12th International Workshop on the Mechanisms of Vacuum Arcs (MeVArc 2025)

Sunday 1 June 2025 - Friday 6 June 2025

Book of Abstracts

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Growth Technique of Single-Walled Carbon Nanotube Production Technology Using Shochu as a Raw Material

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Carbon nanotubes (CNTs), which have garnered significant attention as a novel material, have been produced through various proposed synthesis methods [1]. However, the industrial sector demands a simpler and more cost-effective approach for single-walled carbon nanotubes (SWNTs) production. In this study, carbon nanotubes were successfully synthesized using ethanol, a raw material derived from shochu made from Japanese sweet potatoes, via the alcohol catalytic chemical vapor deposition (ACCVD) method [2]. During the synthesis process, Ar gas was used as a carrier gas. Al (10 nm) and Ni (2 nm) were employed as catalysts. The synthesized SWNTs were grown on a Si wafer (100) substrate, where a tandem-structured thin film of iron and nickel was formed via vacuum deposition to function as a catalyst. As-grown SWNTs were analyzed using transmission electron microscopy (TEM), field-emission scanning electron microscopy (FE-SEM), Raman spectroscopy, and X-ray Photoelectron Spectroscopy (XPS) to obtain structural and electronic information. This study proposes a CNTs synthesis technique utilizing ethanol derived from shochu as a raw material, thereby demonstrating the feasibility of substituting industrial ethanol with plant-based ethanol.

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Ref. [2] Husnu Emrah Unalan and Manish Chhowalla; 2005 Nanotechnology 16 2153DOI 10.1088/0957-4484/16/10/031.

Please choose topic that matches most closely your research:

Applications

Modeling and simulations / 5

Numerical Simulation of Vacuum Breakdown Characteristics with Two Emission Sources Based on Particle-in-Cell Method

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Studying the breakdown process in small vacuum gap is very useful to understand the breakdown mechanism and improving
the performance of vacuum switches. In this paper, a two-dimensional vacuum breakdown model with two emission sources
was established based on particle-in-cell (PIC) method to simulate the formation process of cathode plasma during the small
gap vacuum breakdown. Firstly, the field emission electrons from the two emission sources were set as two different particle
types, and it was found that they were influenced each other, accelerating the formation of plasma and subsequently speeding
up the discharge process. Secondly, the field enhancement coefficient of one emission point was varied to investigate its impact.
Finally, the distance between the two emission sources was also changed to study the influence of different center-to-center
distances on the interactions between the emission sources.

Please choose topic that matches most closely your research:

Modeling and simulations

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Simulations for the study of micro-discharges in conditioning experiments at the High Voltage Padova Test Facility

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In the framework of the project for the development of the Neutral Beam Injector foreseen for the ITER tokamak, and in support of operations of the Megavolt ITER Injector and Concept Advancement (MITICA), the High Voltage Padova Test Facility (HVPTF) is in operation in Padova, Italy. The experiments of HVPTF aim at studying and understanding the phenomenology of in-vacuum discharge events for electrodes set at high voltage differences, with the ultimate purpose of mitigating breakdown effects or preventing their occurrence. The setup at the facility is composed of a cylindrical vacuum vessel in which two electrodes are mounted on supports at adjustable distance. Two independent power supplies, of which the current and voltage signals are sampled during the experiments, are used to supply voltage differences up to 800kVDC. The pressure at the walls of the chamber, together with the composition of the gas outgoing from the chamber, is monitored as well. Additionally, multiple lines of sight allow for various diagnostics to be installed at different points of the chamber. The dynamics of the emissions during discharge events can thus be observed in the visible/IR/UV spectra, with cameras, and in the X-ray spectrum altogether, with scintillators and a GEM-based detector.
Previous analyses of the signals collected by the GEM detector have shown promising results, particularly in the study of the X-ray radiation alongside signals from other diagnostics. In addition, they

highlighted the need for theoretical modeling to explain the observed phenomena and justify the experimental data gathered. This paper presents the first steps of development of a multi-environment simulation code, which aims at fully reproducing the main aspects of the dynamics of the micro-discharges observed during the measurement campaigns. Different contributions are considered one at a time and modeled with different software, with the perspective of putting them together in the future for a full-scale simulation of the phenomena involved.

Please choose topic that matches most closely your research:

Experiments and diagnostics

Field emission / 7

Quantum model of field emission from dielectric coatings

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In the present work, the theory of field emission from surfaces covered with both dielectric coatings and naturally formed oxide layers or adsorbates is considered.
A modified Fowler-Nordheim theory was used to describe the field emission processes, considering the two-layer potential barrier formed by the dielectric coating. This allowed us to create analytical models for calculating the field emission current. The process of electron passage through thin (up to 1 nm) and thick dielectric layers was studied. The use of asymptotic approximations for the Airy functions in the case of thin layers provided high accuracy and significant simplification of calculations. For thick dielectric layers, the model showed a good correspondence to simplified expressions for thicknesses not exceeding the average free path length of electrons in the dielectric.
Particular attention is paid to the influence of physical parameters of the dielectric on the field emission current. The dependence of this current on the thickness of the dielectric layer, the strength of the external electric field, the dielectric constant of the medium, and the electron affinity energy is established. The study has shown that at a dielectric layer thickness of up to 1 nm and high electric field strength (over 1 GV/m), the field emission current is significantly reduced due to the increase in the barrier height and width. Instead, an increase in the layer thickness above 1 nm leads to an increase in the field emission current due to a decrease in the width of the potential barrier. This is important for optimizing the operating parameters of accelerator systems.
The paper also compares the quantum model with quasi-classical approaches, in particular the modified Fowler-Nordheim equation. The results show that the quantum model provides a higher emission current density and demonstrates resonant peaks that are not observed in quasi-classical models. This confirms the importance of accounting for quantum effects for accurate field emission calculations.
Thus, the study emphasizes the need to use quantum models to predict the emission characteristics of dielectric-coated materials. The developed analytical solutions improve the accuracy and efficiency of numerical calculations, which is important for the physics of accelerator structures and high voltage technologies.

Please choose topic that matches most closely your research:

Field emission

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Experimental investigation of the initiation of vacuum arcs on solar panels of satellites

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Vacuum arcs induced by electrostatic discharges (ESD) or meteoroids/orbital debris (MMOD) impacts represent a severe risk for survivability of satellites in orbit. When the plasma formed during these events is produced on a solar panel, a secondary arc can be produced between power lines of a solar panel, which can lead to degradation of solar panels performance and ultimately to spacecraft failure when the arc becomes self-sustained.
Electrical discharges and secondary arcs on solar panels have been studied at ONERA over the last 30 years. Facilities include vacuum chambers equipped with instruments alllowing to reproduce the plasma produced during an ESD (through the control of discharge current) or a MMOD impact (hypervelocity impact plasma is simulated with a laser focused on a target). The current supplied to the secondary arc is controlled with an electrical circuit representative of a real solar panel. Specific diagnostics are used to characterize the plasma produced by ESD/laser and the arc (electrical signals, electrostatic probes, high-speed camera imaging). Research studies have led to validation of numerical models though comparison with experimental, evaluation of the arcing risk as a function of electrode geometries (distance, voltage, current), and analysis of the coupling of the discharge with the cathode spot.

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Experiments and diagnostics

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Electron beam charging of tungsten microparticle X-ray targets

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Practical evidence suggests the important role of microparticles for the initiation of vacuum discharges. In the context of improving the performance of X-ray sources we simulated a stream of microparticles that intersect with an electron beam to convert electron energy in bremsstrahlung. Monte Carlo (MC) simulations of electron transport for single micrometer sized tungsten spheres in free space suggest that the comparatively high electron backscatter yield of high atomic number tungsten suppresses charging for impact energies beyond the tens of keV range. The backscattering yield as a function of the primary energy even slightly exceeds unity above a well-defined energy threshold. The simulation reveals that the exit energy of the backscattered electrons and the backscattering yield both decrease with increasing microparticle size, approaching the characteristics of thick targets. Dense streams of microparticles or a levitated layer in front of a plain substrate exhibit higher negative charging as electrons may interact with multiple particles or the substrate with decreasing electron energy at each interaction. Our findings support the understanding of the dynamics of microparticles in high voltage gaps and surface modifications upon their impact on solid electrodes that may cause vacuum discharges.

Please choose topic that matches most closely your research:

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Three-dimensional hybrid simulation on plasma jet formation in Zirconium-Deuterium multi-component vacuum arc discharge

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Metal vapour vacuum arcs (VAs) are widely used in various fields of industry, such as circuit breakers, ion sources, electrical thrusters, and deposition systems. Although experiment is still the main research tool for VAs, numerical modeling has recently made rapid progress in their study. In recent years, our group has developed particle-in-cell (PIC) method [1-3] as well as fluid method [4-6] to simulate the process of vacuum breakdown, plasma jet formation and ion acceleration etc. In this paper, we report a three-dimensional hybrid simulation on the plasma jet formation in vacuum arc discharge with a Zirconium-Deuterium cathode. The hybrid model aims to take advantage of both fluid simulation with low computation cost and particle simulation with high predictive ability with phase-space information of micro-particles. The quasi-neutrality approximation is used in the hybrid model [7, 8], in which ions or neutrals are treated as super-particles by the PIC method, and electrons are treated as inertia-less fluid. The computational cycle is as follows: the velocity of ions is updated by interpolated electromagnetic field using Boris method, and further altered by electron-ion friction force; the position of ions is updated using its velocity, and boundary condition is checked; the magnetic field B is advanced by Faraday's law; the current density is computed by Ampere's law in which the displacement current is neglected; the electric field is computed by general Ohm's law. To obtain high-order accuracy of field solution, the predictor-corrector method is used with virtual-pushing of particle position. The electron density is directly obtained by quasi-neutrality condition, and electron velocity is calculated by the current density and obtained electron density. Inside the computational cycle, the Coulomb collisions between D-D, Zr-Zr and D-Zr ions are performed using Nanbu's method [9], and Monte Carlo collision can be activated by sampling electron macro-particles from their density, velocity and temperature. Electron temperature is updated by considering energy loss between electron-neutral collisions, as well as heat conduction and diffusion. The constraint on spatial step is determined by the minimum of inertial length and mean free path of ions. The constraint on temporal step is usually determined by the ion collision time, resistive term of magnetic diffusion equation, and the stability criterion for waves in the whistler limit [10]. After carefully choosing the appropriate space and time step, we performed hybrid simulation on the plasma jet formation in millimeter scale in all three dimensions. Both single and multiply cathode spot (CS) plasma jet are studied. The radius of one CS is 50 microns with a nominal current density of $3 * 10^9 A/m^2$. The simulated result showed a different behavior of angular distribution of ions with light and heavy mass, which agrees with previous experiment and other simulations.

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Please choose topic that matches most closely your research:

Modeling and simulations

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High-power testing of X-band multiple-sector single-cell test cavities at Nextef2

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Multiple-sector hard-copper X-band accelerating structures were designed and fabricated with four quadrants [Nucl.Instrum.Meth.A 1063 (2024), 169272]. We recently installed one of the structures at Nextef2, an X-band high-power test stand at KEK. In this presentation, we report the status and results of the high-power test as well as how to test and measure the characteristics and performance.

Please choose topic that matches most closely your research:

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Coupling vacuum arc plasma and surface phenomena using MD-PIC simulations

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Vacuum arc development has been previously studied by simulations focusing on different aspects of plasma initiation, surface modification, heating and emission. We describe the development of a model that concurrently couples particle-in-cell (PIC) plasma simulation and molecular dynamics (MD) to study how these phenomena are linked in vacuum arcing. Surface morphology changes influence emission and heating characteristics of metal surfaces under high electric field, which in turn leads to differences in plasma development. Bombardment of ions from this plasma can result in modification of the surface by processes such as sputtering. This coupling is achieved by a particle exchange process between the PIC and MD systems. We simulate the development of the initial plasma around a nanotip and the resulting surface effects using the FEMOCS code. Additionally, we simulate crater formation by energetic ions at a later stage in arcing using molecular dynamics. These developments focus on the initial and final stages of vacuum arcing, aiming to better understand the process from start to finish.

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Electron emission behavior at small gaps in vacuum interrupters

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The contact gap of open vacuum interrupters (VI) is generally set by the lightning impulse withstand voltage and/or capacitor switching duty. These duties require larger contact gaps than other duties such as interrupting short-circuit current and power frequency withstand voltage. The electron emission from gaps with these dimensions is very small, unless some feature of the duty enhances this emission by roughening the contact surface. However, VI applications that do not require a lightning impulse withstand voltage nor back-to-back capacitor switching can potentially use much smaller contact gaps. These small gaps could generate larger field emission currents when under voltage stress. Experimental work characterized the field emission from 0.5-4 mm gaps between Cu-Cr contacts at DC voltages up to 40 kV. These experiments can quantify the change in behavior over a large number of samples as well as the effect of different mechanical and electrical operations.

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High power testing of X-band dielectric assist accelerating structure at Nextef2

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Dielectric assist accelerating (DAA) structures offer a significantly higher shunt impedance compared to conventional normal-conducting copper structures [Phys. Rev. Accel. Beams 19, (2016) 011302]. However, DAA structures face limitations in achievable acceleration gradients (˜12 MV/m [Phys. Rev. Accel. Beams 24, (2021) 022001]) due to multipactor and dielectric breakdown. To address these issues, we conducted tests at Nextef2, an X-band high-power test stand at KEK, to observe the breakdown phenomena during these tests. In this presentation, we report on the current status and progress in the development of the X-band DAA structure.

Please choose topic that matches most closely your research:

Experiments and diagnostics

Poster session / 18

Methodology for analysing post-arc currents of test circuit measurements in vacuum interrupters

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As interest in SF6-free technologies increases, the demand for vacuum interrupters (VIs) capable of operating at higher voltage levels is also growing. To meet these demands, design innovations such as larger contact gaps and the series connection of multiple VIs have been implemented.

During the current interruption process, a high plasma density forms between the electrodes. Once the current is interrupted, the residual ions and electrons allow for the detection of a significantly smaller post-arc current, which typically ranges from 1 to 10 A. Accurately quantifying these post-arc currents after high short-circuit currents, exceeding 1 kA, presents considerable challenges, as it is crucial that the plasma is fully extinguished to ensure a successful interruption. Therefore, understanding the characteristics of this plasma is essential for analysing the switching behaviour of VIs and for designing new arrangements of vacuum circuit breakers to meet higher voltage requirements.

The small post-arc currents obscured by the circuit response current of the test circuit. To resolve this issue, a novel methodology for isolating post-arc currents from circuit-related disturbances are developed. This advancement enables more precise analyses and allows the results to be compared and traced for the first time. This capability is particularly important in high-voltage switch applications, where stray capacitances can significantly influence measurements.

To validate the foundational aspects of this methodology, investigations of post-arc currents during current interruptions of up to 15 kA, utilizing contact gaps of 10 mm are conducted.

Please choose topic that matches most closely your research:

Modeling and simulations / 19

Simulation of electric arcs and discharge plasma on the solar panels of satellites

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Satellites in orbit are constantly exposed to charged particles trapped in the magnetosphere. The differential charging induced by their interaction with solar cells on the panel of satellites can lead to an electrostatic discharge (ESD), also called primary arc. If the latter initiates between two strings of solar cells, the plasma produced by the ESD can short-circuit the conductors and lead to secondary arcing (SA). Sustained secondary arcs can have dramatic consequences, from cell degradation to significative satellite power loss. The high cost of qualification tests of solar panels requires numerical simulation to better understand the transition from the primary to the secondary arc, but also the mechanisms enabling their sustainability. At ONERA, a model of the ESD has been developed, taking into account the cathodic spot, its evolution throughout the discharge and the propagation of the plasma bubble it creates. This simulation consists in the coupling of two codes: the first code divides the near-spot space in 4 zones (including a sheath and a pre-sheath) and computes the characteristics of the plasma created by the cathodic spot, such as temperature and potential. At each timestep, this set of data is then used in the second code to model the propagation of the plasma bubble on the satellite, expanding at the Bohm velocity and neutralizing electrically charged surfaces. After refinement and validation of both codes, the results of the electrostatic discharge numerical simulations have been compared to experimental results from the EMAGS 4 project. The influence of different parameters such as spot radius, panel size and spot material has been tested in this study. In the long term, a model of secondary arcing taking into account material degassing and medium temperature shall be implemented.

Please choose topic that matches most closely your research:

Modeling and simulations

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Enhanced Multi-Spectral Imaging via Optical-Path Reuse: Spatiotemporal Evolution of Plasma Species in Vacuum Arc

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Emission spectroscopy is a widely used non-invasive technique for plasma diagnostics, with bandpass filters combined with high-speed imaging serving as an important method for observing vacuum arc plasmas. However, conventional multi-spectral imaging techniques are limited by intensity attenuation in dispersive optical architectures, which restricts the number of simultaneously observable species and imposes trade-offs between spectral channels and spatiotemporal resolution. As a result, capturing the coupled behavior of multiple plasma species remains challenging, leading to a reduced ability to analyze their dynamic evolution with high precision.To address these limitations, this study presents an optical-path-reuse multi-spectral imaging system, which optimizes the optical design to improve multi-channel spectral separation while minimizing signal loss. By integrating this system with a high-speed camera, we achieve six-channel synchronized imaging, enabling the real-time observation of 2-D spatial distributions and spatiotemporal evolution of six characteristic plasma species. Experiments were conducted under varying current levels and electrode gaps to examine the impact of these parameters on plasma species distribution and transport. The measurements provide valuable data for analyzing particle transport, ionization, and energy exchange mechanisms in vacuum arcs. Compared to conventional methods, the proposed multi-spectral imaging system mitigates the trade-off between channel count and resolution, offering enhanced capability for diagnosing high-dynamic plasmas with both broad spectral coverage and high spatial-temporal resolution. Beyond vacuum arc studies, this approach is applicable to pulsed discharges and laser-induced plasmas, providing a practical tool for precision diagnostics of complex plasma environments.

Please choose topic that matches most closely your research:

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Poster session / 21

Investigation of Metal Particles Sources and Motion Characteristics in High-Current Interruption

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Delayed breakdown in high-current vacuum interruption has emerged as a critical technical challenge restricting the development of high-voltage vacuum interrupters (HVIs). This study focuses on the origin and motion characteristics of metal particles during the post-arc phase, aiming to investigate their potential role as triggers of delayed breakdown. An optical diagnostic platform integrating laser shadow imaging and infrared thermography was established to enable full-process observation of metal particle behavior and electrode surface activity. Experimental results show that metal particles emitted from the cathode molten pool are generally larger in size and slower in speed, and can remain suspended in the post-arc gap for tens to hundreds of milliseconds. These particles typically follow inertial and stable trajectories, without notable reversal or abrupt deviation. This study proposes an intrinsic correlation between the long-term presence of metal particles and the occurrence of delayed post-arc breakdown. The findings suggest that larger particles are more likely to cause dielectric recovery failure in HVIs with wider gaps and higher voltage ratings. Future work will focus on clarifying the formation mechanisms and developing control strategies to improve the reliability of high-current interruption.

Please choose topic that matches most closely your research:

Experiments and diagnostics

Poster session / 22

DC electrical breakdown test setup with in-situ mechanical pulse stress

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We designed and constructed a test system to investigate the high electric field discharge characteristics due to the change in surface properties caused by in-situ mechanical pulse stress. Mechanical pulse stress was applied only near the center of the cathode surface by PIEZO actuator. In this presentation, we report on the status and results of the system characteristics and a DC breakdown test.

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Experiments and diagnostics

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Simulation based investigation on the influence of electromagnetic power in vacuum breakdown initiation process

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Vacuum arcs, also known as breakdowns, are a major limiting factor in various high electric field vacuum applications. However, the physical mechanisms underlying the initiation of this phenomenon remain unclear. Recent experimental and numerical evidence indicates that local electromagnetic power might be the primary limiting factor in arc initiation, rather than the applied electric field and cathode material, as previously assumed. This work aims to provide insight into the power supply's limitations on breakdown initiation through computational modeling, potentially leading to reduced VBD occurrence or higher operating fields in future applications.

The multi-physics code FEMOCS, used for VBD initiation modeling, can be coupled with the external electrical system's impedance response. Thus, the model connects the full system's circuit to local plasma initiation physics. This enables a direct investigation of the effects of different circuit responses on the VBD initiation process. Current work focuses on the RC circuit type models. Results demonstrate the existing electromagnetic power dependence and provide insight into the extent of its influence. Furthermore, the scale effect of the emitting tip is investigated, providing estimated bounds for expected tip size. Critical values related to tip geometry, heating, and impedance limits are identified, if applicable. This includes the hypothesis of a critical current threshold. Additionally, the framework for direct comparison with experimental results, based on the LES testing system at CERN, is revised.

Please choose topic that matches most closely your research:

Modeling and simulations

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Study of electrode erosion in switching vacuum arcs by optical methods

Author: Sergey Gortschakow[None]

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Vacuum interrupters are widely used for switching applications in modern power grid. The lifetime of the electrode system is mainly limited by accumulated thermal load of the electrode surface. The diagnostics of the electrode surface plays, therefore, an important role for understanding of basic phenomena and parameter optimization for switching applications. The right choice of the electrode material is very important for long lifetime and stable operation.
The contact surface changes its morphology when it is loaded with a high current due to melting, evaporation and solidification processes. This can affect the arc properties, like e.g. arc voltage and arc current behavior, arc dynamics, surface temperature dynamics and erosion rate. Those properties were studied for the case of cylindrical contacts made of materials conventionally used for switching applications. Besides various electrode materials, the aspects like current magnitude, electrode polarity, contact opening velocity have been investigated.
The measurements of the arc current and voltage have been accompanied by various optical diagnostics. The arc dynamics was observed by a high-speed camera. Near infrared radiation (NIR) spectroscopy determined the electrode surface temperature after current zero crossing. During the active phase, a high-speed camera equipped by a narrow band filter was applied for acquisition of qualitative distribution of the electrode surface temperature. Special attention was put on the cooling dynamics after current interruption.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Enhanced Vacuum Gap Insulation Between Non-Arc Metal Components in Vacuum Interrupters by Ion Implantation

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High-voltage and high-capacity vacuum interrupters adopt a multi-stage floating shield structure, which can be regarded as an insulation system consisting of multiple vacuum gaps connected in series and parallel. Breakdown occurs not only in the vacuum gap of the main contact but also in unintended regions such as the gaps between shields or between shields and conductive rods. To improve the overall insulation performance of the vacuum interrupter, treatment of non-arc metal surfaces is required. This paper investigates ion implantation on the surfaces of stainless steel ball-to-ball and ring-to-ring electrodes, which are then installed in the vacuum interrupter to simulate non-arc metal gaps. The experiments compare the effects of different types, doses, and acceleration voltages of implanted ions on breakdown voltage improvement. Surface analyses were conducted to examine the surface morphology and elemental composition of the electrodes before and after ion implantation. The results indicate that ion implantation effectively increases the initial breakdown voltage of vacuum gaps. However, as the number of breakdown events increases, the implanted ion layer gradually deteriorates. The improvement in voltage withstand capability is influenced by ion species, implantation dose, and acceleration voltage. The underlying mechanism is attributed to the enhancement of the electrode surface work function due to metal ion implantation. This work provides a theoretical foundation for enhancing the performance and miniaturization of high-voltage vacuum interrupters.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Breakdown precursor fomation on Cs2Te thin-film photocathode through drift-diffusion-Informed field emission simulation

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Semiconductors like Cs_2Te are increasingly being explored as electron emitters in radio-frequency (RF) photoinjectors for high-power accelerators and scientific instruments, including time-resolved electron microscopes and free-electron lasers. Their advantages, such as low intrinsic emittance and high quantum efficiency, make them promising candidates for these applications. However, a major challenge in achieving higher gradients in photoinjectors is the risk of breakdown, which can lead to catastrophic device failure. Despite the importance of understanding the material behavior of materials like Cs_2Te under such extreme conditions, research on semiconductor physics in accelerator applications remains limited.

In this work, we develop a self-consistent model of a Cs_2Te thin film subjected to intense surface fields exceeding 300 MV/m. Using a drift-diffusion approach, we capture the evolution of charge density due to electron and hole transport within the material. As the applied field increases, electrons are emitted from the thin-film surface, generating heat through localized Joule heating and the Nottingham effect. Our findings indicate that the combined effects of electric field and induced heating can drive the formation of breakdown precursors, which may ultimately lead to catastrophic failure.

Please choose topic that matches most closely your research:

Modeling and simulations

Poster session / 28

Analytical Investigation of Electron Trajectories in Vacuum Arc Ignition Under Static Electric and Magnetic Fields

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Vacuum arcs have been studied for over a century due to their relevance in high-voltage engineering, accelerator science, and power switching. In applications such as muon colliders and vacuum interrupters, magnetic fields are present and may influence the early stages of plasma formation in vacuum arcs. In this study, we explore electron trajectories during the ignition phase of a vacuum arc under the influence of static electric and magnetic fields with different co-orientations. Our approach is based on a system of differential equations governed by the Lorentz force, where trajectory equations are parameterized by the relevant field components.

Please choose topic that matches most closely your research:

Modeling and simulations

Field emission / 29

A Systematic Study of Metallic and Semiconductor Heterojunction 2-terminal Lateral Nanoscale Vacuum Field Emission Devices

Author: Harris Hall[1]

Co-authors: Dennis Walker Jr. [2]; James Hart [3]; Jonathan Ludwick [2]; Jonathan O'Mara [2]; Marc Cahay [3]; Nathaniel Hernandez [3]; Tyson Back [2]

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In the last 15 years there has been renewed interest in vacuum field effect transistors (VacFETs) with nanoscale feature sizes for their potential to transcend performance limitations associated with solid state transistors while maintaining some of the benefits of complex scaling and large-scale batch fabrication common to integrated circuits. Specifically, the vacuum channel of a VacFET offers potentially superior device operation for high temp and radiation hard environments, faster switching for high power/high frequency applications, and can be a surface for sensitive gas adsorbate sensing [1]. Employing wide bandgap semiconductor materials for VacFETs is of practical interest because their high covalent bond strength offers robustness for long-term reliable operation and the potential for hybrid on-chip integration with solid-state circuitry.

Our team has successfully demonstrated repeatable DC operation (< 30 V) of AlGaN/GaN heterojunction based nanoscale vacuum field emission diodes that emit from the edge of the two-dimensional electron gas (2DEG). Specifically, we have demonstrated the first 2DEG cathode / 2DEG anode variant and a 2DEG cathode / Metallic anode variant that performed at the largest current (~600 μA) reported to date for this class of device [2]. The team has also developed a computationally efficient and capable 3D modeling and simulation approach suitable for lateral metallic field emission devices [3]. On-going examination of 2-terminal metallic (Au/Cr) lateral nanoscale vacuum devices has been central towards its development, particularly for the consideration and inclusion of practical leakage effects that could occur [4]. This presentation will share an overview of these efforts and our projected posture towards extending our computational tools to accommodate nanoscale semiconductor field emission [5] and demonstration of 3-terminal VacFET devices.

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Please choose topic that matches most closely your research:

Field emission

Applications / 30

Post-arc Current of Forced-current-zero Vacuum Arcs

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Vacuum circuit-breakers (VCBs) are commonly applied in mechanical type direct current circuit-breakers (DCCBs). A high frequency (HF) current is injected to help create a forced current zero (CZ) and facilitates DC interruption in these DCCBs. This work is focused on investigation of the forced-current-zero vacuum arc and the following post-arc current.

A circuit capable of producing high di/dt and imposing the HF current in two opposite ways onto the breaking current by VCB is first constructed, providing better completeness in terms of interruption duties for investigation.

Study of post-arc current indicates that the peak post-arc current can reach higher than 100 A when di/dt reaches hundreds of A/μs and rate of rise of initial transient interruption voltage (ITIV) reaches kV/μs. However, it lasts only about 1 μs. It is summarized from groups of experiments that post-arc current is only influenced by a memory time no longer than 4.5 μs before the forced CZ. The residual plasma density only depends on current in this short interval. The memory time actually reflects how fast charged particles are escaping out of the gap. Analysis of experiments with different gap distances and opposite polarities of the breaking current suggests that the high post-arc current after forced CZ is nothing more than a rapid movement of residual charges. It has no impact on interruption performance. Besides, failure modes are classified according to features of post-arc current and ITIV. The impact of breaking currents, peak arcing current and distance of gap on post-arc re-ignition or restrike has been further investigated.
This research improved the understanding of electrical properties around the forced CZ. It is possible to enhance DC interruption performance where VCBs are applied.

Please choose topic that matches most closely your research:

Applications

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Exploring RF Breakdown and Conditioning in High-Gradient Accelerating Cavities

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High-gradient accelerating cavities are a key research area in the development of compact and efficient linear accelerators. These structures enable higher acceleration gradients, reducing the size and cost of future accelerator facilities. However, their performance is fundamentally constrained by non-linear electromagnetic effects that become more pronounced at high electric fields, including RF breakdowns, dark currents, and radiation. Understanding and mitigating these limitations is essential for improving the reliability and efficiency of high-gradient accelerators.
In this talk, we will present recent research efforts conducted at CERN's X-band and RFQ test facilities, as well as at the IFIC S-band facility. We will focus on the latest conditioning results of various high-gradient structure prototypes, examining their performance under extreme operating conditions. Additionally, we will discuss ongoing studies on breakdown phenomena, shedding light on the mechanisms that trigger RF breakdowns and strategies to enhance structure resilience. These findings contribute to the broader goal of optimizing high-gradient accelerator technologies for future applications in particle physics, medical accelerators, and industrial applications.

Please choose topic that matches most closely your research:

Experiments and diagnostics

Modeling and simulations / 32

Mechanisms of bubble growth and blistering on metals exposed to hydrogen via machine-learned interatomic potentials

Author: Alvaro Lopez Cazalilla[1]

Co-authors: Eetu Makkonen [2]; Julio Gutiérrez-Moreno [1]; Flyura Djurabekova [3]

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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. One of the most promising green energy production sources, nuclear fusion reactors, is based on reactions between hydrogen isotopes. Hence, the insights on the interaction of H with metals will shed light on processes developing in fusion-related materials as well.

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. 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-indice crystallographic directions. In addition, we present a new H-Cu machine-learned (ML) interatomic potential using GAP methodology, which opens the gate to a full understanding of bubble growth.

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.

Please choose topic that matches most closely your research:

Modeling and simulations

Field emission / 33

Characterization of surface damage on a polished stainless electrode biased to 500 kV DC in SF6 and to 259 kV DC in vacuum

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Localized surface damage sites developed on a polished stainless steel cathode after applying 500 kV DC in SF6, followed by 259 kV DC in vacuum. Polished stainless electrodes are commonly used in high voltage photo-emission electron guns for accelerator applications. Achieving field-emission-free operation at bias voltages 200-400 kV DC requires biasing the electrodes ˜ 100 kV higher than the target operational voltage to process field emitters. The electrode was affixed to the narrow, sealed end of a custom conical vacuum feedthrough made from partially conductive alumina. This assembly was mounted in a cylindrical stainless steel chamber with the open end of the feedthrough connected to a sulfur hexafluoride (SF6) gas-insulated Cockcroft-Walton power supply by means of a commercial cable, commonly used in the X-Ray tube industry. Colored spots with diameter ranging from 1 to 5 cm, as well as black 0.1 cm diameter spots were found in the test chamber inner walls upon removing the electrode-feedthrough assembly. Such damage has never been encountered in any of the electron gun vacuum chambers at Jefferson Lab. This contribution describes optical imaging, profilometry and chemical composition results from surface damage sites on a polished stainless steel cathode biased to 500 kV in SF6 and to 259 kV in vacuum.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.

Please choose topic that matches most closely your research:

Field emission

Poster session / 34

Dislocations role on conditioning and plastic activity: a DDD study

Authors: Alvaro Lopez Cazalilla[None]; David Kurunczy-Papp[1]; Lasse Laurson[1]; Flyura Djurabekova[2]

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The vacuum electrical breakdown (BD) or vacuum arcing happens when a conducting plasma arc forms in vacuum between electrodes under high voltage. For decades, researchers have studied this phenomenon through experiments, theories, and computational models, focusing on different material properties affected by this process.

Generally, one of the material's property that seems related to this effect is the crystal structure, where hexagonal closed-package (HCP) materials show the greatest resistance to BD, followed by body-centered cubic (BCC) and, lastly, face-centered cubic (FCC) materials. This suggests a connection between BD event and the higher movement of dislocations in FCC materials. Therefore, the way materials deform may affect this phenomenon, especially during the electrode conditioning. This process consists on a slow increasing of the voltage to reach a maximum electric field. This process is done to prevent high BR rates (BDR): increasing voltage too quickly can lead to breakdowns happening after few pulses (high BDR), while starting from a lower voltage and gradually increasing it, won't significantly affect the number of pulses between breakdown events. This suggests that at low voltages, the electric field mostly induces elastic shocks on the electrodes and rarely causes BD events, if the process is gradual enough.

In this work, we use discrete dislocation dynamics (DDD) to explore the response of copper, the main candidate in accelerator techonology devices, when exposed to tensile stress (mimicking the electric field) under different schemes and plastic conditions.

Please choose topic that matches most closely your research:

Modeling and simulations

Field emission / 35

Investigating Field Emission and Vacuum Breakdown in a 300 kV Bushing Using Fast Frame Imaging, LIBS, and SEM

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Avalanche Energy's Orbitron, a next-generation compact fusion device, requires the reliable transmission of hundreds of kilovolts of direct current (kVDC) into a vacuum maintained at pressures below 10^{-8} Torr. To address this, a novel compact feedthrough is under development and successfully transmits voltages exceeding 300 kV. A major challenge in this effort is mitigating vacuum breakdown and surface flashover across the bushing's insulator. In order to achieve these high voltages, high-voltage conditioning experiments are conducted to eliminate field emission sites where these breakdown mechanisms often originate. This process can result in transient discharges, which can be destructive when they are of high frequency and intensity. This prompts further investigation into their underlying mechanisms. As such, experiments are carried out in which in situ high-speed

imaging captures these events in real time, while post-experimental analysis utilizes surface profilometry, laser-induced breakdown spectroscopy (LIBS), and scanning electron microscopy (SEM). These studies suggest that vacuum breakdown and surface flashover mechanisms are both influenced by contamination-induced field emitter formation and subsequent ablation on the cathode. Understanding these mechanisms is essential for improving the reliability of high-voltage bushings in fusion applications and represents a critical step toward a stable fusion plasma in the Orbitron.

Please choose topic that matches most closely your research:

Field emission

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Observing plastic evolution related to high-field conditioning

Author: Yinon Ashkenazy[1]

Co-authors: Iaroslava Profatilova ; Inna Popov ; Lee Millar [2]; Marek Jacewicz [3]; Sergio Calatroni [2]; Victoria Madeleine Bjelland ; Walter Wuensch [2]

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High-field breakdown has been associated with surface plastic evolution through models and observations that explore how breakdown rates depend on electric field strength and vary with the surface structure, composition, and temperature. Currently, there is no clear, direct observation of plastic activity related to this phenomenon. Initial isolated observations demonstrated the formation of dislocation-denuded zones in regions subjected to high electric fields, offering a potential link to surface conditioning.

Building on these initial findings, we aim to identify systematic changes in samples exposed to electric fields using Transmission Electron Microscopy (TEM) on both hard and soft copper. However, differentiating between the damage caused by sample preparation and the effects of field exposure is challenging, necessitating the use of various sample preparation techniques and trying to validate a consistent way to measure field exposure effects. Based on our current observations, we will discuss future work needed to form a systematic measurement of conditioning.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Field emission current evolution during cryogenic conditioning process

Authors: Mircea-George Coman[None]; Marek Jacewicz[1]; Iaroslava Profatilova[None]

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The maximum achievable accelerating field of both normal and superconducting cavities is limited by field emission and by vacuum arcs, but can be improved during a long conditioning process. That ultimate level is also greatly increased by lowering the temperature of the material. A consistent set of data for different materials and at a wide range of temperatures is needed in order to help understand the processes behind the nucleation of vacuum arcs and conditioning.

Our current understanding of the theory behind the conditioning process supposes that the vacuum arc breakdowns are a run-away process, initiated by field emission from nano-scale tips on the cathode surface. Multiple conditioning experiments have been carried out at FREIA laboratory, in Uppsala, using a cryogenic HV system. The field emission current has been measured at regular intervals during the conditioning process.

At cryogenic temperatures, the field emission current follows very well the Fowler-Nordheim theory. The field emission data can be fitted at each point during conditioning in order to extract the Fowler-Nordheim parameters (the effective area and the field enhancement factor). So far, it has been observed a clear decrease in field enhancement factor and a large increase in the effective area. In addition, for all materials, we have observed changes in the field emission currents that, as we currently believe, are due to hydrogen adsorbing on the nano-tips of the cathode surface.

The results from the cryo-DC system allow selecting the best material for given operational conditions (e.g. warm vs LN-cooled or LHe-cooled) for the HV electrodes and high-gradient devices and allow developing a strategy for the conditioning of the large number of high electric field devices to assure an extremely low spark rate during operation.

During this talk, results of the field emission measurements will be presented for different materials (Cu, Nb, Ti-6Al-4V, Au-platted Al).

Please choose topic that matches most closely your research:

Field emission

Poster session / 38

Novel method for measuring surface resistivity during conditioning

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Currently, the cryogenic HV DC pulsing system located at FREIA laboratory is used to investigate the conditioning process for different materials both at cryogenic and at room temperature. In order to understand the mechanisms that determine the increase in resistance to vacuum arcing during the conditioning process, new novel methods are needed to obtain as much information about the state of the system as possible.

Currently, we are developing a surface characterization method that consists in measuring the surface resistivity of the metal surface during the conditioning process. The surface resistivity will be measured by inducing, in addition to the HV DC pulses, a low-power, high-frequency (8.8 GHz) radio-frequency current in a parallel plate system. The system will act as a resonant cavity, and by measuring the quality factor of a resonant mode, we can obtain information about the surface resistivity. An increase in surface resistivity could indicate the formation of dislocation underneath the metal surface. It has been speculated that it plays a role in the conditioning process. The measurements need to be done at cryogenic temperature in order for the measurement to be sensitive

to the resistivity given by the dislocations, and they need to be done at high frequency in order to measure the changes near the surface and not in the bulk.

In this poster session, I will report on our progress in implementing this method into our system.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Investigation of Dark Current in Vacuum Pre-breakdown Phase

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Before vacuum breakdown occurs, there exists a pre-breakdown stage characterized primarily by field electron emission. The weak current associated with field electron emission is typically not observable through optical means, and is thus referred to as dark current. It is well established that the evolution of dark current can precipitate vacuum breakdown, playing a crucial role in the investigation of the intrinsic mechanisms underlying this phenomenon.
However, current research on dark current remains insufficiently comprehensive, lacking experimental observations and simulation studies concerning its development process. Therefore, this paper first examines the influence of different cathode geometries on electron emission. Subsequently, the study focuses on the transient simulations of a needle-plate electrode, which exhibits the most pronounced phenomena, investigating the time-dependent behavior of the electron emission current. Finally, two-dimensional images of electron emission under a weak electric field over extended periods are observed.
The research findings indicate a close correlation between dark current and the cathode shape parameter, β. Notably, dark current significantly affects β, with increases magnifying it by factors ranging from 4 to 10, resulting in a minimum three orders of magnitude increase in dark current. Simulation results reveal that space charge influences the electron emission current and induces noise fluctuations. The two-dimensional electron images demonstrate that random breakdown events typically occur following the appearance of bright spots in the electron spectra after prolonged exposure to weak electric fields. Importantly, these bright spots may dissipate without leading to breakdown, underscoring their critical role as precursors for random breakdowns. Furthermore, the fluctuations in the electron emission current exhibit no clear correlation with the bright spots but arise instead from space charge, which is consistent with simulation outcomes. These bright spots are indicative of localized electron bursts on the cathode surface, likely resulting from Joule heating induced by emission and the modification of the surface due to electric field forces. During the presence of bright spots, dark current may surpass the limitations imposed by space charge, ultimately leading to vacuum breakdown.

Please choose topic that matches most closely your research:

Field emission

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A high-resolution optical study of repetitive but random vacuum arc spot ignition

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Repetitive vacuum arc spot ignition is studied using an image-amplified, high resolution streak camera in combination with a long-distance microscope. A key feature of the experimental setup was the use of a magnetically steered arc, where the most likely path of the apparent spot motion is aligned with the direction of the camera's entrance slit. In this way, spot ignition events and spot lifetime in terms of optical emission of the spot plasma have been investigated with the goal to determine characteristic times of cyclic events should such characteristic times exist. The point was to verify and quantify statements such as "the characteristic lifetime of cathode spots is xxx microseconds or nanoseconds". The experiment did not identify any characteristic times, rather, a broad distribution of optical spot lifetimes. Fast Fourier transform analysis shows a linear distribution in a log-log plot of fluctuation intensity versus frequency, indicative for fractal properties. As with all fractal models in the physical world (as opposed to mathematics), cutoff consideration for self-similarity should be discussed. In the case of optical emission, the resolution cutoff is determined by the finite lifetime of excited states of the light-emitting particles (atoms and ions). We note that while the magnetically steered arc has a preferred direction of the apparent spot motion, the analysis of the individual streak images shows a random distribution of "steps"in both the retrograde and Amperian direction, which is a complication when trying to model the ignition of an arc spot based on the presence of plasma from a previously active plasma emission site.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Optical and electrical parameters for classifying arc mode and movement using TMF-contacts

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For research of new vacuum interrupter (VI) technologies like larger contact gaps or serial VI arrangement, optical and electrical investigations are conducted. The aim is to investigate the dynamics of vacuum arcs through computer-aided evaluation under different conditions. The dynamics of a vacuum arc, like arc mode, movement and contact erosion is influenced by different factors like current, gap and material. By selecting specific parameters related to vacuum arcs, the automation of the motion analysis of these arcs is targeted. Furthermore, a comprehensive database is being developed to enable global comparisons across diverse studies.

Preliminary investigations and analyses compare different factors and responses using black-box modelling techniques. Traditional examinations of current, voltage, and gap characteristics are augmented with optical analyses to identify the dynamics of the arc and its associated hot spots, as influenced by current charge and resulting contact erosion. A design of experiment approach is employed to generate regression functions that assess the factors exerting the greatest influence on various responses. This research contributes to a deeper understanding of arc behaviour in vacuum interrupters, facilitating advancements in the development of more efficient and reliable electrical devices.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Self-consistent Simulation of Post-arc Plasma Dynamics in Vacuum Circuit Breakers with Circuit Coupling

Authors: Jiaqi Zhao[None]; Rui Li[None]; Zhenxing Wang[None]

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The insulation recovery capability of vacuum circuit breakers after current interruption is fundamentally determined by post-arc plasma dynamics. Following current zero, the extinction of cathode spots terminates plasma generation, while residual plasma continues to evolve under transient recovery voltage (TRV). This process governs critical phenomena including post-arc current (PAC) generation and sheath formation. Current analytical approaches - including the Continuous Transition Model, Langmuir probe theory-based models, and conventional plasma simulations - face limitation in capturing the characterization of spatially distributed residual plasma.
This study proposes a novel co-simulation framework integrating three critical advancements: First, a hybrid plasma modeling approach that resolves the non-uniform plasma distribution through kinetic simulation. Second, self-consistent coupling between plasma dynamics and external circuit interactions to capture TRV's feedback effects. Third, an innovative 3D simulation architecture incorporating stochastic cathode spot extinction patterns to quantify residual plasma heterogeneity.
Through this integrated methodology, we successfully reproduce the complete TRV evolution process. The simulation quantitatively establishes two findings: (1) The identification of plasma density threshold governing zero-voltage phase termination (2) Correlation between cathode spot distribution patterns and dielectric recovery characteristics. These results provide new physical insights for optimizing vacuum interrupter design and developing more accurate post-arc predictive models.

Please choose topic that matches most closely your research:

Modeling and simulations

Poster session / 44

Phenomenological description and detailed modelling of vacuum breakdown

Authors: Camila Cró[None]; Helena Kaufmann[None]; Mikhail Benilov[None]; Nelson Almeida[None]; Pedro Almeida[None]

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Vacuum breakdown is an important limitation in the performance of many technical devices, such as high-voltage circuit breakers and particle accelerators. Field emission, the process through which electrons are emitted from a cold cathode under a strong electric field, is a necessary step in the development of breakdown. The average electric field in the gap between electrodes in breakdown experiments is insufficient to lead to field emission - enhancement of the applied electric field by a factor of 10^2 or higher is needed for breakdown to occur. Various theories of enhanced field emission have been proposed, such as mobile dislocations [1], plasmons [2] or nonmetallic electron emission [3], but the exact processes that lead to field emission from cold electrodes in vacuum are still not well understood. As breakdown develops, other mechanisms come into play, such as the transition

from field to thermionic emission, vaporisation, ionisation of the metal vapour and production of plasma and deformation of the electrode's surface.

A phenomenological description of field emission is used in this work. The surface electric field and the resulting emission current is given by the Fowler-Nordheim formula, from which the field enhancement factor - the ratio between the macroscopic (applied) electric field and the microscopic (enhanced) electric field - in a field emission centre can be determined. Simulations were done for a 2D axially symmetric, cylindrical copper cathode using COMSOL Multiphysics, using a numerical model that builds upon the works in [4, 5]. The surface electric field was increased over a time interval of 10 ns, until a maximum effective electric field of 10 GV/m was reached, and a limitation on the circuit's current was imposed, analogous to having an external circuit that containing a ballast, so that the maximum current would not rise to values much higher than around 30 A.
Calculations for a field emission centre with a radius of 1 μm show that during the first 5 ns, the current is zero and there is no heating. Then, as the field enhancement factor and consequently the electric field increase, there is a rise in the emission current density and the total current, and the cathode starts heating up. When high enough currents are reached, the external circuit has the effect of slightly lowering the effective electric field; the current continues to rise, but at a slower rate, and the temperature keeps increasing. Finally, after about 13 ns, we transition into the thermionic regime, the emission current density increases dramatically, the contribution from the sheath electric field leads to an overall increase of the field on the surface of the cathode, and the cathode heats up quickly, reaching the critical temperature of copper in less than 1 ns.

By varying the field emission centre radius, it was determined that field emission centres with radius of order of 1 μm are the most favourable for breakdown. Field emission centres that are larger (e.g., $\sim 10\ \mu$m) than this lead to emission current densities that are too low to lead to breakdown, and the total current, which is limited by the external circuit, would need to be much higher. Smaller field emission centres ($\sim$ 100 nm) lose heat too quickly, and a steady state is reached at a temperature that is too low.

In addition to this, calculations taking into account hydrodynamics and surface deformation were done. Comparing the simulated current with experimental current oscillograms, such as in [6], the simulated current is in reasonable agreement with the experimental data. The final results are to be presented at the conference.

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Acknowledgements
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Please choose topic that matches most closely your research:

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Study on glow-arc transition characteristics via a unified fluid model

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The excimer lasers are based on the formation of a large volume of uniform and stable glow discharge for high power injection efficiency and laser power gain, arc discharge mode should be completely avoided. In this work, a unified fluid discharge model is established and introduced to study the glow-arc transition characteristics. This model solves the continuity equation and energy conservation equation of electrons and heavy particles, as well as Poisson's equation coupled with the external circuit. The processes such as cathode electron emission, reaction enthalpy change, and cathode heat conduction are also considered. The model simulates the discharge process of an inter-electrode of 0.4 mm with argon across a wide range of pressures. Typical full-mode discharge current-voltage characteristics (CVCs) are obtained, containing a Geiger-Muller discharge regime, a Townsend discharge regime, a subnormal, normal, and abnormal glow discharge regime, and an arc regime. Based on this model, a study is conducted on the transition characteristics from glow to arc discharge. The results show that, with a constant discharge gap distance, the transition voltage (V_t) decreases while the transition current density (J_t) increases as gas pressure rises. Further research reveals that the V_t is inversely proportional to the J_t, meaning that the transition power density ($p_t = V_t \cdot J_t$) is constant. This research contributes to understanding the discharge mode transition mechanism in excimer lasers and provides the theoretical foundation for improving the output quality of excimer lasers.

Please choose topic that matches most closely your research:

Modeling and simulations

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Influence of X-ray radiation to the electric breakdowns

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As part of the FCC feasibility studies, it is observed that vacuum breakdown rates in septa systems are significantly higher than expected. The electric fields there are much lower than in many high field applications, such as CLIC where 100 MV/m macroscopic fields are exploited. This is in stark contrast with previous observations but can be explained by the fact, that strong X-ray radiation is present in these systems due to the synchrotron radiation.

In this study we follow the hypothesis that vacuum breakdowns are initiated by the formation of surface protrusions, created due to biased adatom diffusion in high electric field. We initially hypnotize that X-ray radiation will create sufficient amount of adatoms on the surface, finally leading

to the formation of sufficiently large surface modifications. We combine molecular dynamics, finite element analysis and X-ray simulations with Fluka to demonstrate strong foundation of this hypothesis. As such we see that X-ray radiation can act as catalyst of vacuum breakdown, providing strong support for the theory that biased diffusion is fundamental mechanism behind the initiation of vacuum breakdowns.

Please choose topic that matches most closely your research:

Modeling and simulations

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Nanowires as a model structure for diffusion experiments

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One of the problems arising with linear accelerators such as CLIC [1] is the breakdown phenomenon [2] causing damage to the accelerating structures and disturbances in the accelerated beam. The cause of the vacuum breakdowns is still under investigation and the electrodes are regularly investigated for clues. One possible explanation for the cause of breakdowns is the hypothesis stating the formation of nanoprotrusions in the electrodes. These protrusions can enhance the local electric field, being a possible cause of breakdowns, but up to this point protrusions on the electrode surfaces have not been observed.
To study the possibility of metal tip formation by atom diffusion, nanowires (NW) can be used as model structures. Metal NWs, either Cu, Ag or Au, can be heated up to observe diffusion processes. Heating in different configurations and environments with varying heating times and applied temperatures results in restructuring of the NWs [3-5]. Restructuring occurs at temperatures much lower than the melting temperatures of the metals being studied mostly resulting in spherical particles.

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Please choose topic that matches most closely your research:

Poster session / 50

PIC-DSMC Simulations of Plasma Dynamics and Expansion During Vacuum Arc Initiation

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Recent work on vacuum discharge with electrodes held at cryogenic temperatures [1] found interesting anode breakdown spot morphology that exhibited a "shielded"region at the center of the spot where melt did not occur. If the surface melt is due to electron energy flux, then the observed anode spot feature suggests a central region where the electron flux is excluded. This bears a striking resemblance to the electron focusing dynamics observed in simulations of high energy beam transport through a background gas [2]. In this work we use Sandia's Particle-In-Cell (PIC) Direct Simulation Monte Carlo (DSMC) code, Empire, to perform 3D simulations of vacuum arc initiation accounting for the observed arc properties in the FREIA cyrogenic discharge experiments and examine the evolution of the arc plasma and energy flux to the anode in order to understand the observed anode features.

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Please choose topic that matches most closely your research:

Modeling and simulations

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Simulating electrostatic forces under electric fields using machine learning

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High electric field systems, such as Compact Linear Collider accelerating structures, are susceptible to electric breakdowns or plasma arcs. Spontaneously forming surface protrusions or field-enhancing tips are currently assumed to be the main factor initiating the arc. While the evolution of the plasma arc is relatively well understood, the formation of the tips is still unclear. Several theories try to explain this, such as subsurface dislocation activities or electric field-biased surface diffusion. To understand the magnitude and influence of biased surface diffusion, electrostatic forces induced by electric fields must be characterized in local atomic environments -these forces depend on the polarization characteristics of the surface atoms and the electric field profile. Calculating dipole moment and polarizability of the atoms by density functional theory (DFT) is computationally expensive and not affordable for molecular dynamics (MD) simulations. This study proposes a machine learning method based on Gaussian Process Regression (GPR) using a new tailored descriptor to predict the local dipole moment, polarizability, and field-induced forces. The model is trained based on the dataset produced by DFT. The descriptor presented in this study is based on smooth overlap of atomic positions (SOAP). Because of the rotational equivariance properties of the dipole moment, the descriptor should not be rotationally invariant. Therefore, we have added a rotation part to the SOAP descriptor derived from the principal axes of the local atomic environment represented as quaternions. The new descriptor is agile and affordable because it has only four more parameters than SOAP and paves the way towards doing MD simulations under an electric field with DFT accuracy.

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Monte Carlo simulations of vacuum breakdown occurrence dynamics and statistics

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Although substantial experimental data exist on Vacuum Breakdown (VBD) occurrence, conclusive insights into the underlying physical mechanisms remain evasive. One key obstacle is that many existing VBD models operate on a microscopic scale, preventing direct quantitative comparisons with experimental observations. Most microscopic mechanisms proposed to explain VBD cannot make predictions that are directly comparable and testable versus macroscopic observations of VBD occurrence statistics and related experiments. This work is an initial attempt to address this missing link by modeling VBD as a sequence of stochastic events using a Monte Carlo approach. This Monte Carlo approach can evaluate several proposed mechanisms on the dynamics of VBD occurrence. Here we propose and simulate a mechanism that is based on the following assumptions:

1. The metal surface is locally characterized by an applied electric field (E), a power coupling impedance (Z), and a surface state parameter (β), which represents the field enhancement factor of the sharpest protrusion.
2. Surface state deteriorates (β increases) randomly at a constant rate
3. During each pulse, a surface protrusion can undergo Thermal Runaway (TR) with probability proportional to the field-emitted current density.
4. A TR can either lead to VBD occurrence or "silently" destroy the protrusion that caused it, thus improving the local surface state. The probability of a TR leading to VBD depends on the local applied electric field and the local power coupling impedance value Z.

5. After a VBD occurrence, the surface is considered to be locally "reset," i.e., its surface state is randomly sampled.

Our model's predictions align well with experimental data on current spike statistics and accurately reproduce the conditioning curves observed in large electrode VBD systems.

Please choose topic that matches most closely your research:

Modeling and simulations

Poster session / 53

High Gradient Exposure of Additive Manufactured Electrodes

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Additively manufacturing (AM) is becoming a viable solutions to difficult milling. However, it is unknown how well it can hold high electric fields. Therefore, a pair of AM electrodes were fabricated to test the field holdings of the material. Results indicate field holding of 45% comparable to diamond machined electrodes.

Please choose topic that matches most closely your research:

Experiments and diagnostics

Poster session / 54

Dielectric Voltage Holding and its Triple Point Investigation

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CERN's specialized short pulsed DC test stand, called the LES, have been adapted to test the voltage holding of dielectric materials. Events such as current spikes, pressure increase and light events were recorded. Not only can we measure the maximum applied voltage across the material, but also indicate distinct behavior and help understanding how to handle the material without permanently reducing the votlage limit.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Updates on Conditioning and Field Emission studies from CERN's pulsed DC experiment.

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A fast pulsed DC system at CERN is used to study the origin of breakdowns, called the Large Electrode System (LES). Not only will we update the field holding of a list of materials (irradiated and non-irradiated), but also present results from field emission studies. Other specialized experiments will be covered and focus will be placed on two distinct studies. The first, is the Field Dependence on Conditioning. A specialized frustum shaped anode was made, varying the spatial electric field over the cathode surface. Due to the breakdown localization cameras, we can in real time place the breakdowns and realte them to the exposed electric field. The results shown, give the first experimental insights into the relation between conditioning and breakdowns. Second, we will focus on the experimentally observed realtion between observed field emitters and breakdowns. No clear correlation between the two phenomenons were observed.

Please choose topic that matches most closely your research:

Experiments and diagnostics

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Longitudinal Electromagnetic (EM) Force Demonstration and its Role in Vacuum Arc Mechanisms including Ion Jet Acceleration

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The main purpose of this work was to investigate historical claims of the existence of a net longitudinal EM force component acting on metallic atomic current elements in a direction parallel to the current flowing through them. This is not a component of the Lorentz force and thus lies outside textbook physics predictions, yet its existence has been indicated previously and if eventually confirmed and accepted will have a significant effect on all technological applications involving high current density (>109 A/m2). Vacuum arc cathode spots as well as many other existing pulsed power technologies from railguns to foil accelerators, and high energy plasma devices including fusion, may consequently be affected by this new area of physics knowledge. The claim of the existence of a longitudinal EM force component has been under investigation for over 200 years without definite resolution. The features that distinguish the experiment discussed here [1] from previous attempts elsewhere were the combination of (a) high-fidelity continuous force measurement on a small copper element embedded within a liquid metal circuit section and (b) a relatively low DC current density (~106 A/m2). The coaxial geometry limited all measured on-axis forces to the direction of interest, namely parallel to the current. Multiple experimental phases allowed it to distinguish between the EM and mechanical forces acting on the test armature. The data related the net axial force on the armature to the current flowing through the circuit and deliberately excluded current streamline convergence and divergence as an explanation. The raw and processed results are presented, and it

was possible to discriminate between the axial mechanical contact forces and the longitudinal EM force, thereby adding supporting evidence to the claim of its existence. The original EM force law, proposed in 1822 by Ampère, has been found to be consistent with all EM experiments to date including these reported findings and is considered a candidate explanatory theory.
A vacuum arc ion acceleration calculation based on Ampère's force law was published in 1993 [2] and accurately predicted the velocity and high anisotropy of the ion jet from copper vacuum arc electrodes without consideration of the currently favoured isotropic gas pressure gradient and electron ion friction models or the now less popular potential hump model. It successfully related ion momentum to the material dependent cathode spot current, predicted the measured equal and opposite electrode reaction force and also provided a possible explanation of cathode spot retrograde motion. Despite being rarely cited, this novel electromagnetic Ampère force arc mechanism will be briefly presented. Although not yet explored, a longitudinal EM force is likely to be a dominant mechanism in other vacuum arc and circuit breaker mechanisms such as electron emission and the electrode "blow off"force and possibly more. It is hoped this presentation will inspire future modelling in these areas, leading to enhanced understanding of EM forces and vacuum arc product developments.

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Please choose topic that matches most closely your research:

Experiments and diagnostics

Field emission / 57

A Data-Driven Model for the Prediction of Field Emission Current from Broad-Area Electrodes

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Field emission is fundamental to electron microscopy, vacuum interrupters, and high-gradient structures in vacuum. However, conventional models based on the Fowler-Nordheim and Murphy-Good equations often fall short when applied to broad-area electrodes in real-world conditions. Their predictive effectiveness is limited due to their heavy dependence on precise data on emission site geometry and the micro- and nano-scale constituents on the surface.
To address these challenges, this work introduces a machine learning-based approach for predicting total field emission current. By leveraging over 259 hours of experimental data, electrostatic simulations, and material surface characteristics, this model significantly improves prediction accuracy. A key achievement so far is the development of a data-driven model capable of predicting total field emission current from broad-area electrodes with a coefficient of determination exceeding 98%. Various supervised machine-learning techniques were explored, with gradient-boosting regression proving particularly effective in capturing complex nonlinear relationships between cathode voltage, current, electric field distribution, and material properties. Unlike traditional curve-fitting methods, this approach provides high-fidelity predictions, making it a valuable tool for optimizing high-voltage designs for vacuum applications.

Please choose topic that matches most closely your research:

Field emission

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Exploring the sensitivity of vacuum arc models to anode generated bremsstrahlung radiation with PIC simulations

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Modeling vacuum arcs with accuracy depends on coupling multiple physical processes together. Current particle-in-cell (PIC) simulations of vacuum arcs include the effects of collisions, electromagnetic fields, and some surface processes that mediate the evolution of the arc. However, photons generated from energetic electrons hitting the anode are often not included. Such bremsstrahlung generated photons could be a significant source of secondary electrons or cathode surface modification. Here we couple an Empire PIC model of a vacuum arc with a model for bremsstrahlung radiation from the anode to test how sensitive the discharge is to the resultant photoemission from the cathode across a range of applied voltage (and gap sizes) between 1kV and 100kV.

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Modeling and simulations

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Development of a high-gradient thermionic electron gun for a future X-ray free-electron laser

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The 500-kV pulsed DC thermionic electron gun with a single-crystal CeB6 cathode is being used for the X-ray free-electron laser (XFEL) SACLA in Japan. In order to increase brightness of the gun beam for higher XFEL output, we are developing high-gradient accelerating electrodes to increase the surface and gap electric fields because they are indispensable to increase emission density of the electron beam and to avoid the space charge effect which can deteriorate the beam emittance. Recently, we have succeeded to achieve more than 40-MV/m surface field in a few micro-second pulse. The electrodes were made of ultra-pure titanium with hot-isostatic-pressure process and final surface treatment using chemical etching. Such high field have never been achieved in our gun by using clean-stainless steel and molybdenum. We will present the R&D status of the gun, especially experimental results of the high voltage performances.

Please choose topic that matches most closely your research:

Applications

Poster session / 66

Development of Field Emitters for High Power Vacuum Electron Devices and Linear Accelerators

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Vacuum tube-based RF sources, such as those used in linear accelerators, plasma heating systems, and advanced imaging applications, critically depend on the performance of electron emitters—particularly with respect to longevity, efficiency, and reliability. Field emitter (FE) technologies offer several advantages that make them especially suitable for these high-frequency devices: they eliminate the need for external heating, enable high average current densities, and support uniform, copious electron emission with nonlinear current-voltage characteristics. These properties are especially beneficial in pulsed and high-repetition-rate applications typical of LINACs and vacuum electron devices (VEDs). Moreover, field emitters contribute to sustainability by reducing the use of critical or rare materials. Advancements in field emitter technology accelerate the development of RF sources for accelerators and heating systems and imaging and support broader applications such as electron microscopy, precision instrumentation, and compact X-ray sources.
Among various types, metal field emitters are particularly crucial for both VEDs and linear accelerators due to their ability to provide high current densities at room temperature, significantly improving startup times and reducing power consumption. Their robust mechanical and thermal stability under ultra-high vacuum and high-voltage conditions make them ideal for long-term operation in devices such as klystrons, CFAs, magnetrons, and LINAC RF guns. Metals such as tungsten, molybdenum, and stainless steel (e.g., SS316) offer excellent resistance to ion bombardment, arcing, and chemical degradation—factors that enhance emitter durability and reduce system failure rates. Additionally, metal emitters are compatible with modern fabrication techniques, such as additive manufacturing, enabling the creation of complex designs and scalable, cost-effective production. This also supports sustainability goals by minimising the use of coated, fragile, or rare-material cathodes.

To harness these advantages, I have developed a 3D-printed cathode using stainless steel 316 (SST316), which provides a robust and efficient platform for designing, prototyping, and integrating field emitters in next-generation vacuum electron devices and compact linear accelerator systems.
In our preliminary studies, we applied a voltage of −12 kV across a 1 mm anode–cathode gap. The field emitter, consisting of 29 needles with a diameter of 0.4 mm each, delivered a total current of 58 μA. This corresponds to a current of 2 μA and a current density of approximately 1.59 mA/cm² per needle.

Please choose topic that matches most closely your research:

Field emission

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High gradient RF activities in SXFEL

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The Shanghai X-ray Free Electron Laser (SXFEL) has entered scientific operation. As the main accelerator, the C-band linac currently operates at an average gradient of 37.1 MV/m, achieving a peak gradient of 41.7 MV/m in one unit. However, the existing linear section length is insufficient to meet future energy upgrade requirements under this gradient regime. To address this limitation, research on advanced high-gradient structures, such as the cryogenic RF structures, has been initiated. This work details the design, commissioning, and experimental performance of novel RF technologies in SXFEL, focusing on their role in enabling next-generation accelerator capabilities.

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Investigation of Metal Particles Sources and Motion Characteristics in High-Current Interruption

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Delayed breakdown in high-current vacuum interruption has emerged as a critical technical challenge restricting the development of high-voltage vacuum interrupters (HVIs). This study focuses on the origin and motion characteristics of metal particles during the post-arc phase, aiming to investigate their potential role as triggers of delayed breakdown. An optical diagnostic platform integrating laser shadow imaging and infrared thermography was established to enable full-process observation of metal particle behavior and electrode surface activity. Experimental results show that metal particles emitted from the cathode molten pool are generally larger in size and slower in speed, and can remain suspended in the post-arc gap for tens to hundreds of milliseconds. These particles typically follow inertial and stable trajectories, without notable reversal or abrupt deviation. This study proposes an intrinsic correlation between the long-term presence of metal particles and the occurrence of delayed post-arc breakdown. The findings suggest that larger particles are more likely to cause dielectric recovery failure in HVIs with wider gaps and higher voltage ratings. Future work will focus on clarifying the formation mechanisms and developing control strategies to improve the reliability of high-current interruption.

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Enhanced Vacuum Gap Insulation Between Non-Arc Metal Components in Vacuum Interrupters by Ion Implantation

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High-voltage and high-capacity vacuum interrupters adopt a multi-stage floating shield structure, which can be regarded as an insulation system consisting of multiple vacuum gaps connected in series and parallel. Breakdown occurs not only in the vacuum gap of the main contact but also in unintended regions such as the gaps between shields or between shields and conductive rods. To improve the overall insulation performance of the vacuum interrupter, treatment of non-arc metal surfaces is required. This paper investigates ion implantation on the surfaces of stainless steel ball-to-ball and ring-to-ring electrodes, which are then installed in the vacuum interrupter to simulate non-arc metal gaps. The experiments compare the effects of different types, doses, and acceleration voltages of implanted ions on breakdown voltage improvement. Surface analyses were conducted to examine the surface morphology and elemental composition of the electrodes before and after ion implantation. The results indicate that ion implantation effectively increases the initial breakdown voltage of vacuum gaps. However, as the number of breakdown events increases, the implanted ion layer gradually deteriorates. The improvement in voltage withstand capability is influenced by ion species, implantation dose, and acceleration voltage. The underlying mechanism is attributed to the enhancement of the electrode surface work function due to metal ion implantation. This work provides a theoretical foundation for enhancing the performance and miniaturization of high-voltage vacuum interrupters.

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Characterization and Localization of Vacuum Breakdowns in RFQ

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In 2020, following a successful commissioning phase, CERN's Linear Accelerator 4 (Linac4) became the primary proton source for the CERN accelerator complex. The first accelerating structure in Linac4 is a 3-meter-long Radio-Frequency Quadrupole (RFQ), operating at an inter-vane voltage of 78 kV and a peak surface electric field of 34 MV/m. In 2025, a dedicated campaign was launched to condition and test a new RFQ, offering a valuable opportunity to investigate vacuum breakdown behavior in a structure with significantly different characteristics.

This poster presents preliminary results from studies aimed at understanding breakdown (BD) limitations in the new RFQ. In addition, it focuses on localizing breakdown events using signals from 16 antennas distributed along the cavity. These measurements are compared with RF simulations to correlate signal patterns with breakdown locations and gain insight into the underlying physical processes.

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