11th International Workshop on the Mechanisms of Vacuum Arcs (MeVArc 2024)

Report of Contributions

Contribution ID: **1** Type: **Oral**

Theory of field emission through dielectric pores in the metal surface layer

The influence of pores filled with a dielectric, in particular hydrogen, on the current of field electron emission from the structural materials of accelerator structures was studied. A review of the literature shows that pores can form in the near-surface layer in which dielectric, in particular hydrogen, can accumulate. Therefore, the study of the influence of dielectric inclusions in the metal surface layer is important and needs to be studied. The theoretical model of the potential barrier for the metal-dielectric-metal-vacuum system was constructed. An analytical expression for the electron tunneling coefficient from the metal was found. It is shown that the current has a resonant character and in the resonant region can be amplified up to 4 times compared to the current from the region without such pores. It is also worth noting that in the case when the pore thickness is d>0.2 nm, a decrease in the field electron emission current will be observed regardless of their depth. At the same time, the resonance region increases with the increase of the affinity energy.

Primary author: LEBEDYNSKYI, Serhii (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Co-authors: KHOLODOV, Roman (Institute of Applied Physics, National Academy of Sciences of Ukraine); LEBEDYNSKA, Yuliia (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Presenter: LEBEDYNSKYI, Serhii (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Contribution ID: **2** Type: **Oral**

Exploring high gradient limit with cryogenic experiments at FREIA laboratory

Tuesday, 5 March 2024 14:30 (30 minutes)

A cryogenic, HV conditioning system integrated in a stand-alone cryocooler is operated at FREIA laboratory in Uppsala in order to investigate the fundamental mechanisms of field emission and breakdown nucleation. A series of high-field measurements has been carried out with pairs of metal electrodes (copper, niobium and titanium) at temperatures ranging from ambient down to 4K.
The cryogenic capability of the system give unique opportunity to observe variations of the behavior of the electrodes conditioned and tested in cold vs warm state. We previously reported on the notable increase of the field holding capability of the cooled electrodes that rises with decreasing temperatures.
In the recent experiments, we investigated further the state of the surface during conditioning by detailed field emission experiments and analysis of the accompanied residual gas outflow. We have also designed and are currently implementing additional diagnostics of the conditioning process. After the conditioning, the morphology of the surface has been studied as well, looking for differences on the surface between cold and warm conditioning samples. Different surface modifications were found on cathode conditioned at cold, with many atypical BD spots of a star-like shape. The number of atypical spots increased significantly with decreased temperatures.
In the presentation, we will report on these and other experimental results from Uppsala, and provide our interpretation. The data should help to refine theoretical models and potentially discriminate between various underlying physical mechanisms, thus eventually improving our understanding of BD phenomena.

Primary authors: JACEWICZ, Marek (Uppsala University (SE)); COMAN, Mircea (Uppsala University)

Presenter: JACEWICZ, Marek (Uppsala University (SE))

Session Classification: Field Emission

Track Classification: Experiments and Diagnostics

Contribution ID: **3** Type: **Oral**

Fireball-Triggered Vacuum Breakdown in Particle Accelerators

Wednesday, 6 March 2024 16:00 (30 minutes)

There are various hypotheses for vacuum-breakdown trigger mechanisms in normal-conducting accelerating structures. It has been experimentally turned out that the dominant trigger of RF breakdowns in normal-conducting UHF continuous-wave cavities is a hot micro-particle with a high sublimation point [Phys. Rev. Accel. Beams 21, 122002 (2018)], later named a "fireball" by this presenter. On the other hand, SuperKEKB accelerator at KEK, Japan, is suffering from a serious obstacle of sudden beam losses in the collider rings, that limits the luminosity improvement. Recently, this presenter has proposed a hypothesis that the same mechanism as in the fireball breakdown can be a trigger of the sudden beam losses at SuperKEKB. In this presentation, the presenter will explain the fireball hypothesis and its experimental demonstration, leading to better understanding of the fireball breakdown mechanism.

Primary author: Dr ABE, Tetsuo

Presenter: Dr ABE, Tetsuo

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **4** Type: **Oral**

Analysis of the micro-scale dynamics of X-Ray emission profiles collected with a GEM detector in needle-plane experiments at HVPTF

Wednesday, 6 March 2024 08:00 (30 minutes)

The High Voltage Padova Test Facility (HVPTF) is an experiment set in Padova, Italy, operating in the framework of the Neutral Beam Test Facility project of the ITER tokamak. The purpose of HVPTF is to study the phenomenology of discharge events occurring between electrodes at high voltage differences over long vacuum gaps, which is crucial in the development of the Neutral Beam Injector (NBI) foreseen for ITER. The facility hosts a cylindrical vacuum vessel with stable pressure control, where two electrodes of different possible geometries can be mounted. Two independent power supplies allow for a total voltage difference up to 800 kVDC, with adjustable gap widths up to 250 mm. A monitoring system records current and voltage of the two power supplies, together with pressure and composition of the gas extracted from the chamber, all sampled at a rate of 100 Hz. Additional sets of diagnostics are installed to observe the dynamics of the emissions during the discharges, both in the visible/IR/UV (by fast cameras at different angles) and in the X-rays spectra (by scintillators and Gas Electron Multiplier(GEM)-based detectors).
During the last year, several experimental campaigns have taken place, with different electrodes configurations. This paper presents a study of the stainless-steel needle-plane configuration. The analysis is based on the data collected by the GEM detector, together with the information on current and voltage of the two power supplies. The observed events are characterized in terms of both temporal and spatial evolution, providing sequential emission profiles with millimetric resolution on timescales of the order of hundreds of nanoseconds. Additionally, preliminary electron transport simulations performed with a custom-developed software are presented, in support of a tentative explanation of the observed phenomena.

Primary author: CARUGGI, Federico (Universita & INFN, Milano-Bicocca (IT))

Co-authors: Mr CELORA, Agostino (Università di Milano-Bicocca, Dipartimento di Fisica "G. Occhialini"); Dr CORDARO, Luigi; Dr DE LORENZI, Antonio (Consorzio RFX); Dr GROSSO, Giovanni (Istituto per la Scienza e Tecnologia dei Plasmi, CNR); Mr GUIOTTO, Federico (Dipartimento di Fisica, Università di Padova); LOTTO, Luca (Consorzio RFX); PILAN, Nicola; SPAGNOLO, Silvia (Consorzio RFX); TARDOCCHI, Marco; CROCI, Gabriele (Universita & INFN, Milano-Bicocca (IT)); MURARO, Andrea (CNR-ISTP)

Presenter: CARUGGI, Federico (Universita & INFN, Milano-Bicocca (IT))

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **5** Type: **Oral**

High Gradient C-band Cryogenic Copper Silver Structures

Tuesday, 5 March 2024 13:30 (30 minutes)

C-band accelerators have been of particular interest in recent years due to their ability to provide high gradients and transport high charge beams for applications such as colliders and medical technologies. These technologies are made possible by new advancements in high gradient technologies that can suppress the breakdown rate in a particular structure by using distributed coupling, cryogenic cooling, and copper alloys. Previous work has shown each of these separately to significantly improve the maximum achievable gradient. In this work, for the first time, we will combine all three methods in an ultra-high gradient structure and benchmark the difference between copper (Cu) and copper silver (CuAg). The exact same structures were previously tested at room temperature and showed gradients in excess of 200 MeV/m and a 20% improvement in the copper silver version over its pure copper counterpart [M Schneider et al Appl. Phys. Lett. 121, 254101 (2022)] . In this test, these structures are tested at 77K simultaneously through a hybrid manifold. They were found to perform similarly due to the presence of significant beam loading caused by a suppression in the quality factor as a function of time. Taking beam loading into account, we still were able to observe a maximum achievable gradient of 200 MeV/m achieved for a 1 µs pulse at an input power of 5 MW into each cavity with a breakdown rate of 10ˆ-1 breakdown/pulse/m .

Primary author: SCHNEIDER, Mitchell (SLAC National Accelerator Laboratory)

Co-authors: Mr DIEGO, Amirari (Radiabeam); Dr KRASNYKH, Anatoly (SLAC National Accelerator Laboratory); Dr DHAR, Ankur (SLAC); NANNI, Emilio (SLAC National Accelerator Laboratory); Dr BERRY, Robert (Radiabeam); Dr AGUSTSSON, Ronald (Radiabeam)

Presenter: SCHNEIDER, Mitchell (SLAC National Accelerator Laboratory)

Session Classification: Field Emission

Track Classification: Field Emission

Contribution ID: **6** Type: **Oral**

Field emission assisted heating of Cs2Te photocathode: Implication toward RF breakdown

Wednesday, 6 March 2024 10:30 (30 minutes)

The occurrence of breakdown events are a primary limiting factor for future accelerator applications aiming to operate under high field-gradient environments. Experimental evidence often leads to a hypothesis that breakdown events are associated with temperature and dark current spikes on the surface of RF devices. In the past decade, there has been increased interest in unveiling the mechanism behind breakdown in metal copper and copper alloys; however, there has been a limited effort regarding breakdown phenomenon in photocathode relevant semiconductors.

In this work, we explore field emission assisted localized heating via Nottingham and Joule processes. Field emission from intrinsic cesium telluride ultra thin film coated on top of a copper substrate was modeled within Stratton–Baskin–Lvov–Fursey formalism, describing the processes and effects in the bulk and at the surface of a semiconductor exposed to a high applied electric field. These heating effects were incorporated into the surface diffusion model, where the surface gradient of the chemical potential defines the time evolution and resulting reorganization of the surface.

Primary authors: Dr PEREZ, Danny; SHINOHARA, Ryo; Dr BARYSHEV, Sergey; Dr BAGCHI, Soumendu (Los Alamos National Laboratory)

Presenter: SHINOHARA, Ryo

Session Classification: Field Emission

Track Classification: Field Emission

Contribution ID: **7** Type: **Poster**

Observation of fireball-triggered RF breakdowns in a 509-MHz normal-conducting cavity and its initial simulation study

Monday, 4 March 2024 16:35 (20 minutes)

At KEK, fireball-triggered RF breakdowns [1] have been observed in 509-MHz normal-conducting accelerating cavities. It has been found that the breakdown was caused by a high-temperature microparticle that we call "fireball"now. Recently, the fireball-triggered breakdown attracts interests again in relation to the SuperKEKB accelerator that is suffering from sudden beam losses. A hypothesis is proposed that similar phenomena with the fireball breakdown could cause the sudden beam losses [2]. Because of such growing interests, we have started experimental study of the fireball-triggered breakdown in the accelerating cavity, again. In this study, we are trying to observe more detailed characteristics of the fireball-triggered breakdown, such as the emitted total current at the moment of breakdown. Furthermore, using the Particle-in-Cell simulation of CST Studio Suite, we are trying to reproduce the breakdown phenomena observed in the experiment. The results will be useful for better understanding the mechanism of the sudden beam loss in SuperKEKB. In this workshop, we report the initial experimental and simulation results.

[1] T. Abe, et al., Phys. Rev. Accel. Beams 21, 122002 (2018).
[2] T. Abe, this workshop.

Primary author: YAMAGUCHI, Takaaki (KEK)

Co-authors: Dr ABE, Tetsuo; Dr KOBAYASHI, Tetsuya

Presenter: YAMAGUCHI, Takaaki (KEK)

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **8**		Type: **Oral**

Effect of desorbed gases in the onset of HVDC breakdown between stainless steel electrodes insulated by high vacuum

Monday, 4 March 2024 14:45 (30 minutes)

The present contribute describes and analyzes recent experimental results obtained at the High Voltage Padova Test Facility (HVPTF), the laboratory aimed at supporting the development of the prototype for the ITER NBI.
Evidences that bursts of electrons hitting the anode surface are the precursors of breakdown in a in a significative fraction of vacuum discharges were observed using a fast acquisition system composed of a single pixel x-ray detector triggered by a high-speed camera.
A simple model explaining the development of the vacuum arc starting from a gas bubble desorbed on the anode surface is proposed and validated on experimental results

Primary author: PILAN, Nicola

Co-authors: MURARO, Andrea (CNR); Dr DE LORENZI, Antonio (Consorzio RFX , Padova, Italy); Dr SPADA, Emanuele (Consorzio RFX , Padova, Italy); Mr CARUGGI, Federico (Università di Milano-Bicocca, Dipartimento di Fisica "G. Occhialini"); GUIOTTO, Federico (Dipartimento di Fisica, Università di Padova); Dr PINO, Felix (Dipartimento di Fisica, University of Padova, Italy); CROCI, Gabriele (Universita & INFN, Milano-Bicocca (IT)); Dr SERIANNI, Gianluigi (Consorzio RFX); Dr MARIO, Isabella (Consorzio RFX,Padova, Italy); Mr FRANCHIN, Luca (Consorzio RFX , Padova, Italy); LOTTO, Luca (Consorzio RFX); Dr CORDARO, Luigi; Mr FINCATO, Michele (CNR-ISTP, Padova, Italy); MARCONATO, Nicolò; Dr DEAMBROSIS, Silvia (CNR-ICMATE, Padova, Italy); SPAGNOLO, Silvia (Consorzio RFX); PATTON, Tommaso; Dr CHITARIN, giuseppe (University of Padova and Consorzio RFX); Dr AGOSTINI, matteo

Presenter: PILAN, Nicola

Session Classification: Applications

Track Classification: Applications

Contribution ID: **9** Type: **Oral**

The influence of arcing on radio-frequency capacitively coupled plasma

Tuesday, 5 March 2024 10:30 (30 minutes)

While arcing formation mechanism has been widely studied, the influence of arcing on background plasma has remained underexplored. In this study, we investigated the effect of arcing on capacitively coupled plasma by employing arcing induced probe (AIP), which plays a role in localizing arcing on probe tip edge. We analyzed behavior of capacitively coupled plasma by analyzing various diagnostics: the voltage of a floating probe, which can represent plasma potential, voltage and current of discharge electrode, and time variation of electron density of plasma using the Fourier cutoff probe method. We found different behavior of discharge impedance component, that is an increase in the resistance and a decrease in the reactance with arcing formation. It suggests that electrons, which are emitted from arcing spot, can disrupt the sheath on the discharge electrode by flowing toward the discharge electrode. Time variation analysis on electron density and sheath thickness supports the sheath disruption induced by arcing. This research offers valuable understanding on the interaction between arcing and background plasma.

Primary author: CHO, chul hee (Chungnam national university)

Co-authors: Dr KIM, Sijun (Chungnam national university); Dr LEE, Youngseok (Chungnam national university); Mr SEONG, Inho (Chungnam national university); Mr JEONG, Wonnyoung (Chungnam national university); Mr CHOI, Minsu (Chungnam national university); Mr CHOI, Byeong yeop (Chungnam national university); Mr SEO, Seong hyun (Chungnam national university); Dr SEOL, Youbin (Chungnam national university); Mr LEE, Woo been (Chungnam national university); Prof. YOU, Shinjae (Chungnam national university)

Presenter: CHO, chul hee (Chungnam national university)

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **10** Type: **Oral**

Simulation approach to investigate the influence of electromagnetic power in vacuum breakdown

Wednesday, 6 March 2024 16:30 (30 minutes)

Vacuum arcs, also known as breakdowns (VBD), are a major limiting factor for various applications such as particle accelerators, fusion reactors, vacuum interrupters, X-ray sources, and space applications. However, the physical mechanisms underlying the very initiation of the phenomenon still remain unclear. Recent experimental evidence indicates that the distribution of electromagnetic power might be the main limiting factor of the arc initiation, instead of applied electric field and the cathode material as previously assumed. This work aims to understand the physics underlying the power supply limitation on the VBD initiation by developing computational models that predict its behavior, leading to reduced VBD occurrence or to higher operating fields in future applications.
The multi-physics code FEMOCS, used for VBD initiation modeling, now accounts for impedance based descriptions of external systems. Thus, connecting the full system's circuit to local plasma initiation physics. This allows to directly investigate the effects of different circuit responses on the VBD initiation process. Comparison between different impedance functions are made. The effects of power flow during plasma initiation is investigated and preliminary conclusions outlined. Furthermore, the framework for direct comparison with experimental results is introduced.

Primary author: TIIRATS, Tauno (University of Tartu)

Co-authors: KYRITSAKIS, Andreas; KOITERMAA, Roni (University of Helsinki); Prof. ZADIN, Veronika (University of Tartu (EE))

Presenter: TIIRATS, Tauno (University of Tartu)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **11** Type: **Oral**

Searching for Rare Events in the Field Emitted Current of High-Field RF Cavities

Monday, 4 March 2024 14:15 (30 minutes)

It has been proposed that breakdown nucleation in high vacuum high field systems results from a critical transition linked to plastic activity in the surface of the metal exposed to the field [1]. It is also known that field emission is associated with, and generally considered to be a necessary precursor to, breakdown. Recently, a theoretical link was offered between the intensity and frequency of fluctuations in the pre-breakdown field emitted current and the ensuing breakdown nucleation event, and this link was investigated experimentally [2]. In fact, such a link is proposed to exist independent of the exact mechanism of breakdown, and the details of the fluctuations can serve to constrain models of the generative processes.

In this work, the field emitted current in high-field RF cavities has been monitored on a pulse-to-pulse basis leading up to the breakdown in an attempt to discern whether an observable evolution in the signal characteristics is present and whether a link between phenomena may be extracted. The challenges associated with this work are discussed, and the preliminary results are discussed.

[1] - "Theory of electric field breakdown nucleation due to mobile dislocations" Phys. Rev AB, 22 (2019) 083501
[2] - "Dark current spikes as an indicator of mobile dislocation dynamics under intense dc electric fields" Phys. Rev AB, 23 (2020) 123501

Primary authors: Mr MILLAR, Lee (CERN); BORONAT, Marçà (IFIC - CSIC); ASHKENAZY, Yinon (The Hebrew University of Jerusalem (IL))

Presenter: Mr MILLAR, Lee (CERN)

Session Classification: Applications

Track Classification: Field Emission

Contribution ID: **12** Type: **Oral**

Field Dependence of Conditioning Part 1: Electrode Simulation and Design

Wednesday, 6 March 2024 13:00 (30 minutes)

A model has been developed at CERN to simulate the procession of conditioning in high-field systems [1]. Any arbitrary geometry may be meshed and simulated in spatially resolved fashion, and the effects associated with a variation in the surface electric field, and different algorithmic approaches to conditioning, have been investigated. To test and validate these hypotheses, the model was employed to design two chamfered electrodes, which were later tested in CERN's Large Electrode System (LES). This talk will discuss the predictions made, and the design of the electrodes used to test them.

[1] - "Monte Carlo Model of High-Voltage Conditioning and Operation" . In Proceedings of the LINAC'22, Liverpool, UK, DOI: 10.18429/JACoW-LINAC2022-MOPORI24

Primary author: Mr MILLAR, Lee (CERN)

Presenter: Mr MILLAR, Lee (CERN)

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **13** Type: **Oral**

Field emission current evolution during conditioning at cryogenic temperatures

Tuesday, 5 March 2024 15:00 (30 minutes)

In order to investigate the mechanisms behind vacuum arc formation, it is beneficial to use as many diagnostic tools as possible at a wide temperature range for different metals. The cryogenic HV pulsing system in FREIA laboratory is experimentally following this line of research. We study vacuum arc breakdowns and surface conditioning using high-repetition rate DC pulses at a wide range of temperatures, from room temperature, down to 4K. In our experiments, we have tested different materials commonly found in the accelerator technology like copper, niobium and titanium.

It has been previously shown that vacuum breakdowns are initiated by field emission (FE). In order to better understand the mechanisms behind vacuum arc breakdowns and the conditioning process, we are measuring FE currents at different temperatures during the conditioning process. The behavior of the FE current in function of the field at cryogenic temperatures give very clean data that follow almost perfectly theoretical Fowler-Nordheim theory despite large emission area (high field area of >1200 mmˆ2). The extracted Fowler-Nordheim parameters can therefore very accurately describe the current state of the surface and allows us to follow the changes due to conditioning process.

We have observed and quantify for instance the decrease of the field enhancement factor as well as the change in the emitted area during conditioning. We have also observed that the field emission current can decrease during long field emission measurements or when the system is slightly heated up. A rest gas analyzer (RGA) was added to the system to look for changes in the partial pressures of trace gases that correlate to these variations in current.

We will present the results of the conditioning process, together with the field emission and RGA measurements for different materials. We hope that the results shown in this talk will be useful for improving our current understanding of vacuum arcs.

Primary authors: PROFATILOVA, Iaroslava; JACEWICZ, Marek (Uppsala University (SE)); COMAN, Mircea (Uppsala University)

Presenter: COMAN, Mircea (Uppsala University)

Session Classification: Field Emission

Track Classification: Field Emission

Contribution ID: **14** Type: **Oral**

Field Dependence of Conditioning-Experimental Measurements

Wednesday, 6 March 2024 13:30 (30 minutes)

Two chamfered electrodes were tested in the Large Electrode System (LES) at CERN. Having a flat-shaped cathode and a frustum shaped anode gives a higher electric field in the centre of the electrodes, while it linearly decays towards the edge.
Normal breakdown rates are observed in the centre of the electrodes. However, lower breakdown rates with regards to the electric field was found for the rest of the surface. A higher density of breakdowns occurred in the cerntral, high field region. This area effectively controlled the conditioning algorithm, leading to a lower density of breakdowns for equivalent fields.This corresponds well with Monte Carlo simulations.

Primary authors: Mr MILLAR, Lee (CERN); BJELLAND, Victoria Madeleine; WUENSCH, Walter (CERN)

Presenter: BJELLAND, Victoria Madeleine

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **15** Type: **Oral**

Aspect of High Field Testing

The Large Electrode System (LES) is a high voltage pulsed DC test stand to investigate breakdowns. Many materials have undergone testing by conditioning, as well as field emission measurements and light spectroscopy investigation.

Primary authors: BJELLAND, Victoria Madeleine; WUENSCH, Walter (CERN)

Presenter: BJELLAND, Victoria Madeleine

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **16** Type: **Oral**

X-ray Micro-Discharges Fine Dynamics in a Vacuum High Voltage Experiment

Wednesday, 6 March 2024 08:30 (30 minutes)

The High Voltage Padova Test Facility (HVPTF) is an experimental device for investigating High Voltage Direct Current insulation in vacuum, in support of the realization of MITICA, the prototype of a neutral beam injector for ITER. Inside a high vacuum chamber, two stainless steel electrodes, separated by a few centimeters gap, can achieve a voltage difference up to 800 kV. During the conditioning process of the electrodes, current micro-discharges (MD) and associated X-rays are observed, along with a global increase of gas emission (in particular, H2 and CO2 have been detected by the Residual Gas Analyser). During the last five years, different X-rays detectors have been installed on HVPTF, with the aim to investigate the physical processes behind the conditioning.
In this contribution, the fine dynamics of the micro-discharge phenomenon is studied with the purpose to sketch a possible physical interpretation of MD mechanism: data suggest that after a first burst of electrons, some gas is emitted by the anode and ionized. Then, the generated ions, hitting the vacuum chamber and the electrode supports, produce secondary electrons, partly collected by the anode. This could be the reason of the measured asymmetry between MD current values at positive and negative electrodes. Experimental observations and theoretical evaluations supporting the hypothesis of gas emission from the anode are presented.
A first study about the statistical behavior of micro-discharge phenomenon is introduced. In particular, the distribution of the time intervals between successive MD suggests the occurrence of almost two different trigger mechanisms, evolving during the electrode conditioning.

Primary author: SPAGNOLO, Silvia (Consorzio RFX)

Co-authors: Dr CORDARO, Luigi; PILAN, Nicola; Dr DE LORENZI, Antonio (Consorzio RFX); Dr FONTANA, Cristiano (European Commission, Joint Research Centre (JRC), Geel, Belgium); PATTON, Tommaso; PINO, Felix (Dipartimento di Fisica, University of Padova, Italy); LOTTO, Luca (Consorzio RFX); Prof. MARTINES, Emilio (Università di Milano-Bicocca, Dipartimento di Fisica 'G. Occhialini', Piazza della Scienza 3, Milano, Italy); SPADA, Emanuele (Consorzio RFX); ZUIN, matteo

Presenter: SPAGNOLO, Silvia (Consorzio RFX)

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **17** Type: **Oral**

Study of different materials exposed to low energy H- irradiation and its effects on high voltage breakdown resistance

Wednesday, 6 March 2024 09:30 (30 minutes)

During the operation of LINAC4, up to 25% of the source beam current is routinely lost in the Radio Frequency Quadrupole (RFQ) at an energy between 0.045 and 3 MeV. These losses can cause surface modifications which in turn may lead, in areas of high electric field, to an increased vacuum breakdown rate. An experimental study has been made to identify materials with high electric field capability and robustness to low-energy irradiation. Seven materials have been tested using high pulsing voltage after and before being exposed to H- low voltage irradiation. Surface analysis was preformed after each test using advanced microscopic techniques such as Scanning Electron Microscope, Electron Back Scattered Diffraction, Energy-dispersive X-ray Spectroscopy and conventional optical microscopy. Carbon contamination in some of these materials is also explored with the aim of understanding the existence of a correlation between the presence of Carbon on the materials surface and the breakdown testing.

Primary author: SERAFIM, Catarina (CERN)

Co-authors: LOMBARDI, Alessandra (CERN); GRUDIEV, Alexej (CERN); PEREZ FONTENLA, Ana Teresa (CERN); SARGSYAN, Edgar (CERN); DJURABEKOVA, Flyura (University of Helsinki); CALATRONI, Sergio (CERN); Dr SGOBBA, Stefano (CERN); BJELLAND, Victoria Madeleine; WUENSCH, Walter (CERN)

Presenter: SERAFIM, Catarina (CERN)

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **18** Type: **Poster**

Relativistic 1D PIC-MCC modeling and simulation of impedance collapse in high-voltage diodes

Monday, 4 March 2024 16:15 (20 minutes)

A relativistic one-dimensional particle-in-cell (PIC) Monte Carlo Collision (MCC) model is developed to study velvet cathode plasma formation and expansion in high-voltage diodes. Velvet cathodes are used in high-power vacuum diodes for pulsed power systems such as magnetically insulated line oscillators (MILOs) for generating high-power microwaves (HPMs) and magnetically insulated transmission lines (MITLs) used in Z-pinch. A self-consistent plasma simulation model is required to understand the power scaling of these devices as they operate at higher applied voltages up to megavolts (MVs)[1]. The 1D PIC-MCC simulation model considers physical processes such as Fowler-Nordheim field emission (FNFE) with field enhancement, electron-neutral/ion-neutral collisions, and electron-electron/ion-electron Coulomb collisions. Simulation results predict gap closure rates consistent with experiments. Studies conducted on the effect of critical parameters, such as outgassed neutral layer (type of gas, density), pulse waveform, and field-enhancement factor, will be presented.

[1] Dale R. Welch, David V. Rose, Nichelle Bruner, Robert E. Clark, Bryan V. Oliver, Kelly D. Hahn, and Mark D. Johnston. Hybrid simulation of electrode plasmas in highpower diodes. Physics of plasmas, 16(12):123102–123102, Dec 2009.

Primary author: SHARMA, Vedanth (Stanford University)

Co-authors: Mr CASTILLO, Andres Marcelo (Stanford University); Dr YAMASHITA, Yusuke (Stanford University); Dr HARA, Kentaro (Stanford University)

Presenter: SHARMA, Vedanth (Stanford University)

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **19** Type: **Oral**

Modified Theory and Fluid Modeling for DC Breakdown

Tuesday, 5 March 2024 09:30 (30 minutes)

Breakdown in DC gas discharges is primarily described by Paschen's law. While Paschen's law accounts for the flux balance correctly, the relation between the reduced electric field and the ionization coefficient is given empirically. In this study, we investigate DC breakdown using a full-fluid moment (FFM) model, which is benchmarked against a particle-in-cell/Monte-Carlo collision (PIC-MCC) model and a conventional drift-diffusion (DD) model. In the FFM model, the electron energy equation is solved consistently and inertial effects are accounted for. The results for argon show excellent agreement between FFM and PIC-MCC, including in the left branch (Pd<1 Pa m, where P is the gas pressure and d is the gap distance), where discrepancies with results obtained using a conventional DD model are observed. A double-valued breakdown curve is found using all models in the low Pd range, i.e., the left branch of the Paschen curve. Breakdown theory is revisited using a fluid formulation to derive modified breakdown conditions. The modified theory predicts a multivalued left branch, which is not predicted by the conventional Paschen's law, and shows good agreement with computational results. Finally, the energy budget obtained from the fluid model is presented, showing a change from volumetric energy losses due to collisions at low reduced electric field to convective energy losses at smaller Pd where reduced electric field increases.

Primary author: MANSOUR, Adnan (Stanford University)

Co-authors: VIALETTO, Luca (Stanford University); YAMASHITA, Yusuke (Stanford University); HARA, Kentaro (Stanford University)

Presenter: MANSOUR, Adnan (Stanford University)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **20** Type: **Oral**

High gradient RF challenges in the muon collider

Monday, 4 March 2024 13:45 (30 minutes)

High gradient RF challenges in the muon collider will be presented and discussed.

Primary author: GRUDIEV, Alexej (CERN)

Presenter: GRUDIEV, Alexej (CERN)

Session Classification: Applications

Track Classification: Applications

Contribution ID: **21** Type: **Poster**

PIC Simulations of the Anode Sheath in Low-Pressure DC Discharges

Monday, 4 March 2024 15:55 (20 minutes)

The behavior of plasma in the anode region of a DC discharge is complex due to its dependence on the geometry of the anode, gas type and pressure, and discharge current. Understanding this behavior is an ongoing effort due to its importance in developing a general theory for gas discharges and designs for charged particle sources. The anode plasma sheath displays interesting phenomena such as self-organization into complicated stationary or moving patterns and sign reversal of the potential drop across the sheath. This poster will describe recent efforts to better understand the physical mechanisms and characteristic length scales that govern the change in electric potential and its influence on plasma properties within the sheath in the electron-diffusion-dominated regime. A high-fidelity modeling approach using Sandia's massively parallel plasma code, Aleph, is used to simulate the positive column and anode region plasma. Simulation results will be compared to recent theoretical work that has identified a similarity criterion that characterizes the transition between two unique modes of transport: the free-flight mode, where electrons are highly kinetic and the potential always decreases, and the drift-diffusion mode, where the potential can increase or decrease depending on the relative strength of diffusive forces [1].

References

[1] V. Martens, Elsevier 218, 112675 (2023).

This work used the capabilities of the SNL Plasma Research Facility, supported by DOE SC FES. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Primary author: GORMAN, Grant (Sandia National Laboratories)

Co-authors: HOPKINS, Matthew (Sandia National Laboratories); Prof. KOLOBOV, Vladimir (The University of Alabama at Huntsville)

Presenter: GORMAN, Grant (Sandia National Laboratories)

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **22** Type: **Poster**

Arc Generation Under High Vacuum Conditions

Large area diodes under high vacuum (1e-6 Torr) can exhibit similar characteristics to pressurized arcs via several mechanisms such as stimulated emission of ions, thermal ion emission, and bipolar ion flow. Generally these diodes are under high electric field stresses (above 200kV/cm) where field emission of electrons from the cathode are expected. The ions in each mechanism above are liberated from the anode by the intense electron beam. This work demonstrates a diode in which an intense electron beam is shown to liberate secondary (stimulated or knock-on) ions from adsorbed contaminants (e.g. water, oil, etc.) that causes the electron beam to pinch. The pinch then leads to anode spot-heating, which yields thermal ion emission. This is a positive feedback problem that is eventually limited by bipolar flow. In this work, bipolar flow is undesirable as this is typically accompanied by damage to the anode, but was nonetheless observed in experiment. Electromagnetic particle-in-cell simulations performed in EMPIRE yield insight into these ion generation processes, and ultimately into experimental results.

Primary author: POWELL, Troy

Presenter: POWELL, Troy

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **23** Type: **Poster**

Morphology Changes due to Ohmic Heating of Surfaces

Monday, 4 March 2024 15:35 (20 minutes)

In this work we present our efforts to simulate the effect of Ohmic heating due to field emission on the morphology (shape) of a surface region. A popular model of field emission leading to material supply and eventual vacuum arc breakdown relies on the existence of protrusions with high electric field enhancement factors (β). β can sometimes be initialized to values as high as 100. However, finding such protrusions on surfaces has been quite difficult. While they have been found in a very few number of places (e.g., tin whiskers), their lack of presence in a general way leads to a criticism of these popular models because their basic assumption appears to not be met. This work endeavors to track the evolution of a moderately flat surface region exposed to high electric fields, and thus high temperatures, ideally transforming into a protrusion. The simulation methodology employed here is a parallel coupled finite element method, including a level set representation of the surface and adaptive mesh refinement, in the Sandia code Aria. Aria's model will couple current density, temperature, mass transport, surface tension, and electric fields. It can track phase change, resulting in a transition from solid bulk material to liquid to vapor or microdroplets (via level set representation).
SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Primary authors: MOORE, Chris; HOPKINS, Matthew

Presenter: HOPKINS, Matthew

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **24** Type: **Poster**

A 500 kV SF6 insulated feedthrough for inverted insulator photoguns

Tuesday, 5 March 2024 11:30 (30 minutes)

Nuclear physics experiments at Jefferson Lab (JLab) require spin-polarized electron beams generated from delicate semiconductor photocathodes in a photoemission electron gun (photogun). The JLab photogun operates at 130 kV using an inverted geometry alumina insulator (feedthrough) as a holding structure to the highly polished stainless steel cathode electrode inside an ultra-high vacuum chamber. The alumina feedthrough is conical in shape for connecting the photogun to the power supply using commercial high voltage cable connectors. The use of compact inverted feedthroughs in high voltage dc photoguns was implemented by Jefferson Lab in 2010 and it is now a well-established technology in all high voltage photoguns which have since been built. Although the state of the art photoguns with inverted feedthroughs are capable of operating at 200-300 kV, proposed polarized high intensity electron beams as a driver in the production of polarized positrons, requires photoguns operating at higher voltage to generate the electron beam at ten times the intensity in the present JLab photogun. This will require emission from larger areas in the photocathode to spread out ion damage for sustaining photocathode lifetime. The present feedthroughs are limited to ˜ 300 kV, but higher voltage is required to condition the electrodes for field emission free operation at the desired voltage. This contribution describes the development of an unprecedented feedthrough tested to 500 kV. The alumina feedthrough was connected to a high voltage power supply using a commercial cable connector via a modified epoxy receptacle with intervening SF6 layer and a test electrode in a vacuum vessel.

Primary author: PALACIOS SERRANO, Gabriel (Thomas Jefferson National Accelerator Facility)

Co-authors: Dr HERNÁNDEZ GARCÍA, Carlos (Thomas Jefferson National Accelerator Facility); Dr POELKER, Matthew (Thomas Jefferson National Accelerator Facility)

Presenter: PALACIOS SERRANO, Gabriel (Thomas Jefferson National Accelerator Facility)

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **25** Type: **Oral**

Gas conditioning of DC high voltage photoguns using krypton

Monday, 4 March 2024 16:35 (20 minutes)

Obtaining field-emission-free operation of a DC high voltage photo-electron gun (photogun) can be challenging, particularly at bias voltages > 200 kV. Polarized electron beams employ delicate GaAs-based photocathodes. Any level of field emission from the photogun cathode electrode can degrade the vacuum inside the photogun leading to a rapid decrease in photocathode quantum efficiency. High voltage gas conditioning using noble gasses has become a common technique to successfully eliminate field emission and thereby prolong the operating lifetime of the photocathode. In the presence of field emission, the gas introduced into the photogun vacuum chamber becomes ionized. The ions are then accelerated towards the negatively biased cathode electrode, sputtering away the field emitter and becoming implanted which serves to increase the work function. Noble gasses are used because they are not pumped by the non-evaporable getter pumps inside the photogun: after the flow of noble gas has been halted, the photogun vacuum quickly recovers. Initial attempts to 'gas condition'electrodes employed helium. This contribution describes Jefferson Lab's experience with krypton gas conditioning of high-voltage dc photoguns and its effect on voltage-induced gas desorption. In addition, the technical challenge of needing voltage headroom to eliminate field emission will be discussed. For example, successful field emission free operation of the DC high voltage photogun operating at 200 kV might require gas conditioning at voltage up to 300 kV and this can lead to insulator electrostatic failure.

Primary author: HERNANDEZ-GARCIA, Carlos

Co-authors: PALACIOS SERRANO, Gabriel (Thomas Jefferson National Accelerator Facility); MAMUN, MD ABDULLAH (Jefferson Lab); POELKER, Matt

Presenter: HERNANDEZ-GARCIA, Carlos

Session Classification: Poster Session

Track Classification: Experiments and Diagnostics

Contribution ID: **26** Type: **Oral**

General Thermal-Field Emission and Space-Charge Limits for Particle-In-Cell and Nexus Theory

Wednesday, 6 March 2024 11:30 (30 minutes)

Jensen's model[1] for General Thermal-Field (GTF) emission enables increased precision for injecting electrons self-consistently into physics simulations where electron emission is important, such as vacuum arcs, transmission lines in pulsed power systems, or vacuum diodes. Due to increased computational expense, however, it is important to understand when simpler models may be reasonably used. Of perhaps greatest potential impact: when can simple, effective, space-charge limited (SCL) models be used? By applying the incredibly simple theoretical technique of nexus theory[2] (only slightly more sophisticated than scaling arguments), one can find parameters "in the ballpark"where GTF or SCL are appropriate. To test nexus theory of the GTF-SCL transition, simple Particle-In-Cell simulations in EMPIRE-PIC[3] will be presented. Details of the GTF and SCL implementations in EMPIRE will be briefly discussed, especially as they pertain to serious local instabilities in GTF which, nevertheless, result in nearly-correct aggregate behavior.

[1] K. L. Jensen, "A reformulated general thermal-field emission equation,"J. Appl. Phys. 126, 065302 (2019).
[2] A. M. Darr, C. R. Darr, and A. L. Garner, "Theoretical assessment of transitions among thermionic, field, and space-charge-limited emission,"Phys. Rev. Research 1, 033137 (2020).
[3] M. T. Bettencourt et al., "EMPIRE-PIC: A performance portable unstructured Particle-in-Cell code,"Communications in Computational Physics 30, SAND-2021-2806J (2021).

Acknowledgements:
This work was supported by the Assured Survivability and Agility with Pulsed Power (ASAP) Mission Campaign sponsored Maxwell Fellowship awarded to Adam M. Darr under the Laboratory Directed Research and Development program at Sandia National Laboratories.
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Primary authors: DARR, Adam; POWELL, Troy

Presenter: DARR, Adam

Session Classification: Field Emission

Track Classification: Field Emission

Contribution ID: **27** Type: **Poster**

On effect of surface carbon diffusion on growth of field emitting tips under high electric fields

Monday, 4 March 2024 15:55 (20 minutes)

In the presence of strong electric fields, a plasma-induced arc of intense current is capable of establishing a connection between two metal surfaces, even within the confines of ultra-high vacuum conditions. According to the hypothesis, the presence of tall and sharp nanotips on a surface exposed to strong electric fields undergoes heating via field emission currents, ultimately resulting in melting and the evaporation of neutral atoms contributing to plasma buildup. However, the mechanism governing the growth of nanotips with a significantly high aspect ratio remains unclear. Previous experimental research has demonstrated that the application of a thin carbon film on a metallic surface enhances the rate of vacuum arc events.

This study employs the Nudged Elastic Band method to systematically investigate the migration barrier of various carbon structures onto diamond, amorphous carbon, graphite and graphene surfaces. The primary objective is to estimate the probability of carbon surface diffusion, specifically considering the influence of an electric field gradient. The investigation aims to discern whether carbon surface diffusion, biased by the presence of such a gradient, can facilitate the transport of atoms, ultimately leading to the formation of nanotips.

Keywords:

Nudged Elastic Band, Migration Barriers, Surface Diffusion, Carbon, Amorphous Carbon, Diamond, Graphite, Graphene, Vacuum Arc, Nanotip

Primary authors: TOKTAGANOVA, Marzhan; KIMARI, Jyri; DJURABEKOVA, Flyura (University of Helsinki)

Presenter: TOKTAGANOVA, Marzhan

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **28** Type: **Oral**

3D PIC-DSMC Simulation of Strongly Coupled Cathode Spot Plasma Dynamics During Vacuum Arc Initiation: A Cautionary Tale

Thursday, 7 March 2024 09:00 (30 minutes)

As HPC computational resources increase, 3D simulations of vacuum arc initiation via the Particle-In-Cell (PIC) Direct Simulation Monte Carlo (DSMC) method are becoming more and more feasible since typically the initiation is modeled as starting from an extremely small region (e.g., the cathode spot). Using Sandia's PIC-DSMC code EMPIRE, we have performed simulations of a cathode spot plasma during initiation and encountered a variety of numerical challenges and physical accuracy concerns. Prior models of electrode ablation/vaporization have found that the typical electrode-gas density is approximately solid density very close (˜100 nm) to the electrode. Thus, the ionization mean free path is <10 nm with an ionization frequency of ˜1 ps⁻¹ resulting in nearly complete ionization as the neutral gas expands away from the near-electrode region. The ion densities (10²⁷-10²⁸ m⁻³) and temperatures (˜2000K) result in a strongly coupled plasma (Γ_i > 10) and, for explicit PIC calculations, the required mesh resolution to avoid numerical heating is dx<10⁻¹⁰ m. This results in less than one physical particle per element volume which results in "late"(˜100ω_p⁻¹) time numerical heating. If we use computational particle weights less than one or accept some numerical heating at longer times by increasing the mesh size, then we will not capture the physical disorder induced heating (DIH) that should occur [1]. Furthermore, at these densities the traditional DSMC method's assumption of a dilute gas is, at best, extremely questionable and even if that error is small, the ionization rates will be wrong due to unphysical density spikes. This talk will discuss these limitations and challenges in more depth as well as the role that DIH might play in the evolution of the cathode spot plasma.

[1] Acciarri, Moore, Beving, and Baalrud, "When should PIC simulations be applied to atmospheric pressure plasmas? Impact of correlation heating", PSST, submitted.

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Primary author: MOORE, Chris

Co-authors: ACCIARRI, Marco (University of Michigan); BAALRUD, Scott (University of Michigan); HOPKINS, Matthew; BEVING, Lucas

Presenter: MOORE, Chris

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **29** Type: **Oral**

Deducing the size of breakdown inducing tips from their beam spot shape

Wednesday, 6 March 2024 11:00 (30 minutes)

This talk presents theoretical work on the nano-protrusion hypothesis. We review and expand the theorical work on the study of the electron beam shape, as a mean to determine the dimensions of the hypothetical nano-protrusion where the electrons come from. State-of-the-art field emission theory and computational tools have been used to calculate the kinetic energy of the electrons as a function of the scale of the emitter for several beta invariant shapes. We present and discuss our findings and suggest a new series of experiments to validate our hypothesis.

Primary authors: KYRITSAKIS, Andreas; BARRANCO CÁRCELES, Salva (University of Edinburgh)

Co-authors: Prof. UNDERWOOD, Ian (University of Edinburgh); Prof. ZADIN, Veronika (University of Tartu (EE))

Presenter: BARRANCO CÁRCELES, Salva (University of Edinburgh)

Session Classification: Field Emission

Track Classification: Field Emission

Contribution ID: **30** Type: **Oral**

Cryogenic High Gradient RF Dark Current Studies at CYBORG Beamline

Tuesday, 5 March 2024 14:00 (30 minutes)

In order to address the needs of the high brightness electron beam and novel cathode communities, the CYBORG (CrYogenic Brightness-Optimized Radiofrequency Gun) beamline was developed and constructed at UCLA. The primary accelerating cavity is a 1/2 cell C-band structure designed to operate at cryogenic temperatures and accelerating gradients above 100 MV/m with a removable back plate for future cathode testing. We discuss here the testing motivations as an application of high gradient RF cavities with cryogenically enabled breakdown reduction. We will further present results from dark current and relevant material physics measurements down to cryogenic temperatures. Finally, we will introduce future high gradient RF cavity applications and experiments planned to operate in excess of 200 MV/m taking advantage of the effects of cryogenic temperatures and possibly Cu alloys.

Primary author: LAWLER, Gerard

Co-authors: FUKASAWA, Atsushi (UCLA); BOSCO, Fabio; ROSENZWEIG, James (UCLA); WILLIAMS, Oliver (UCLA); SAKAI, Yusuke (UCLA)

Presenter: LAWLER, Gerard

Session Classification: Field Emission

Track Classification: Field Emission

Contribution ID: **31** Type: **Poster**

A Method for Uncertainty Quantification of Electron Scattering Cross Sections in Plasma Physics Simulations

Monday, 4 March 2024 15:15 (20 minutes)

Electron beam driven plasmas are rich in complex physics, including atomic physics, molecular physics, plasma physics, collisions, plasma chemistry, thermodynamics, and scattering. The study of such a system is paramount for understanding and modeling of ionospheric physics and low-temperature plasmas. A reduced order model known as the rigid beam model has recently been developed by NRL to capture the relevant physics of such systems while greatly reducing the simulation times [1]. Such models require electron scattering cross sections to compute reaction rates to track the state of the gas during a simulation. There exists variability in these cross sections as reported for nitrogen in the published literature, which is a source of uncertainty. In this work, a characterization of the uncertainty in the electron scattering cross sections for nitrogen will be presented. Using this uncertainty characterization, a basic forward propagation uncertainty quantification technique is then applied to the rigid beam model. In this method, the rigid beam model is run many times to build probability density functions for the quantities of interest, such as the electron density or the net current. This work will then report on these probability density functions and compare them to previously published simulation and experimental results.

[1] A. S. Richardson et al., "Modeling intense-electron-beam generated plasmas using a rigid-beam approximation,"Phys. Plasmas 28 093508 (2021).

Primary author: RITTERSDORF, Ian

Co-authors: ISNER, Nancy; SWANEKAMP, Stephen (US Naval Research Laboratory)

Presenter: RITTERSDORF, Ian

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **32** Type: **Oral**

Power flow and vacuum breakdown in variable-impedance transmission lines under high self-magnetic fields

Monday, 4 March 2024 13:15 (30 minutes)

In the vacuum transmission lines of terawatt pulsed-power accelerators such as Sandia National Laboratories'Z machine, high electric fields (MV/m) result in field emission of electrons from cathodes. Left unchecked, these electrons are lost to and heat anode surfaces, leading to the emission of positive ions, and the generation of expanding electrode plasmas ($10^{16} - 10^{18}$ cm^{-3}). Altogether, mega-amperes of current can be lost from a nominal 26 MA current pulse. High self-magnetic fields ($1 - 100$ T) have been leveraged successfully for decades to mitigate these issues in pulsed-power accelerators by dynamically insulating anodes from emitted electrons; however, these accelerators have only employed constant-geometric-impedance transmission lines. Recent studies [1] have suggested there could be significant advantages using magnetically-insulated transmission lines (MITLs) with a variable geometric impedance.

In this talk, we present simulation-based studies assessing the viability of using variable-geometric-impedance transmission lines as an enabling technology for future pulsed-power accelerator designs; this includes characterizing power flow and magnetic insulation properties. Particle-in-cell simulations were performed using EMPIRE: a performance portable, massively parallel, three-dimensional electromagnetic plasma simulation code developed at Sandia National Laboratories. We showcase results from small-scale simulations of surrogate geometries under Z-relevant conditions and report on differences revealed therein compared to conventional (constant impedance) MITL theory. Finally, we present results from at-scale simulations of the Z accelerator.

[1] R. B. Spielman, D. B. Reisman; On the design of magnetically insulated transmission lines for z-pinch loads. Matter Radiat. Extremes 1 March 2019; 4 (2): 027402. https://doi.org/10.1063/1.5089765

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

Primary author: SIRAJUDDIN, David (Sandia National Laboratories)

Co-authors: HUTSEL, Brian (Sandia National Laboratories); POWELL, Troy; Dr CARTWRIGHT, Keith (Sandia National Laboratories); DARR, Adam; Dr SPIELMAN, Rick (University of Rochester); SHAPOVALOV, Roman (University of Rochester)

Presenter: SIRAJUDDIN, David (Sandia National Laboratories)

Session Classification: Applications

Track Classification: Applications

Contribution ID: **33** Type: **Poster**

R&D of X-band deflecting structure applied on SHINE

Monday, 4 March 2024 15:35 (20 minutes)

For the development of X-band deflecting structure at Shanghai Synchrotron Radiation Facility (SSRF), two units of X-band deflecting structures totally including six RF structures have been used on SXFEL successfully for ultra-fast beam diagnostics. The construction of another new FEL facility has started from 2018, which is named Shanghai high repetition rate XFEL and extreme light facility (SHINE). Four units of X-band deflectors will be installed on SHINE. The design and measurement of the first prototype has been finished, and the high power test will be carried out soon, in this paper, the design and measurement results will be presented.

Primary author: TAN, Jianhao

Co-authors: WANG, Cheng; FANG, Wencheng (Shanghai Advanced Research Institute (SARI-SSRF))

Presenter: TAN, Jianhao

Session Classification: Poster Session

Track Classification: Applications

Contribution ID: **34** Type: **Poster**

Atomic and electronic structure of pure liquid copper by density functional theory and molecular dynamics simulation

Monday, 4 March 2024 15:15 (20 minutes)

Copper is widely used in electric vehicles, for example in bus bars for motors and battery modules. Of course, it is also used in accelerators.
The optical properties of pure liquid copper near the melting point have been investigated [1] using density functional theory with the Quantum ESPRESSO package [2].
In this paper, the atomic and electronic structure of pure liquid copper from the melting point to the boiling point were investigated using density functional theory with the Quantum ESPRESSO package and molecular dynamics simulations with the LAMMPS [3].

[1] S. Kato et al., J. Phys.: Condens. Matter 35, 324004 (2023).
[2] P. Giannozzi et al., J. Phys. Condens. Matter 21, 395502 (19pp) (2009). P. Giannozzi et al., J. Phys.: Condens. Matter 29, 465901 (2017). Giannozzi, P. et al., J. Chem. Phys. 152, 154105 (2020).
[3] A. P. Thompson et al., Comp. Phys. Comm. 271, 10817 (2022).

Primary author: KATO, Susumu

Presenter: KATO, Susumu

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **35** Type: **Oral**

Study on Transition from Field Emission to Delay Breakdown

The application of an electric field to a metal surface induces field emission (FE), serving as the initial electron source for vacuum breakdown. Delay breakdown, occurring randomly under a relatively low electric field, poses a critical challenge in engineering applications compared to immediate breakdown. However, the physical mechanisms that lead from FE to delay breakdown are still unclear.
This paper aims to elucidate the process leading from FE to delay breakdown by obtaining two-dimensional FE patterns over an extended time scale (4 –6 h). We established an experimental platform capable of concurrently capturing FE patterns and measuring electron current. Tip emitter DC voltages were manually set to generate electron signals in the FE pattern while avoiding immediate breakdown.
The experiment results show that delay breakdown always occurs after the manifestation of bright spots in the FE electron pattern. Notably, bright spots may dissipate without inducing delay breakdown, emphasizing their role as a necessary condition for delay breakdown Additionally, the occurrence of bright spots did not induce a significant change in the magnitude of the electron current, indicating that the total number of electrons remained essentially constant and FE persisted within the space-charge limited regime. The appearance of bright spots signifies localized, intense electron emission due to surface modifications on the tip apex under emission-generated heat and field-induced force. During the presence of bright spots, there exists the potential to overcome space charge limitations, ultimately leading to delay breakdown.
Our results provide a description of in the conditions leading to delay breakdown, contributing to the enhancement of reliability and continuous performance in vacuum devices and systems.

Primary authors: ZHANG, Xinguo; WANG, Zhenxing; Mr LI, Rui

Presenter: ZHANG, Xinguo

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **36** Type: **Oral**

Hybrid Modelling of Vacuum Arc in Current Zero

Tuesday, 5 March 2024 16:30 (30 minutes)

Vacuum arc interruption is the core issue in vacuum circuit breaker. The interruption process can be generally divided into two parts, arc-burning stage and post-arc dielectric recovery stage. Between these two stages, current zero serves as a connection, in which the arc plasma varies dramatically that the variation in the particle density can exceeds multiple orders of magnitude. The complexity of this physical process causes trouble to the continuous simulation of the whole interruption process. Thus, previous simulation researches chose only one stage for the most part, leading to the plasma evolution during the whole vacuum interruption remaining unclear. To understand the vacuum interruption comprehensively, it is inevitable to fulfil a continuous simulation. In this work, hybrid modelling of vacuum arc is conducted from the arcing stage to the current zero and then to the post-arc stage. During the arcing stage, hybrid plasma model, which treats ions as particles and electrons as fluid, is established, dynamic behaviors of cathode spots also considered. As the circuit current is cut off, the plasma distribution from hybrid plasma model is set as the initial condition of the post-arc stage, and then the plasma dissipation is simulated through hybrid Maxwell-Boltzmann model. Factors, such as plasma density, drift velocity of ions, concentration and asymmetry in plasma distribution, on the plasma dissipation are investigated. This simulation work gives a more accurate description for the physical process in the continuous transition in the vacuum interruption.

Primary authors: LI, Rui; WANG, Zhenxing; SUN, Liqiong; GENG, Yingsan (Xi'an Jiaotong University); WANG, Jianhua (Xi'an Jiaotong University)

Presenter: LI, Rui

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **37** Type: **Oral**

Signs of plastic response in surfaces exposed to high electric fields.

Wednesday, 6 March 2024 14:00 (30 minutes)

Various theoretical efforts explored the link between breakdown nucleation and pre-breakdown plastic activity in surfaces exposed to high electric fields. However, identifying such a mechanism is challenging as there are no clear indications of what structural evolution evidence should be identifiable in ex-situ post-mortem samples. The current state of research efforts to identify and measure the direct and indirect effects of such evolution is presented with specific emphasis on results and challenges of TEM microscopy of subsurface structure as depicted from cross-sectional lamellas. This is followed by a discussion of future experimental scenarios and current estimates of derived constraints on response to external field and exposure conditions.

Primary authors: SERAFIM, Catarina (University of Helsinki (FI)); POPOV, Inna; Mr MILLAR, Lee (CERN); CALATRONI, Sergio (CERN); BJELLAND, Victoria Madeleine; WUENSCH, Walter (CERN); ASHKENAZY, Yinon (The Hebrew University of Jerusalem (IL))

Presenter: ASHKENAZY, Yinon (The Hebrew University of Jerusalem (IL))

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **38** Type: **Poster**

Monte Carlo simulation of vacuum breakdown occurence

One of the most extensively studied characteristics of vacuum breakdown (VBD) is the conditioning process and the VBD occurrence statistics, in various systems, including Radio-Frequency (RF) accelerators and pulsed-DC large electrode systems. Despite abundant data on VBD statistics, drawing useful conclusions regarding the physical processes that determine various patterns within those data is extremely challenging. The existing VBD models focus on low-level physical mechanisms and thus cannot produce direct quantitative predictions that are comparable to the aforementioned data.

Here we attempt to bridge this gap between theory and experiment with a Monte-Carlo model that simulates the occurrence of VBD based on various general assumptions. We model VBD occurrence as a Markov chain process. The metal surface is separated into small elements, each of which is described by a local field E, a power coupling impedance parameter Z, and a surface state parameter β. On each pulse, each surface element is randomly tested for the occurrence of thermal runaway. The probability of thermal runaway (TR) is a sharply increasing function of βE. The occurrence statistics of TR are fitted to the experimental measurements of dark current fluctuations interpreted here as TR events that did not lead to full VBD.

Then elements where TR occurred are tested for development into full VBD, depending on E and the power coupling parameter Z of each point. The surface state parameter β of a point is updated after each pulse in a different manner, depending on whether nothing, TR, or VBD occurred.

Finally, we test the above method for various distributions of the simulation parameters, fitting them to reproduce well-known experimental conditioning curves and other VBD statistics.

Primary author: KYRITSAKIS, Andreas

Co-authors: Ms JAARMA, Marie (University of Tartu); Prof. ZADIN, Veronika (University of Tartu (EE))

Presenter: KYRITSAKIS, Andreas

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **39** Type: **Oral**

Unintended gas breakdowns in narrow gaps of advanced plasma sources for semiconductor fabrication industry

Tuesday, 5 March 2024 09:00 (30 minutes)

Predicting the occurrence of unintended gas breakdown in narrow gaps within plasma processing chambers is essential for the development of future plasma sources in the semiconductor industry. This study[1] conducted experimental and theoretical analyses focusing on the unexpected discharge events in narrow gaps. We observed a notable drop in the gas breakdown voltage when exposed to an existing background plasma facing the gap. Kinetic simulations suggest that a much higher initial current leaking from the plasma into the gap enhances the electric field. This results in a greater ionization rate, thus reducing the required voltage for breakdown. Furthermore, experimental results showed that the breakdown voltage decreases after several breakdown events. The eroded wall tends to increase the secondary electron emission, thus increasing the ionization and lowering the breakdown voltage. Preventing wall erosion due to the first discharge is therefore crucial to mitigate this undesired effect.

[1] Son, S. H., Go, G., Villafana, W., Kaganovich, I. D., Khrabrov, A., Lee, H.-C., Chung, K.-J., Chae, G.-S., Shim, S., Na, D., & Kim, J. Y. (2023). Unintended gas breakdowns in narrow gaps of advanced plasma sources for semiconductor fabrication industry. Applied Physics Letters, 123(23), 232108. https://doi.org/10.1063/5.0172566

Primary author: Dr VILLAFANA, Willca (Princeton Plasma Physics Laboratory)

Co-authors: Dr KHRABROV, Alexander (Princeton Plasma Physics Laboratory); Dr NA, Donghyeon (Samsung Electronics Co. Ltd., Hwaseong); Dr GO, Geunwoo (Department of Nuclear Engineering, Seoul National University); Dr CHAE, Gwang-Seok (Department of Semiconductor Science, Engineering and Technology, Korea Aerospace University); Dr LEE, Hyo-Chang (Department of Electronics and Computer Engineering, Korea Aerospace University); KAGANOVICH, Igor (Princeton Plasma Physics Laboratory); Dr KIM, June Young (Department of AI Semiconductor Engineering, Korea University); Dr CHUNG, Kyoung-Jae (Department of Nuclear Engineering, Seoul National University); Dr SHIM, Seungbo (Samsung Electronics Co. Ltd., Hwaseong); Mr SON, Sung Hyun (Princeton Plasma Physics Laboratory)

Presenter: Dr VILLAFANA, Willca (Princeton Plasma Physics Laboratory)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **40** Type: **Oral**

Nonlinear simulation of the electrothermal instability in electrode plasmas

Wednesday, 6 March 2024 17:00 (30 minutes)

The electrothermal instability (ETI), ubiquitous in materials which carry large currents, is driven by the dependence of the material resistivity on temperature. The filamentation mode of the instability occurs in plasmas, where the gradient of the Spitzer resistivity with temperature is negative, and results in non-uniform filaments of hot, current-dense plasma. The ETI is potentially significant for a variety of pulsed power applications since its growth rate depends on the current density squared.

Previous studies have shown that this instability may limit the utility of exploding wires, z-pinches, and magnetized liner implosions. However, these studies often neglect losses such as Coulomb collisions, thermal conductivity, and radiation. Furthermore, the saturation mechanism of the instability has not been carefully studied, so it is unclear what the final state of the plasma will be.

In this study, we conduct idealized 2D simulations of a current-carrying plasma subject to the electrothermal instability. A steady state plasma is initialized in the domain, where Ohmic heating is balanced by collisional and/or radiative losses. The growth rate predicted by linear theory is assessed, where a peak growth rate appears that is dependent on the wavenumber, k. The instability is triggered by a small sinusoidal perturbation in the current density at this peak wavenumber and the resulting growth rate is compared with linear theory. Later in the simulation, harmonics of the original perturbation wavelength appear, leading to nonlinear saturation of the instability. Implications of this saturation and the final state of the plasma are discussed in the context of pulsed power plasmas.

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Primary author: VAZSONYI, Alexander R. (US Naval Research Laboratory)

Co-author: SWANEKAMP, Stephen (US Naval Research Laboratory)

Presenter: VAZSONYI, Alexander R. (US Naval Research Laboratory)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **41** Type: **Oral**

Decoupled discretization of plasma-material interfaces in multiphysics PIC simulations

Thursday, 7 March 2024 08:30 (30 minutes)

In high power vacuum arcs, the physics of the plasma and the surrounding surfaces can be strongly coupled both thermally and materially by energy deposition from the plasma to the materials and by gas-phase species emitted from the materials into the plasma, respectively. The former can also produce surface geometry modifications which then feed back to the electric field. The first step in capturing such couplings beginning with a Particle-In-Cell (PIC) approach to modeling the plasma is to model heat conduction within the electrode(s) with thermal fluxes corresponding to a combination of impacting particles and heat loss to particle emission. However, numerical constraints of these two models, especially when modeling the plasma using semi-implicit PIC (SIPIC) [1], are at odds with one another. Specifically, the time step size is constrained by the CFL requirement for electrons in the near-surface elements while the mesh element size is constrained by the high thermal gradients in the solid. Constraining the time step size and the mesh size to the most restrictive requirements leads to excessive temporal refinement in the electrodes and spatial refinement in the plasma which together require several orders of increased and unnecessary computational costs.

In this work we present an algorithm for decoupling the spatial discretizations in finite element PIC simulations from the material discretization, allowing larger elements in the plasma domain and a corresponding larger overall time step in the simulations. Specifically, a preprocessing step constructs a mapping across non-conformal surface meshes at the electrode-plasma interface that allows efficient and conservative two-way data transfers of fluxes between the domains. Results are presented for thermal conduction in an electrode driven by impacting particles. We demonstrate that the non-conformal surface mesh data transfers produce results with accuracy and numerical convergence consistent with matching spatial discretizations but at significantly reduced computational cost using element sizes in the plasma over two orders of magnitude larger than that required for matching surface meshes. Together with the allowed increase in time step in the plasma domain, this approach enables production simulations that would otherwise be intractable.

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[1] D. C. Barnes, "Improved C1 shape functions for simplex meshes", J. Comp. Phys, 424, 109852, 2021.

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Primary author: ECKERT, Zakari (Sandia National Laboratories)

Co-authors: BRANDT, Steven (Sandia National Laboratories); HOOPER, Russell (Sandia National Laboratories)

Presenter: ECKERT, Zakari (Sandia National Laboratories)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **42** Type: **Oral**

PIC-Simulations of an Intense Electron Beam Plasma using EMPIRE

Tuesday, 5 March 2024 08:30 (30 minutes)

PIC simulations are preformed to model NRL's Febetron experiment, a small pulsed power device that injects an intense electron beam into a gas cell. The parameters of the pulsed power device are a 100 kV, 4.5 kA, and 100 ns pulse. Three-dimensional models of the vacuum diode and the gas cell are used in EMPIRE simulations. The kinetic model depends on the magnitude of the electron-beam current and energy, and the gas pressure. Within EMPIRE we utilize and compare different emission models for the diode and the gas cell and included a weakly-ionized chemistry set for molecular nitrogen. Simulations assess a range of pressures between 100 mTorr and 10 Torr. The results analyze the electric field, the current enclosed contours (2πrB_θ/μ_0), the electron density and the plasma density of various state populations such as electronic, vibrational and rotational states. Additionally, we evaluate different numerical methods in EMPIRE and compare to experimental data.

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Primary author: ISNER, Nancy

Co-authors: MOORE, Chris; CARTWRIGHT, Keith (Sandia National Laboratories); SWANEKAMP, Stephen (US Naval Research Laboratory)

Presenter: ISNER, Nancy

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **43** Type: **Oral**

Emission Characteristics of a Broad-Area Molybdenum Cathode under an Inhomogeneous Electric Field

Tuesday, 5 March 2024 11:00 (30 minutes)

In electrostatic fusion reactors like the Orbitron, maintaining reliable high-voltage levels is crucial for the confinement of charged particles. Avalanche Energy's ultra-compact bushing, MAKO, plays the key role of transferring voltage from ambient pressure to an ultra-high vacuum environment with pressures below 1e-8 Torr. It features a coaxial configuration with a 1.8-5 cm gap distance and is designed to handle a nominal voltage of 300 kV. However, the high voltages required present complex challenges, such as explosive field emission from the cathode and surface flashover across the insulator. These issues become more pronounced at voltages above 200 kV, where the system's stored energy is sufficient to increase the probability of explosive cathode emissions. The electric field strength across the cathode in the >200 kV regime can reach up to 30 MV/m, although the field at the triple-junction point is effectively shielded to never exceed 0.05 MV/m. Recent experiments have focused on using gases like Ar, N2, and Kr for surface conditioning to eliminate sharp emission sites on the cathode, with Kr proving particularly effective in removing tenacious field emission sites, as evidenced by both cathode current profiles and visual recordings. Despite a minimal triple-junction field, surface flashover may still occur due to surface charging of the ceramic insulator and charge accumulation from electron beam exposure. Nevertheless, explosive emissions from the cathode that result in persistent deposits can be substantially reduced through gas conditioning with heavier atomic species.

Primary author: BORGHEI, Moein (Avalanche Energy)

Co-author: LANGTRY, Robin (Avalanche Energy)

Presenter: BORGHEI, Moein (Avalanche Energy)

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **44** Type: **Oral**

Motion of Arcs in RF Accelerating Cavities

Although fundamental in many technologies, the physics of arcs is not completely understood, since unambiguous experiments are limited by physical access, unpredictability and short time scales. Unipolar arc tracks showing arc motion have been seen in several tokamaks (but the arcs seem to move in the opposite direction from that expected from J x B forces). There has been little data on arc motion in rf cavities, since the phenomenon is even less accessible there, however images of field emission from the irises of an 805 MHz cavity in a 3 T magnetic field seem to show field emitters exhibiting circumferential motion around the cavity axis. Limited data showed that, in the absence of strong magnetic fields, field emitters did not move. We discuss modeling and experiments that would improve our understanding of these phenomena.

Primary author: NOREM, Jim (Argonne National Lab)

Co-authors: HASSANEIN, Ahmed (Purdue University); INSEPOV, Zeke (Purdue University)

Presenter: NOREM, Jim (Argonne National Lab)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **45** Type: **Oral**

Concurrently coupled particle-in-cell, emission, and heating simulations of vacuum arc plasma initiation

Tuesday, 5 March 2024 17:30 (30 minutes)

Vacuum arcing involves the coupling of multiple physical mechanisms starting from electron emission and leading to plasma formation. The importance of different physical interactions for arc occurrence is an important aspect which is still largely not understood. Here we use particle-in-cell simulations with Monte Carlo collisions concurrently coupled with electron emission and heating calculations (FEMOCS code) to study vacuum arc initiation. We identify the factors that contribute most significantly to the formation of the initial plasma. The dynamics of the initial plasma around a nanotip is simulated to study the coupling between different physical interactions.

Primary author: KOITERMAA, Roni (University of Helsinki)

Co-authors: KYRITSAKIS, Andreas; DJURABEKOVA, Flyura (University of Helsinki); TIIRATS, Tauno (University of Tartu); Prof. ZADIN, Veronika (University of Tartu (EE))

Presenter: KOITERMAA, Roni (University of Helsinki)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **46** Type: **Poster**

Dependence of vacuum arc initiation dynamics on the application of a static magnetic field

Monday, 4 March 2024 16:15 (20 minutes)

The role of the magnetic field in vacuum arcing has been neglected in many experimental and computational studies, while it is present in many applications. Future accelerators such as muon colliders and technologies such as vacuum interrupters involve significant magnetic fields that potentially influence the plasma initiation dynamics of vacuum arcing, as they can significantly focus the initial electron beam. Here we use our concurrently coupled approach of FEMOCS combining particle-in-cell, emission, and heating, to study how the addition of an external magnetic field can influence the heating behavior of the cathode and anode.

Primary authors: TOKTAGANOVA, Marzhan; KOITERMAA, Roni (University of Helsinki)

Co-authors: KYRITSAKIS, Andreas; DJURABEKOVA, Flyura (University of Helsinki); TIIRATS, Tauno (University of Tartu); Prof. ZADIN, Veronika (University of Tartu (EE))

Presenter: KOITERMAA, Roni (University of Helsinki)

Session Classification: Poster Session

Track Classification: Modeling and Simulations

Contribution ID: **47** Type: **Oral**

Mechanisms of bubble growth and blistering on metals exposed to hydrogen

Thursday, 7 March 2024 08:00 (30 minutes)

Increasing demands of energy, along with the yet increasing concern for the development of environmentally friendly technologies, call for exploring new ways of cost-efficient energy production. Hydrogen is one of the primary candidates for this purpose, due to its abundance and diverse ways of how it can be used. Moreover, hydrogen-based technologies are carbon-neutral, and hence their use could have a major effect on slowing down the climate change. Hence, the insights on the interaction of H with metals are crucial to reach that ambitious goal.

Blistering is a process that usually takes place close to the surface of metals when they are irradiated, as can be seen in radio-frequency quadrupoles accelerating structures. This pronounced change of the surface morphology has been measured when extended irradiation is
done with energetic light ions.

We use computational methods to address the fast bubble growth in Cu, associated with blistering, when exposed to H- irradiation [1]. We analyze the interaction of the formed dislocation loops with the different surface orientations of copper. Furthermore, we focus on the H depth profile and vacancy distributions along low-indices crystallographic directions [2].

We find a strong correlation between the blistering and crystallographic orientations. The distance between the mean penetration depth of H and the vacancies (recoils) creation is considerably different along the considered directions, and provides an explanation of the resistance
to blistering of some grain orientations. Furthermore, we introduce some successful initial tests performed with the newly developed ML potential.

References
[1] Alvaro Lopez-Cazalilla, Flyura Djurabekova, Fredric Granberg, Kenichiro Mizohata, Ana Teresa Perez Fontenla, Sergio Calatroni, Walter Wuensch Acta Materialia, 225 (2022) 12
[2] Alvaro Lopez-Cazalilla, Catarina Serafim, Jyri Kimari, Milad Ghaemi, Ana Teresa Perez-Fontenla, Sergio Calatroni, Alexej Grudiev, W. Wuensch, F. Djurabekova submitted (2023)

Primary author: LOPEZ CAZALILLA, Alvaro

Co-authors: SERAFIM, Catarina (University of Helsinki (FI)); DJURABEKOVA, Flyura (University of Helsinki); CALATRONI, Sergio (CERN); WUENSCH, Walter (CERN)

Presenter: LOPEZ CAZALILLA, Alvaro

Session Classification: Modeling and Simulations

Track Classification: Experiments and Diagnostics

Contribution ID: **48** Type: **Oral**

In-situ observation of field-induced nano-protrusion growth on a carbon-coated tungsten nanotip

Wednesday, 6 March 2024 14:30 (30 minutes)

Nano-protrusion (NP) on metal surface and its inevitable contamination layer under high electric field is often considered as the primary precursor that leads to vacuum breakdown, which plays an extremely detrimental effect for high energy physics equipment and many other devices. Yet, the NP growth has never been experimentally observed. Here, we conduct field emission (FE) measurements along with in-situ Transmission Electron Microscopy (TEM) imaging of an amorphous-carbon (a-C) coated tungsten nanotip at various nanoscale vacuum gap distances. We find that under certain conditions, the FE current-voltage (I-V) curves switch abruptly into an enhanced-current state, implying the growth of an NP. We then run field emission simulations, demonstrating that the temporary enhanced-current I-V is perfectly consistent with the hypothesis that a NP has grown at the apex of the tip. This hypothesis is also confirmed by the in-situ observation of such a nano-protrusion and its continued growth during successive FE measurements in TEM. We tentatively attribute this phenomenon to field-induced biased diffusion of surface a-C atoms, after performing a finite element analysis that excludes the alternative possibility of field-induced plastic deformation.

Primary authors: MENG, Guodong; LI, Yimeng; KOITERMAA, Roni (University of Helsinki); Prof. ZADIN, Veronika (University of Tartu (EE)); CHENG, Yonghong (Xi'an Jiaotong University); KYRITSAKIS, Andreas

Presenter: KYRITSAKIS, Andreas

Session Classification: Experiments and Diagnostics

Track Classification: Field Emission

Contribution ID: **49** Type: **Oral**

Aspect of High Field Testing

Wednesday, 6 March 2024 09:00 (30 minutes)

The Large Electrode System (LES) is a pulsed high-voltage DC test stand located at CERN where its main objective is investigating the origin behind breakdowns. Breakdowns are an important limiting factor in high electric field applications and ongoing studies are performed to better understand the origin behind this phenomenon. Our experimental setup requires two electrodes, having a gap between 20um to 100um. A program used to evaluate and compare the high-field behaviour of materials such as Hard Cu, Soft Cu, Nb, TiAl, Ta, CuCrZr and others, has been carried out. It identifies their field holding capabilities, breakdown rates, conditioning behavior and breakdown locations. In addition, field emission tests are conducted to find the surface field enhancement of the different materials. Light spectra are also observed during field emission and can withold important information as to where the surface field enhancement originates from.

Primary authors: SERAFIM, Catarina (University of Helsinki (FI)); CALATRONI, Sergio (CERN); BJELLAND, Victoria Madeleine; WUENSCH, Walter (CERN)

Presenter: BJELLAND, Victoria Madeleine

Session Classification: Experiments and Diagnostics

Track Classification: Experiments and Diagnostics

Contribution ID: **50** Type: **Oral**

Theory of field emission through dielectric pores in the metal surface layer

The influence of pores filled with a dielectric, in particular hydrogen, on the current of field electron emission from the structural materials of accelerator structures was studied. A review of the literature shows that pores can form in the near-surface layer in which dielectric, in particular hydrogen, can accumulate. Therefore, the study of the influence of dielectric inclusions in the metal surface layer is important and needs to be studied. The theoretical model of the potential barrier for the metal-dielectric-metal-vacuum system was constructed. An analytical expression for the electron tunneling coefficient from the metal was found. It is shown that the current has a resonant character and in the resonant region can be amplified up to 4 times compared to the current from the region without such pores. It is also worth noting that in the case when the pore thickness is d>0.2 nm, a decrease in the field electron emission current will be observed regardless of their depth. At the same time, the resonance region increases with the increase of the affinity energy.

Primary author: LEBEDYNSKYI, Serhii (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Co-authors: KHOLODOV, Roman (Institute of Applied Physics, National Academy of Sciences of Ukraine); LEBEDYNSKA, Yuliia (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Presenter: LEBEDYNSKYI, Serhii (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Track Classification: Modeling and Simulations

Contribution ID: **51** Type: **Oral**

Theory of field emission through dielectric pores in the metal surface layer

Tuesday, 5 March 2024 08:00 (30 minutes)

The influence of pores filled with a dielectric, in particular hydrogen, on the current of field electron emission from the structural materials of accelerator structures was studied. A review of the literature shows that pores can form in the near-surface layer in which dielectric, in particular hydrogen, can accumulate. Therefore, the study of the influence of dielectric inclusions in the metal surface layer is important and needs to be studied. The theoretical model of the potential barrier for the metal-dielectric-metal-vacuum system was constructed. An analytical expression for the electron tunneling coefficient from the metal was found. It is shown that the current has a resonant character and in the resonant region can be amplified up to 4 times compared to the current from the region without such pores. It is also worth noting that in the case when the pore thickness is d>0.2 nm, a decrease in the field electron emission current will be observed regardless of their depth. At the same time, the resonance region increases with the increase of the affinity energy.

Primary author: LEBEDYNSKYI, Serhii (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Co-authors: KHOLODOV, Roman (Institute of Applied Physics, National Academy of Sciences of Ukraine); LEBEDYNSKA, Yuliia (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Presenter: LEBEDYNSKYI, Serhii (Institute of Applied Physics, National Academy of Sciences of Ukraine)

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **52** Type: **Oral**

Study on Transition from Field Emission to Delay Breakdown

Tuesday, 5 March 2024 17:00 (30 minutes)

The application of an electric field to a metal surface induces field emission (FE), serving as the initial electron source for vacuum breakdown. Delay breakdown, occurring randomly under a relatively low electric field, poses a critical challenge in engineering applications compared to immediate breakdown. However, the physical mechanisms that lead from FE to delay breakdown are still unclear.
This paper aims to elucidate the process leading from FE to delay breakdown by obtaining two-dimensional FE patterns over an extended time scale (4 –6 h). We established an experimental platform capable of concurrently capturing FE patterns and measuring electron current. Tip emitter DC voltages were manually set to generate electron signals in the FE pattern while avoiding immediate breakdown.
The experiment results show that delay breakdown always occurs after the manifestation of bright spots in the FE electron pattern. Notably, bright spots may dissipate without inducing delay breakdown, emphasizing their role as a necessary condition for delay breakdown Additionally, the occurrence of bright spots did not induce a significant change in the magnitude of the electron current, indicating that the total number of electrons remained essentially constant and FE persisted within the space-charge limited regime. The appearance of bright spots signifies localized, intense electron emission due to surface modifications on the tip apex under emission-generated heat and field-induced force. During the presence of bright spots, there exists the potential to overcome space charge limitations, ultimately leading to delay breakdown.
Our results provide a description of in the conditions leading to delay breakdown, contributing to the enhancement of reliability and continuous performance in vacuum devices and systems.

Primary authors: ZHANG, Xinguo; WANG, Zhenxing; Mr LI, Rui

Presenter: ZHANG, Xinguo

Session Classification: Modeling and Simulations

Track Classification: Modeling and Simulations

Contribution ID: **53** Type: **Poster**

Monte Carlo simulation of vacuum breakdown occurence

Monday, 4 March 2024 16:55 (20 minutes)

One of the most extensively studied characteristics of vacuum breakdown (VBD) is the conditioning process and the VBD occurrence statistics, in various systems, including Radio-Frequency (RF) accelerators and pulsed-DC large electrode systems. Despite abundant data on VBD statistics, drawing useful conclusions regarding the physical processes that determine various patterns within those data is extremely challenging. The existing VBD models focus on low-level physical mechanisms and thus cannot produce direct quantitative predictions that are comparable to the aforementioned data.

Here we attempt to bridge this gap between theory and experiment with a Monte-Carlo model that simulates the occurrence of VBD based on various general assumptions. We model VBD occurrence as a Markov chain process. The metal surface is separated into small elements, each of which is described by a local field E, a power coupling impedance parameter Z, and a surface state parameter β. On each pulse, each surface element is randomly tested for the occurrence of thermal runaway. The probability of thermal runaway (TR) is a sharply increasing function of βE. The occurrence statistics of TR are fitted to the experimental measurements of dark current fluctuations interpreted here as TR events that did not lead to full VBD.

Then elements where TR occurred are tested for development into full VBD, depending on E and the power coupling parameter Z of each point. The surface state parameter β of a point is updated after each pulse in a different manner, depending on whether nothing, TR, or VBD occurred.

Finally, we test the above method for various distributions of the simulation parameters, fitting them to reproduce well-known experimental conditioning curves and other VBD statistics.

Primary author: KYRITSAKIS, Andreas

Co-authors: Ms JAARMA, Marie (University of Tartu); Prof. ZADIN, Veronika (University of Tartu (EE))

Presenter: KYRITSAKIS, Andreas

Session Classification: Poster Session

Track Classification: Modeling and Simulations