO second harmonic frequency. HRPM operation was characterized in simulation and experiment, with the LBO frequency and SBO quality factor (Q) as the independent variables. It is concluded that the oscillators act as a damped, driven, harmonic oscillator system, where the LBO is the driving oscillator, the SBO is the driven oscillator, and the harmonic content in the beam spokes is the coupling mechanism between them. In standard-HRPM experiments, the SBO generated 9.5 ± 1.4 MW (high Q), 19 ± 6 MW (moderate Q), and 28 ± 9 MW (low Q) in the ?-mode. In isolated-SBO experiments, the output power was not significantly different, but the primary operating state was the 5?/6 mode. Therefore, implementation of the LBO enabled mode control of the SBO.

8.5 - Design and Simulation of a Relativistic S-Band Inverted Magnetron

- *Timothy P. Fleming, Peter J. Mardahl*
  Air Force Research Laboratory

A Giga-Watt class Inverted relativistic Magnetron Oscillator (IMO) was designed and simulated using the massively parallel electromagnetic particle-in-cell code ICEPIC and scaling/redesign of an existing L-Band IMO. The IMO presented here is designed to operate in S-Band at low magnetic fields (B ~ 0.13 T). An axial RF power extraction method is employed. This technique eliminates the need for waveguide combiners, mode conversion apparatus, and complex radiating structures. ICEPIC simulations confirm that the above features combined with the IMO's stable, robust and reliable performance in the desired mode yield a Giga-Watt class HPM source notable for its size and absence of downstream current loss.

8.6 - Ka Band 20-Vane Non-π-Mode Magnetron - keynote

- *Bekir Bekirov, Sergey N. Terekhin, Viktor V. Zavertanniy, Victor D. Yeryomka, Mihail V. Milcho, Kostyantyn Ilyenko*
  Institute for Radiophysics and Electronics of NAS of Ukraine

- *Valentyn P. Dzyuba*
  State-Owned Enterprise Plant "Generator"
- *Tetyana Yatsenko*
  Becton, Dickinson and Company (BD)

We report development at IRE NAS of Ukraine of pulsed Ka band (8-mm/37.5 GHz) 20-vane unstrapped 8-mm magnetron. It operates in a non-pi-mode of the "-1" spatial harmonic. Results of numerical modelling and experimental investigations of anode slow wave structure (anode block) for (N/4 - 1)-mode (N = 20) are presented and discussed.

Session 9:
Scandate Cathodes

Chair: Daniel Busbaher, 3M

9.1 - Lifetime Performance of Nanocomposite Scandate Tungsten Cathodes

- *Michelle Gonzalez, Neville C. Luhmann, Jr.*
  University of California, Davis
- *Diana Gamzina*
  SLAC National Accelerator Lab
- *Colin McElroy, Carl Schalansky*
  Vacuum Process Engineering Inc.

Nano-composite scandate tungsten cathodes have shown superior performance to other thermionic cathodes. Lifetime emission data is an essential evaluation metric of powder quality for use in vacuum electron devices. Commercially viable large batch scale production of NST powder with lifetime data meeting industry demands will be essential to the vacuum electron device industry. Comparing commercially fabricated NST powder to laboratory NST powder is an evaluation metric for determining powder quality.

9.2 - Advanced Nano-Scandate Cathode

- *Daniel E. Bugaris, Claudia Goggin*
  Engi-Mat Co.
- *Kerry Baker, John Balk*
  University of Kentucky
- *Daniel Busbaher*
  Ceradyne, Inc., a 3M Company
- *Jack Tucek*
  Multispectral Solutions, Northrop Grumman Corporation

Scandate cathodes have the potential to replace conventional cathodes because of their improved emission characteristics. Nevertheless, it remains a challenge in this field to produce scandate cathodes with uniform surface emission in a reproducible manner. In this study, we

report on scandate cathode emitters prepared from a novel nano-scandia/tungsten composite powder. Processing improvements have been developed to yield high-quality emitter surfaces. Emission testing demonstrates a greater than 200°C decrease (improvement) in knee temperature versus the standard M-type cathode. There is an on-going effort to quantify the work function of the cathode surface prior to and following activation.

9.3 - Recent Progress on Scandate Cathodes - keynote

- *Bernard Vancil, Michael Kleschuk, Victor Schmidt, Allen Vancil*
  e beam, inc.
- *Douglas Jones*
  Omega Analytical Services
- *Wayne Ohlinger, Michael Green*
  Consultant

We report recent progress on scandate impregnated cathodes, including development of a miniature cathode assembly with cathode diameter 0.035 inch and dissipating less than 0.5 watt. Also, the synthesis of new impregnants which provide better barium delivery is reported on. Scandate cathodes, as a rule, are deficient in barium and must be pressed and sintered to low densities to compensate. Auger studies on operating cathodes showing scandium evolution and replenishment are presented.

9.4 - Temperature Effects on Desorption Behavior and Characteristic Wulff Shapes of Scandate Cathodes

- *Mujan N. Seif, Thomas John Balk, Matthew J. Beck*
  University of Kentucky

Scandate cathodes have been shown to exhibit superior emission properties to other classes of thermionic cathodes. However, a deeper understanding of their fundamental operating behavior is crucial before widespread technological integration. It is a widely held hypothesis that the electron emission of scandate cathodes is related to Ba availability on the surfaces of the porous W matrix. In addition, extensive characterization of scandate cathodes motivates an additional hypothesis that high-performance cathodes all contain W nanoparticles of a particular shape. These attributes, Ba availability and nanoparticle shape, are significantly affected by temperature -- the former due to desorption and the latter to the temperature-dependence of surface excess free energies. Here, we report computed Ba desorption rates for surfaces at 1000 C. We show that total Ba evaporation from the Ba/O-decorated W(110) surface is ~10 orders of magnitude higher than Ba/O-decorated W(112). We also report that temperatures on the order of 1000 C imply that chemical environments sufficient to reduce BaO are required to form the W particle shapes observed in high-performing Sc cathodes.

9.5 - Characterization of Material Phases on the Surface and in the Near-Surface Region of Scandate Cathodes

- *Xiaotao Liu, Matthew J. Beck, T. John Balk*
  University of Kentucky
- *Bernard K. Vancil*
  E Beam, Inc.

The impressive electron emission capabilities of scandate cathodes continue to receive significant research attention, although there remain gaps in understanding the mechanistic reasons for their performance. This is partly due to lingering questions about the materials and microstructure of the cathode emitting surface. In the current study, scandate cathodes fabricated using related but distinct processes were emission-tested and then characterized using advanced electron microscopy and analytical spectroscopy techniques. The cathode surfaces were consistently observed to consist of faceted tungsten grains decorated with ~100 nm oxide ($BaAl_2O_4$ and Sc_2O_3) particles and ~20 nm Ba-containing particles.