9th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2021)

Report of Contributions

https://indico.cern.ch/e/966437

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

Electrostatic discharges on very large spacecrafts solar panels: coupled model of a cathode spot and flash-over expansion in vacuum

The increase of the onboarded power on Spacecraft is actually still limited by the charging issue due to the plasma natural environment. The charging of the external dielectrics is due to the complex geometry, the number of different materials and the presence of biased conductor. It leads to a high potential difference on solar cells edges that can reach several kilo-volts. In this conditions, an electrostatic discharge (ESD) may appear. The ESD emits a current called a flash-over that will expand on the surface of the solar panel. It takes the form of a plasma bubble i.e. a conductor environment in which secondary arcs may appear. Our objective is to identify the duration and extinction conditions of the flash-over. Indeed, it has been shown that the plasma bubble can cover panels a few meters long but there is no clue about bigger ones (some dozen of meters long). Based on known literature, we tailored cathode spot and plasma expansion in vacuum models to our specific case and coupled them. Both models are developed in parallel to create a closed system without free parameters other than the ESD initial position and the initial charging state of the solar panel surface (obtained from the known environment).

We present the coupled cathode spot-plasma expansion model, detailing the physical assumptions made to fit to our particular environment and close our system. The cathode spot model is developed for different materials and we focus on the impact of the cathode spot on the extinction of the flash-over. The results of the coupled model are compared to experimental measurements of flash-over expansion on large solar panel area performed at ONERA's facilities. Those measurements reveal that the extinction occurs before the complete neutralization of the charge. We show that, even-though the cathode spot has a direct impact on the plasma bubble lifetime, the characteristics of the solar panel also have its influence on the flash-over extinction.

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Presenter: MONNIN, Loanne

Session Classification: Field emission

Contribution ID: **3** Type: **Virtual Poster**

Analysis of surface temperature dynamics of switching vacuum arc contacts

Wednesday, 10 March 2021 16:45 (20 minutes)

The advantages of the vacuum technology such as environmental compatibility and emission-free solutions make the vacuum interrupters attractive for switching applications in power grids. The lifetime of the contact system is mainly limited by accumulated thermal load of the electrode surface. Therefore, various measures are applied for the reduction of this load. Two types of electrode systems are widely used for the control of arc behavior. Radial magnetic field (RMF) contacts induce the arc rotation, thus, reducing the arc dwell at local position. Axial magnetic filed (AMF) contacts maintain a diffuse arc causing the overall thermal load reduction.
This contribution presents the results of comparative study of typical RMF and AMF contact systems used in vacuum interrupters at similar operation conditions. An AC current pulse with a peak value up to 28 kA and frequency of 50 Hz was used. Electrodes were made of CuCr alloy. Conventional 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 anode 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 anode surface temperature. Special attention was put on the cooling dynamics after current interruption. The results for measured evolution of anode surface temperature will be presented and discussed.

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Session Classification: Poster Session

Contribution ID: **4** Type: **Virtual Poster**

Study of X-ray spectra emitted during High Voltage DC conditioning in high vacuum

Wednesday, 10 March 2021 15:45 (20 minutes)

High voltage insulation across a single gap in vacuum and low-pressure gas is a critical issue in relation to the development and realization of the electrostatic accelerator for the ITER Neutral Beam Injector (NBI).
The present paper describes and analyzes the recent experimental results obtained at the High Voltage Padova Test Facility (HVPTF), the laboratory aimed at supporting the development of the Beam Source of MITICA, the prototype of the ITER NBI now at the beginning of the commissioning phase, in Padova

The high voltage conditioning procedure is an in situ treatment based on progressively increase of the voltage with frequent breakdown aimed at reaching the ultimate voltage holding, by eliminating the sources of breakdown located on the surface of the electrodes (microtips, particles, adsorbed gas) insulated by high vacuum (<10-3 Pa).
High voltage conditioning procedure, though the high-voltage insulation in vacuum technology dates back to the beginning of the last century, has still remained more an empirical knowledge than a consolidate technology. As a matter of fact a large amount of literature has been dedicated to this topic, but so far a consolidated explanation of the physical phenomena appearing during the voltage conditioning doesn't exist yet.
HV conditioning is featured by electron emissions and gas desorption processes. This paper focuses on the rich phenomenology associated to the X-ray emission during HV conditioning due to the bremsstrahlung radiation of energetic electrons impinging the electrode surfaces. An interesting results is the possibility to measure the electron component of the current. The method allows to measure the fast transient (electron) current bursts (always associated to the voltage conditioning) which cannot be measured with nA ammeter.
The technique adopted to observe the time evolutions of X ray emissions up to fractions of ms is the Time-Correlated Single Photon Counting (TCSPC). The analysis of the TCSPC appears a promising, not invasive method, to identify, in a multi electrode system, the stage where pre-breakdown currents and microdischarges are present.
The X-ray spectra measured at the HVPTF are interpreted by a simple analytical model based on the Kramer equation, extended to any multi-electrode system insulated by high vacuum gaps like the MITICA electrostatic accelerator.

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Session Classification: Poster Session

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

General scaling laws of space charge effects in field emission

Wednesday, 10 March 2021 14:00 (30 minutes)

The characteristics of field electron and ion emission change when the space charge formed by the emitted charge is sufficient to suppress the extracting electric field. This phenomenon is well described for planar emitting diodes by the one dimensional (1D) theory. Here we generalize for any 3D geometry by deriving the scaling laws describing the field suppression in the weak space charge regime. We propose a novel corrected equivalent planar diode model, which describes the space charge effects for any geometry in terms of the 1D theory, utilizing a correction factor that adjusts the diode's scaling characteristics. We then develop a computational method, based on the Particle-In-Cell technique, which solves numerically the space charge problem. We validate our theory by comparing it to both our numerical calculations and existing experimental data, either of which can be used to obtain the geometrical correction factor of the corrected equivalent planar diode model.

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Presenter: VESKE, Mihkel

Session Classification: Field emission

Contribution ID: **6** Type: **Virtual Poster**

FEbeam: A Comprehensive Field Emission Data Processing for Field Emission and Breakdown Analysis in RF Environment

Wednesday, 10 March 2021 16:35 (25 minutes)

As the ubiquity of field emission sources becomes more prevalent in that a variety of cathode materials and geometries are being tested or used, an easy-to-use data processing pipeline FEbeam was developed, and it is a part of the FEmaster platform [1-3]. This algorithm processes and converts raw data to the standard format enabling further physics interpretation: combining 17 different subroutines, it processes the raw waveforms obtained from the bidirectional coupler and Faraday cup into the final field emission parameter space, Fowler-Nordheim and Millikan coordinates. FEbeam's modular design also allows for direct interfacing with FEpic, an image processing software to determine the number of emitters from images that can be obtained in situ at AWA's ACT facility, while providing postprocessing analysis options and can be completely automated when paired with FEbreak. FEbeam was originally designed for ACT but can be extended for using in any RF system with ease. This algorithm also uses a knee point selection to search if cathode emission behavior diverge from Fowler-Nordheim law. Thus, FEbeam is a useful tool enhancing the ease of development for the next generation of field emission injectors.

References:
[1] E. Jevarjian, M. Schneider, and S. V. Baryshev, arXiv:2009.13046
[2] T. Y. Posos, O. Chubenko, and S. V. Baryshev, arXiv:2012.03578
[3] M. Schneider, E. Jevarjian, J. Shao, and S. V. Baryshev, arXiv:2012.10804

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Presenter: SCHNEIDER, Mitchell (Los Alamos National Laboratory)

Session Classification: Poster Session

Contribution ID: **7** Type: **Oral**

FEbreak: A Comprehensive Diagnostic and Automated Conditioning Interface for Analysis of Breakdown and Dark Current Effects

Friday, 12 March 2021 15:00 (30 minutes)

As breakdowns are a major concern in the use of vacuum electronics systems and DC/RF accelerators, there is a need then to be able to characterize these breakdowns and measure the probability rate during conditioning of these devices in real time [1,2]. This results in the need for a software that can automate the conditioning process. Such automation could allow for high accuracy calculations of the breakdown probabilities associated with the conditioning process which can be used to instruct the conditioning procedure without the need of human intervention or human error. This led to the development of FEbreak which is part of the FEmaster platform [3,4,5] and is a breakdown software module for statistics collection and conditioning automation. FEbreak directly interfaces with the rest of FEmaster to automate the data collection and data processing to not only analyze the breakdown probability but also the dark current effects associated with these high gradient structures. FEbreak uses a combination of Matlab and NI measurement studios to allow for a modular design that can be interfaced with the variety of diagnostics and can perform the breakdown analysis and controlling of klystron power with adjusted??? timeframe. At the moment, the diagnostics that are interfaced are the pressure controls, temperature controls, breakdown probability rate, and the Faraday cup current. A detailed concept and early results will be presented.

References:

[1] E. I. Simakov, V. Dolgashev, S. G. Tantawi, NIMA 907 221 (2019)

[2] D. Shiffler, S. Fairchild, W. Tang, B. Maruyama,K. Golby, M. LaCour, M. Pasquali, and N. Lockwood, IEEE Trans. Plasma Sci. 40, 1871 (2012)

[3] E. Jevarjian, M. Schneider, and S. V. Baryshev, arXiv:2009.13046

[4] T. Y. Posos, O. Chubenko, and S. V. Baryshev, arXiv:2012.03578

[5] M. Schneider, E. Jevarjian, J. Shao, and S. V. Baryshev, arXiv:2012.10804

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Session Classification: Experiments & Diagnostics

Contribution ID: **8** Type: **Virtual Poster**

FEgen v.1: Fowler-Nordheim Equation Based Initial Particle Distribution Freeware for Advanced Beam Dynamics Simulations

Wednesday, 10 March 2021 16:10 (25 minutes)

As field emission effects play critical role in the physics of breakdown, modelling these effects is a critical aspect to better understand and mitigate breakdown. Proposed here is an initial particle distribution generator called FEgen version 1 (based on the time dependent Fowler-Nordheim equation), a part of the FEmaster platform which is a comprehensive toolkit for field emission diagnostics, modeling and analysis [1,2,3]. FEgen is an open-source python code that creates initial field emission distributions both in the pulsed dc and rf power environments. For further tracking, generated files can be directly imported into beam dynamics software such as IMPACT-T [4] and GPT [5] which currently do not have any built-in field emission modeling capabilities. Compared to costly PIC codes like Michelle [6] and VSim [7], demonstrated combination FEgen and GPT is ease to use and can be customized for a variety of different scenarios which cannot be done with proprietary commercial PIC codes. FEgen allows for the modeling of not only uniform geometries but also grid and custom pattern of emission which is been shown to match recent experimental measurements [1]. Work is being done to extend FEgen toward newer version, where non-planar/asperity geometry, temperature and semiconductor effects can be taken into account to build realistic energy and momenta particle distributions.

References:

[1] E. Jevarjian, M. Schneider, and S. V. Baryshev, arXiv:2009.13046

[2] T. Y. Posos, O. Chubenko, and S. V. Baryshev, arXiv:2012.03578

[3] M. Schneider, E. Jevarjian, J. Shao, and S. V. Baryshev, arXiv:2012.10804
[4] https://amac.lbl.gov/jiqiang/IMPACT-T/
[5] http://www.pulsar.nl/gpt/

[6] J. Petillo et al., IEEE Trans. Plasma Sci. 30, 1238 (2002)
[7] https://www.txcorp.com/vsim

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Session Classification: Poster Session

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

Quantum regime of field emission based on exchange-correlation effects in a nanogap

Wednesday, 10 March 2021 14:30 (30 minutes)

Considering quantum effects of field emission in a nanogap, we explore the impact of space charge on the field emission current density by using one dimension quantum model which includes exchange-correlation effects and space-charge effects. It is found that the quantum effect is significant within a certain range of applied voltage and gap. Therefore, the quantum regime, high current regime, direct tunneling regime, low current regime and transition regime are divided according to the continuous change of applied voltage and gap for a metal-vacuum-metal system at nanoscale. The smooth transition among these regimes are also demonstrated.

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Session Classification: Field emission

Contribution ID: **10** Type: **Virtual Poster**

Low-Z anode wires testing for particle accelerator electrostatic septa

Wednesday, 10 March 2021 16:05 (20 minutes)

In a quest to identify low density materials for anode wires to be used in electrostatic septa for accelerator particle beam extraction, a basic test set-up was constructed at CERN. The set-up re-uses many components of the former LEAR electrostatic injection septum to limit the cost. As such, it inherits design features from the former septum, such as a displacement system for the anode and the 200 kV high voltage feedthrough. A short new cathode was designed that will allow applying high voltage while minimising field amplification. An existing wire support, serving as the anode, was used to fix anode wires similarly to the clamping system used in the operational septa devices.
This paper outlines the conceptual design of the test set-up as well as the detailed electrode design, before presenting the first experimental results of High Voltage tests with low-Z anode wires, such as carbon nanotube (CNT) and titanium and aluminium alloy wires.

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Presenter: BORBURGH, Jan (CERN)

Session Classification: Poster Session

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

An integrated approach to understanding RF vacuum arcs

Friday, 12 March 2021 17:15 (30 minutes)

Almost 120 years after the isolation of vacuum arcs, the exact mechanisms of the arcs and the damage they produce are still being debated. We describe our simple and general model of the vacuum arc that can incorporate all active mechanisms and aims to explain all relevant data. Our four stage model, is based on experiments done at 805 MHz with a variety of cavity geometries, magnetic fields, and experimental techniques as well as data from Atom Probe Tomography and failure analysis of microelectronics. The model considers the trigger, plasma formation, plasma evolution and surface damage phases of the RF arc. This paper also examines how known mechanisms can explain the observed sharp field dependence, fast breakdown times and observed surface damage. We update the model and discuss new features while also pointing out where new data would be useful in extending the model to a wider range of frequencies.

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Presenter: NOREM, Jim (Argonne Labs (retired))

Session Classification: Modelling and simulations

Contribution ID: **12** Type: **Virtual Poster**

Hydrogen accumulation in copper: hydrostatic effect on dislocations

Thursday, 11 March 2021 16:45 (20 minutes)

When metal surfaces are exposed to the hydrogen ion irradiation, light ions are expected to penetrate deep into the material and dissolve in the matrix. However, these atoms are seen to cause significant modification of surfaces indicating that they accumulate in vicinity of the surface. The process known as blistering may reduces the vacuum dielectric strength above the metal surface, which shows dense population of surface blisters.

In order to study this effect, we use molecular dynamics to investigate the effect of the different pressures and void geometries. This will shed light on the dislocation formation and its role in the change of the surface morphology.

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Session Classification: Poster Session

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

Silicon Field Emitter fabrication by TMAH Etching of convex/concave corners

Thursday, 11 March 2021 14:30 (30 minutes)

Recently a novel fabrication method of silicon field emission arrays (FEAs) was introduced by Edler et al. [1], [2]. By combining wafer saw dicing with anisotropic wet chemical etching a versatile, inexpensive and easy reproducible manufacturing process is being presented. In accordance to literature the formation of the tips is explained by the differing etching rates of silicon crystal facets in tetramethylammonium hydroxide (TMAH) solutions and the etching behavior of TMAH towards convex and concave corners [3], [4]. It is shown that the density and size of the tips within the 4x4 mm2 arrays can be defined by adjusting the diameters of the square based silicon pillars structured by the dicing saw. Electrical I-E measurements at 10-5 mbar and emission currents up to 10 µA show reproducible characteristics of n- and p-doped FEAs fabri-cated with the same dicing parameters. The onset fields of the investigated n-type FEAs start at a few V/µm. Due to the fabrication process a higher tip density leads to a smaller height to radius ratio and variation of the individual tips. Despite the thereby expected decline in field enhancement emission currents of 10 µA are initially reached below 10 V/µm for FEAs with high tip densities. Constant current measurements of different FEAs at 10 µA and 10-5 mbar also suggest a connection between the tip quantity and the degradation over time, which is measured by the shift of the field necessary to obtain the regulated current. Lower degradation rates are measured for higher tip quantities as well as for p-doped FEAs compared to n-doped. Furthermore, it was found that the degradation is partly reversible for n-doped FEAs by heated opera-tion at 200 ℃, whereas the p-doped emitters degraded further through heated emis-sion.
In order to investigate the influence of the aspect ratio an additional process step is being introduced. It is shown that the emission properties of the FEAs can be altered by structuring pillars of different heights underneath the etched tips. Finally, a method to further increase the tip density is being presented. By replacing the pillar structu-ration before etching with a lithography step followed by a dry etching Bosch process the tip densities can be increased beyond the capabilities of the dicing saw.

References
[1] S. Edler et al., "Silicon field emitters fabricated by dicing-saw and wet-chemical-etching,"J. Vac. Sci. Technol. B, vol. 39, no. 1, p. 013205, Jan. 2021, doi: 10.1116/6.0000466.
[2] S. Edler et al., "Silicon Field Emitters fabricated by Dicing-Saw and TMAH-Etch,"in 2020 33rd International Vacuum Nanoelectronics Conference (IVNC), Jul. 2020, pp. 1–2, doi: 10.1109/IVNC49440.2020.9203262.
[3] P. Pal and K. Sato, "A comprehensive review on convex and concave corners in silicon bulk micromachining based on anisotropic wet chemical etching,"Micro Nano Syst. Lett., vol. 3, no. 1, 2015, doi: 10.1186/s40486-015-0012-4.
[4] K. Tokoro, D. Uchikawa, M. Shikida, and K. Sato, "Anisotropic etching properties of silicon in KOH and TMAH solutions,"Proc. Int. Symp. Micromechatronics Hum. Sci., no. May, pp. 65–70, 1998, doi: 10.1109/MHS.1998.745752.

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Session Classification: Field emission

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

Monte Carlo Model of High-Gradient Conditioning and Operation

Friday, 12 March 2021 15:45 (30 minutes)

High-voltage accelerating structures (and other vacuum devices) are limited by the occurrence of vacuum arcs. To operate reliably such components must be subjected to a conditioning process in which the operating voltage is slowly increased over time while monitoring for arcs. This process is performed at great temporal and monetary expense, typically requiring millions of RF pulses or several months of runtime and if performed incorrectly can irreparably damage the components under test.

In most facilities the process is performed based on operator experience and, in this context, a new simulation tool to investigate and optimise the conditioning process for future high gradient-facilities is under development. An outline of the model will be presented followed by preliminary results, a comparison with experimental data, and plans for the future.

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Presenter: Mr MILLAR, Lee (Lancaster University (GB))

Session Classification: Modelling and simulations

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

Real-time observation of strong electric-field-induced surface modification

Tuesday, 9 March 2021 15:45 (30 minutes)

When a metal surface is exposed to a high heterogeneous electric field, surface modifications may occur, leading to the appearance of new, as well as the reconstruction of existing, fine surface features that can act as field emitters. This, on the one hand, is an undesirable process in crucial applications like the CLIC [1] accelerator in CERN, where it causes electrical breakdowns on Cu electrodes. On the other hand, this opens the opportunity for unique surface engineering and the design of novel nanostructures.
Our study is dedicated to the experimental investigation of the processes occurring on metal surfaces under strong electric field in vacuum conditions, in order to gain deeper insights and better control over the electric-field-induced surface modifications. Our intent is to create the conditions for controlled emitter formation and growth in predetermined locations on Cu surface with immediate visual feedback in order to get better understanding of the process. For this, experiments are performed inside a scanning electron microscope (SEM), relying on the advanced nanomanipulation platforms [2], [3]. The investigated samples are placed under a strong electric field generated locally by a counterelectrode attached to a piezo-positioner. Since the high voltage applied to the investigated objects disturbs the e-beam, strong electric fields will be achieved at small voltages via decreasing the curvatures of both the sample and counter-electrode and by reducing the separation distance between them. The use of sharp probes enables reaching extreme local electric field gradients at low voltages due to curvature effects. With curvatures and separation of a few tens of nm, the required field strength is achieved at voltages in the range of 10 V. Localized sample heating by fiber-fed laser irradiation in SEM can be used to boost surface diffusion.
Besides modification of the metal surfaces, a strong non-uniform electric field can affect other processes, such as the deposition of carbon-based molecules ionized by e-beam, a common process inside SEM. In the absence of an external field, deposition is uniform. However, the introduction of a highly localized electric field would direct the ionized molecules to the desired location. It opens opportunities for creating fine conductive surface features with a high degree of control.

References

[1] T.K. Charles, others, The Compact Linear Collider (CLIC) - 2018 Summary Report, CERN Yellow Rep Monogr. 1802 (2018) 1–98. https://doi.org/10.23731/CYRM-2018-002.
[2] S. Vlassov, B. Polyakov, L.M. Dorogin, A. Lõhmus, A.E. Romanov, I. Kink, E. Gnecco, R. Lõhmus, Real-time manipulation of gold nanoparticles inside a scanning electron microscope, Solid State Commun. 151 (2011) 688–692. https://doi.org/10.1016/j.ssc.2011.02.020.
[3] S. Vlassov, B. Polyakov, L.M. Dorogin, M. Antsov, M. Mets, M. Umalas, R. Saar, R. Lõhmus, I. Kink, Elasticity and yield strength of pentagonal silver nanowires: In situ bending tests, Mater. Chem. Phys. 143 (2014) 1026–1031. https://doi.org/10.1016/j.matchemphys.2013.10.042.

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Presenter: VLASSOV, Sergei

Session Classification: Experiments & Diagnostics

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

Copper Surfaces: Comparative Studies in Cryogenic High Fields

Monday, 8 March 2021 16:30 (30 minutes)

Recent tests have been carried out in a cryogenic pulsed high-voltage system in the FREIA Laboratory to investigate the aptness of heat-treated (soft) copper and non-treated (hard) copper as a candidate for CLIC accelerating structures. The surface of the soft copper electrodes was exposed to high electric fields in the range from room temperature to cryogenic temperatures. We calculate the saturation field at different temperatures and will show the improvements of the maximum attainable electric field for the sample that underwent conditioning in the cryogenic environment. We will also compare the results for the soft and hard copper at different temperatures, and discuss the ricochet effect of decreasing electric field after saturation. In addition, field emission experiments were conducted at several temperature points, before and after conditioning, where emitted current was measured as a function of ramping voltage. We will present the trends we observed during the analysis of the data using Fowler-Nordheim theory.

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Session Classification: Experiments & Diagnostics

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

Application of Machine Learning to Breakdown Prediction in CERN's High-Gradient Test Stands

Wednesday, 10 March 2021 16:25 (20 minutes)

Vacuum arcs (breakdowns) limit operation in high-gradient accelerating structures and other high-voltage vacuum devices. To investigate the phenomenon a collaboration has been established at CERN to explore the application of machine learning in the CLIC (Compact Linear Collider) high-gradient test stands.

Currently, a machine learning framework has been developed to analyse the test stand data with the objective of predicting the occurrence of vacuum arcs in CERN's high-gradient prototype accelerating structures. The results may then shed light on the fundamental physics of vacuum arcs and aid in the development of operational tools to improve reliability in modern high-gradient accelerator facilities.

A general overview of the ongoing work is presented, highlighting the motivation for applying machine learning, its potential utility, and plans for the future.

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Presenter: Mr MILLAR, Lee (Lancaster University (GB))

Session Classification: Poster Session

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

In-situ plasma cleaning of Cu surfaces for reducing the generation of vacuum arc breakdowns

Monday, 8 March 2021 17:00 (30 minutes)

One of the major topics in the vacuum arcing community during the recent years has been the balance between the bulk and surface effects on the breakdown generation.

In our recent study, argon and oxygen plasma were used to clean the surfaces of copper electrodes prior exposing them to high-voltace DC pulses and breakdowns. This was done without the need to open the vacuum and expose the electrodes to air in between the cleaning and pulsing.

The plasma cleaning is shown to reduce the number of surface impurities and to speed up the conditioning process of the Cu samples. Especially the achieved electric field until the first breakdown was observed to increase by nearly 100 %.

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Presenter: SARESSALO, Anton (Helsinki Institute of Physics (FI))

Session Classification: Experiments & Diagnostics

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

New Development of BIRD model

Tuesday, 9 March 2021 16:45 (30 minutes)

The possibility that the flow of electrons emitted by a cathode at high dc voltage is essentially due to local emission of a covering dielectric layer is at the basis of the BIRD (Breakdown Induced by Rupture of Dielectric) model. This model assumes that, in presence of sufficient electric field, the electrons trapped in polarization structures of the dielectric layer are extracted by quantum tunneling effect. As a consequence of the layer electron depletion, the electric field inside the dielectric layer increases and the rupture (breakdown) of the layer itself can occur, provided certain conditions are met. To investigate experimentally the features of this model the High Voltage Short Gap Test Facility (HVSGTF) has recently been built in Padua. The experimental dark current measured at different electrode configurations permits us to test the correctness of the model predictions. In particular, we consider the trend of the current as a function of time and its dependence on the characteristic properties of the dielectric layer. From the theoretical side, we investigate the consistency between a semi-classical model and a simple quantum model.

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Presenter: SPADA, Emanuele (Consorzio RFX)

Session Classification: Experiments & Diagnostics

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

Nano-tendril bundles behavior under plasma-relevant electric fields

Thursday, 11 March 2021 16:45 (20 minutes)

Plasma-wall interaction is one of the most critical factors determining plasma parameters in fusion devices. Plasma parameters, material properties, and morphology of plasma-facing components (PFCs) determine this interaction. PFCs must satisfy the needed requirements, such as operation under high thermal and particle irradiation. In the case of tungsten (W) PFC, its surface morphology may change under helium plasma impact, which results in the formation of helium bubbles [1], tungsten fuzz growth [2], or the formation of nano-tendril bundles (NTBs) [3]. The change in the PFCs morphology can dramatically influence the plasma-wall interaction. The appearance of tungsten fuzz increases arc ignition probability [4], leading to an enhanced erosion of PFC.

NTBs are intertwined fibers of fuzz that grow on a tungsten surface at temperatures from 870 to 1300 K due to irradiation of helium plasma that contains impurities (e.g., Ne, Ar, N2) with incident ion energies from 70 to 350 eV [5,6]. These structures can reach a height up to 100 µm with a tip radius of 10 nm and a bottom radius of 10 µm. If these structures cover the surface of PFC, the electric field near NTBs tips can be significantly enhanced. A strong local field can lead to the initiation of field emission from the surface covered by NTBs. As these structures consist of fuzz fibers, they are easily overheated due to the reduced thermal and electrical conductivity [7]. The rise of the structure's temperature due to Ohmic heating by the field emission current can lead to the initiation of thermofield emission, in which current density is higher than both thermal and field separately. Further avalanche-like rise of emission current can initiate an explosive emission with NTBs destruction and erosion of the surface.

In this work, we studied the behavior of NTBs under external electric fields experimentally and with computer modeling. Experimental results were obtained in the vacuum diode. We found that the emission current from NTB samples can reach the value of several 100 µA depending on the geometry of structures. Additionally, experiments revealed the electric field critical value's existence, reaching which led to the destruction of the main emitters on the sample. The modeling was used to study the behavior of a single NTB with different geometries under an externally applied electric field. The Laplace equation was solved for the determination of electric field distribution. The time-dependent heat transfer equation, including Joule heat source, radiation losses, and Nottingham effect, was investigated to study the possibility of the destruction. The obtained results show the possibility of NTBs destruction under plasma-relevant electric field leading to increased erosion.

[1] H. Iwakiri, K. Yasunaga, K. Morishita, N. Yoshida, Microstructure evolution in tungsten during low-energy helium ion irradiation, J. Nucl. Mater. (2000). doi:10.1016/S0022-3115(00)00289-0.
[2] M. Baldwin, R.P. Doerner, Helium induced nanoscopic morphology on tungsten under fusion relevant plasma conditions, Nucl. Fusion. 48 (2008) 35001. doi:10.1088/0029-5515/48/3/035001.
[3] K.B. Woller, D.G. Whyte, G.M. Wright, Impact of helium ion energy modulation on tungsten surface morphology and nano-tendril growth, Nucl. Fusion. (2017). doi:10.1088/1741-4326/aa67ac.
[4] D. Hwangbo, D. Nishijima, S. Kajita, R.P. Doerner, S.A. Barengolts, M.M. Tsventoukh, H. Tanaka, N. Ohno, Ignition and Sustainment of Arcing on Nanostructured Tungsten under Plasma Exposure, IEEE Trans. Plasma Sci. (2019). doi:10.1109/TPS.2019.2910839.
[5] D. Hwangbo, S. Kajita, N. Ohno, P. McCarthy, J. W Bradley, H. Tanaka, J.W. Bradley, H. Tanaka, Growth of nano-tendril bundles on tungsten with impurity-rich He plasmas, Nucl. Fusion. 58 (2018). doi:10.1088/1741-4326/aacd1f.
[6] D. Hwangbo, S. Kajita, H. Tanaka, N. Ohno, Growth process of nano-tendril bundles with sputtered tungsten, Nucl. Mater. Energy. (2019). doi:10.1016/j.nme.2019.01.008.

[7] S. Kajita, T. Yagi, K. Kobayashi, M. Tokitani, N. Ohno, Measurement of heat diffusion across fuzzy tungsten layer, Results Phys. (2016). doi:10.1016/j.rinp.2016.10.025.

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Session Classification: Poster Session

Contribution ID: **22** Type: **Oral**

Application of the Voltage Holding Prediction Model to floating and fixed shield vacuum interrupters

Friday, 12 March 2021 16:15 (30 minutes)

The Voltage Holding Prediction Model (VHPM) is a design technique formulated at Consorzio RFX that combines numerical modelling and experimental data in order to calculate a breakdown probability curve. The cuve is based on the two parameters Weibull distribution for any multi-electrode multi-voltage vacuum insulated system under dc voltage. The progresses in employing the VHPM to predict the Lightning Impulse Voltage Waveform (LIVW) breakdown probability of medium voltage Vacuum Interrupter (VI) are the subject of the present contribution. A new experimental campaign on two Siemens VI models have been carried out at the high voltage laboratory of the Industrial Engineering Department of the Padua University. The use of a convenient methodology of experimental data acctual, called Always Breakdown method, allowed to improve the quality of the data obtaining a well fitted Weibull distribution of the voltage breakdown. This topic is described in detail in another contribution.
The analysis of the two different VI models, with different key features, allowed a better understanding of the ability of the VHPM to describe different physical arrangements and explain the resulting breakdown behavior. This contribution describes the analyses carried out on the two models, in different conditions such as electrodes gap, polarity and maximum applied LIVW voltage, with the Weibull shape and scale parameters (m and W0) calculated by fitting the experimental data for the two tube models, in order to assess the prediction capability of the proposed method. Reason of measurement-prediction discrepancy is supposed to be sought in an arc onset-peak voltage delay time affecting the correct interpretation of the experimental measurements used to estimate m and W0. Preliminary analysis on this specific topic, as well as an assessment of the influence of the parameters adopted in the physical model are also described.

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Presenter: PATTON, Tommaso (Consorzio RFX)

Session Classification: Modelling and simulations

Contribution ID: **23** Type: **Oral**

Kinetic Simulation of the Plasma Dynamics in the Post-arc Stage

Tuesday, 9 March 2021 15:00 (30 minutes)

In this work, a two-dimensional (2D) particle-in-cell/Monte Carlo collisional (PIC/MCC) model is developed to simulate the plasma decay and re-breakdown in the post-arc stage of vacuum circuit breakers. The field distribution is obtained by solving the Poisson's equation in 2D cylindrical coordinate and the positions of charged particles, which are traced as super particles to save the calculation time and computer memory, are given by Newton's law. Various collisions between charged particles and neutrals including elastic scattering, impact excitation and ionization are treated with MCC method. The grid size and time step satisfy the constraints given by the Debye length and plasma frequency. Results show that the plasma residual from the arcing stage gradually expands under the transient recovery voltage in the post-arc stage. An ion sheath forms near the post-arc cathode where the field is significantly enhanced. When the residual metal vapor is considered in the simulation, the plasma propagation is lowered by the collisions between charged particles and metal neutrals. The residual plasma is restricted in the inter-electrode region. When the metal vapor density further increases, the electrons emitted from the post-arc cathode surface could lead to re-breakdown in the post-arc stage.

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Presenter: WANG, Dan

Session Classification: Modelling and simulations

Contribution ID: **24** Type: **Oral**

Characterization of the breakdown voltage of vacuum interrupters by different procedures

Tuesday, 9 March 2021 17:15 (30 minutes)

This work compares three different procedures for the application of the Lightning Impulse Voltage Waveform (LIVW) with 1.2/50 μs front/half value times: Up & Down (UD), Always Breakdown (AwBD) and Multilevel (ML) to obtain the voltage breakdown distribution for Vacuum Interrupters (VIs).
The voltage pulses were applied to several VIs for medium voltage application with both fixed and floating shield with gap lengths ranging from 4mm to 15mm. The repeatability of the results for a given procedure was investigated and the results compared.
The AwBD procedure, where the peak voltage of each pulse is set and kept at the same arbitrary high level to collect a breakdown for each pulse, was thoroughly investigated. This procedure is effective to collect data on many breakdowns very quickly, due to both the speed of the voltage conditioning phase and because breakdown data are collected for each pulse. Furthermore, the memory effect due to the status of the previous pulse (BD or withstand pulse) is reset due to the random distribution of surface microprotrusions produced by the arcing occurrence at each pulse. In contrast, for the ML procedure the status of the ith-pulse depends on the status of the (i-1)th-pulse. On the other hand, the AwBD procedure showed a dependency of the breakdown voltage distribution curves on the set peak voltage applied. This phenomenon has been investigated and might be explained by a delay time between the breakdown onset and the voltage collapse on the rising front of the pulse, where the slope (dV/dt) of the LIVW depends on the chosen set peak voltage. However, the results suggested that after having identified the proper delay time, the results can be corrected providing a similar breakdown voltage distribution independent on the set voltage and close to that obtained with the UD procedure.

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Presenter: Dr D.TAYLOR, Erik (Siemens AG, Smart Infrastructure)

Session Classification: Experiments & Diagnostics

Contribution ID: **25** Type: **Virtual Poster**

Polarization characteristics of adatoms diffusing on W{110} surface under applied electric field

Thursday, 11 March 2021 16:25 (20 minutes)

In this work, we continue looking into polarization characteristics of surfaces in the presence of adatoms by means of density functional theory. We follow the changes of these characteristics during possible transitions of an adatom as an event of self-diffusion on the W{110} surface. We analyze the dependencies of these characteristics on the environment of the adatom when it jumps towards and away from small adatom islands. We calculate effective dipole moment and polarizability of W adatom at hollow and bridge sites and compare these with the dipole moments and polarizabilities of the system as a whole.

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Presenter: BAIBUZ, Ekaterina (University of Helsinki)

Session Classification: Poster Session

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

A New Experimental Method of beta Estimation

Thursday, 11 March 2021 15:00 (30 minutes)

In this talk, I will present a new experimental method of beta estimation that allows for a field-dependent estimation of beta for the first time to our knowledge. I will present the theory behind the method as well as how to use the code supplied for its implementation.

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Presenter: LACHMANN, Sagy Itschak (Hebrew University of Jerusalem)

Session Classification: Field emission

Contribution ID: **27** Type: **Oral**

Light and Electron Emission as Breakdown Probes in X-band rf microscope

Friday, 12 March 2021 14:00 (30 minutes)

Various modern applications rely on maintaining high electric fields in miniaturized environments surrounded by metallic electrodes. High fields trigger the breakdown and arc that may produce (instantaneously or accumulatively) serious physical damage and put long term operation of a high-field device at risk. There is a particular and critical need in accelerator R&D to understand vacuum breakdown and arc. Looking into 2023-2028, the normal conducting rf roadmap lists the achievement of the accelerating gradient in excess of 300 MV/m as a top priority. C- to X-band systems, planned to utilize those high accelerating gradients, are in development for future colliders, high brightness X-ray sources, or therapy systems. Breakdown and arc are a critical issue in that it hinders the progress of increasing the operating accelerating gradient in high power rf systems.

Studying breakdown directly inside an accelerating or high field structure/environment is the most difficult but most effective way to study fundamental processes underlaying the breakdown phenomenon. Because breakdown takes place on micrometer length scale in macroscopic rf cavities, microscopy and spectroscopy with high lateral resolution and sensitivity have been applied in dc and rf environments to study breakdown in situ, in real time that measured dark current and light emission and arc expansion accompanying/triggering breakdown.

Despite profound experimental and computational work, a basic argument still remains whether final/terminating stage of the breakdown and arc is thermally driven or not. To study and refine this argument and extend prior in situ microscopy findings, we designed a test cavity setup of the field emitter at the X-band frequency. The rf configuration includes an X-band cavity operating at the TM02 mode. The field emitter material is plated with various materials that are suitable to enhance the Nottingham heating channel and thus to attempt to find its relation to breakdown. The gun has two viewing ports to conduct microscopy and spectroscopy at the location of the emitting tip, and a Faraday cup to measure the output current as a function of the gradient. Part of the back plate as well as the emitter rod are demountable from the cavity, allowing for exchange of the field emitter. The TM02 mode was chosen such that the design of the demountable back plate does not induce field enhancement at the installation gap. The field in the gap is also negligibly small. We optimized the depth of the insertion rod and the cavity gap to achieve a macroscopic gradient well above 100 MV/m and a maximum energy gain of the emitted electrons. We will present the rf and mechanical design of the cavity and results of beam dynamics associated with its operation.

Work at MSU was supported by DOE under Award No. DE-SC0020429 and under Cooperative Agreement Award No. DE-SC0018362. Work at SLAC was supported by DOE under contract No. DE-AC02-76SF00515.

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Presenter: BARYSHEV, Sergey

Session Classification: Experiments & Diagnostics

Contribution ID: **28** Type: **Virtual Poster**

Field Emission Microscopy of Diamond and Nanotube Materials

Wednesday, 10 March 2021 15:45 (25 minutes)

Spatially resolving electron emission from field emission cathode surface is a crucial step to characterize and quantify emission uniformity and emission area, and therefore, beam brightness and current density. It is especially important for mm-wave/terahertz sources for which narrow beam is a must, or for miniaturized field emission devices where high current density is required. It is also important to compare theoretical and experimental results that can only be connected through using the electric field and current density.

With these intentions, we developed experimental and computational methodologies that allow us to transversely image electron beams in dc and rf environments, evaluate and assess emission properties that include quasi time resolved breakdown dynamics and emission area, as well as perform realistic end-to-end beam dynamics of field emission that are in excellent agreement with imaging.

Examples of field emission microscopy and associated breakdown behavior of diamond and nanotube materials will be given. Additional emphasis will be placed on a fast image processing algorithm that can detect number of emitters and calculate emission area. Obtained results demonstrate deficiency of using Fowler-Nordheim (FN) law to describe emitters but, at the same time, allow to propose new hypotheses to overcome the existing deficiencies. High field high charge behavior of emitters beyond FN law will be given using details of charge transport through emitter bulk and 2D emission physics of the emitter surface.

Work at MSU was supported by DOE under Award No. DE-SC0020429 and under Cooperative Agreement Award No. DE-SC0018362.
Work at ANL was supported by DOE under contract No. DE-AC02-06CH11357.

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Presenter: Mr POSOS, Taha Y. (Michigan State University)

Session Classification: Poster Session

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

Characterization of Cu electrodes after vacuum breakdown with AFM and SEM

Tuesday, 9 March 2021 16:15 (30 minutes)

Cu electrodes are widely used in accelerators, for example in CLIC [1]. One of the problems arising in the accelerator 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 regularly investigated for clues.
In this study a Cu cathode with its surface covered with vacuum breakdown craters, was characterized with an Atomic force microscope (AFM) and a scanning electron microscope (SEM). The AFM was equipped with a Kelvin probe allowing for mapping of surface potential along with surface topography. Different areas of the electrode surface were characterized including both breakdown craters and plain Cu surface. The mapping was performed in ambient conditions with the probe revealing no major differences between the craters and undamaged Cu surface. The SEM imaging of the surface revealed various surface features including protrusion-like and sphere-like structures that are probably caused by rapid melting and solidification of the Cu electrode surface during the breakdown. These structures are an interesting subject for studying as they can potentially contribute to subsequent breakdowns.

[1] Compact Linear Collider (CLIC), last accessed 31 Jan 2021, URL: http://clic.cern/
[2] A. Palaia et al. "Effects of rf breakdown on the beam in the Compact Linear Collider prototype accelerator structure", Physical Review Special Topics - Accelerators and Beams, 16, 8 (2013) 081004. 10.1103/PhysRevSTAB.16.081004

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Presenter: ORAS, Sven (University of Tartu)

Session Classification: Experiments & Diagnostics

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

Identification of Dislocation Structure in Cu Electrodes

Monday, 8 March 2021 16:00 (30 minutes)

It was suggested that breakdown initiation is directly linked to plastic activity in electrodes and specifically to dislocation motion leading to surface evolution. However, the exact mechanism by which various surface and subsurface electrode structural features affect the highest sustainable fields remains unknown. In the present talk, we will show the characteristic features of "intrinsic" dislocation structures observed in the hard and soft Cu electrodes prior to the BD tests. In addition, we will characterize the details of dislocation structures developed in the post-BD samples. The interrelation of pre- and post-BD dislocation landscape and the possible mechanism of dislocation –related field enhancement will be discussed.

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Presenter: POPOV, Inna

Session Classification: Experiments & Diagnostics

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

Micron-scale Field Emission Model for PIC-DSMC Simulations Based on Nanoscale Surface Characterization

Thursday, 11 March 2021 16:05 (20 minutes)

We present a model for stochastic, micron-scale field emission for use in Particle-In-Cell Direct Simulation Monte Carlo (PIC-DSMC) simulations of vacuum discharge. PIC-DSMC simulations of mm-sized electrodes cannot resolve atomic-scale (nm) surface features and therefore we generate micron-scale probability density distributions for an effective "local"work function, field enhancement factor, and emission area. Each micron-scale surface element in the PIC-DSMC simulation draws independent values from the atomic scale measured distributions for local work function and topological field enhancement factor (beta). In the present work, we use data from atomic-scale (nm) surface characterization using Scanning Tunneling Microscopy (STM), Atomic Force Microscopy (AFM), and Photoemission Electron Microscopy (PEEM) to generate a representative probability density distribution of the work function and field enhancement factor (beta) for a sputter-deposited Pt surface. We compare simulated Fowler-Nordheim field emission currents from the (˜nm) mesh-resolved, as-measured surface with the currents generated using the micron-scale model on a coarse mesh with a perfectly flat representative surface. Some effort has been made to compare emission currents for the coarsened model to equivalent current densities from atomic-scale STM current measurements.

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Presenter: MOORE, Chris (Sandia National Labs)

Session Classification: Poster Session

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

Pulsed DC Large Electrode System Study of the effects of H- Irradiation on Breakdowns

Monday, 8 March 2021 15:15 (30 minutes)

In order to determine if beam loss damage can induce breakdown, tests have been done in the pulsed DC system at CERN. This system consists of 2 large surface area high precision machined electrodes that are placed in parallel to each other with a gap between 40um and 100um, under high vacuum. The systems are dedicated to studying electrical breakdown phenomena and conditioning processes. A copper OFE electrode for this system received the same heat treatment as the RFQ and a small area was irradiated using the same energies of H- as estimated for the RFQ. The electrode was then placed in the system acting as a cathode to observe whether the irradiated area had an impact on the breakdown locations, with pulsing parameters as similar to the RFQ as possible. A test was done in parallel with using electrodes of the same material with the same heat treatment to serve as baseline. The main differences observed is an increase in the number of breakdowns during the initial conditioning that reduced with further running. SEM and FIB observations were performed before and after the experiments, and are discussed in another talk. Further tests are foreseen with copper and with alternative materials (CuCrZR an Nb as first candidates)

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Presenter: PEACOCK, Ruth (Lancaster University (GB))

Session Classification: Experiments & Diagnostics

Contribution ID: **33** Type: **Oral**

Theoretical study of field emission from dielectric coated surfaces

Wednesday, 10 March 2021 15:00 (30 minutes)

Electron field emission plays an essential role in a wide range of applications, such as, electron microscopes, X-ray sources, high power microwave sources and amplifiers, vacuum micro-electronics, and emerging nano-electronics [1-5]. Ultra-thin coatings are fabricated onto metallic cathodes to provide chemical and mechanical protection, and longer current stability, smaller turn-on electric field and enhanced current emission due to the lowering of the effective potential barrier [6], [7]. There is still lack of systematic analysis on the parametric scaling of field emission from coated surfaces and the interplay of various parameters to optimize the design of coated field emitters.

In this study, we develop an exact analytical theory for field emission from the dielectric-coated cathode surface, by solving the one-dimensional (1D) Schrödinger equation subject to the double-barrier introduced by the coating layer. The effects of dc electric field, cathode properties (i.e. work function and Fermi level) and dielectric coating properties (i.e. dielectric constant, electron affinity and thickness) are analyzed in detail. It is found the emission current density can be larger than the uncoated case in certain coating conditions. Our quantum model is also compared with a modified Fowler-Nordheim equation [8], [9] for double-barrier, showing qualitatively good agreement in the scaling of the emission current density. The model is also extended to study photoemission and photo-assisted field emission from coated emitters [7]. The theory provides insights for designing field emitters with higher efficiency and better stability.

Work supported by AFOSR YIP Award No. FA9550-18-1-0061 and ONR YIP Grant No. N00014-20-1-2681.

[1] F. Houdellier et al., Ultramicroscopy, 151, 107–115 (2015).
[2] E. J. Radauscher et al., IEEE Trans. Electron Devices, 63(9), 3753–3760 (2016).
[3] G. Cao et al., Phys. Med. Biol., 54(8), 2323–2340 (2009).
[4] P. Zhang et al., Appl. Sci., 8(7), 1175 (2018).
[5] P. Zhang et al., Appl. Phys. Rev., 4, 011304 (2017).
[6] L. W. Swanson and R. W. Strayer, J. Chem. Phys., 48(6), 2421–2442 (1968).
[7] X. Xiong et al., ACS Nano, 14(7), 8806–8815 (2020).
[8] Q. Huang, J. Appl. Phys., 79(7), 3703–3707 (1996).
[9] P. D. Keathley et al., Ann. Phys., 525(1–2), 144–150 (2013).

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Presenter: ZHANG, Peng (Michigan State University)

Session Classification: Field emission

Contribution ID: **34**		Type: **Oral**

Ab initio investigation of Cu nanoparticle behavior under high electric field

Friday, 12 March 2021 16:45 (30 minutes)

Metal cathodes have inevitable surface defects, such as dust, protrusions or small-scale roughness caused by manufacturing. Under high electric field, these defects will generate local electric field enhancement, that can help to initiate vacuum breakdown. When in large, the classical vacuum breakdown mechanism has already been clarified, it demonstrates that small protrusions could be vaporized under external electric field and leave a breakdown crater, the exact mechanism how such tips could form and lead to local electric field enhancement is still unexplained. As such, we consider that extreme electric field could interact with the electronic structure of the metal atoms, thus distorting the classical interatomic potentials (used in molecular dynamics) and opening a way to field enhanced surface diffusion.
In the current study, we investigate several Cu nanoparticle systems using the Gaussian DFT package. Gaussian allows us to focus on nonperiodic structures, thus opening the possibility to extend the understanding of electric field influenced surface behavior beyond structures of the size of a few atoms. The investigated systems consist of a Cu dimer and different nanoparticles such as 1FCC, 2FCC and 4FCC structures. Already simple energy scan of Cu dimer under field, shows a noticeable change in the interatomic potential. In order to get generalized results, the scale of simulation models is increased. Larger systems, such as nanoparticles consisting of 1FCC, 2FCC and 4FCC unit cells, demonstrate a significant field dependent straining that can cause even bending. While the current study focuses on the electric field effects on nanoparticles, our results strongly indicate that electric field may have strong influence to large scale surface defects as well.

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Presenter: WANG, Ye

Session Classification: Modelling and simulations

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

Investigation of Vacuum Breakdown in Pulsed DC Systems

Tuesday, 9 March 2021 14:30 (30 minutes)

Vacuum breakdown in the pulsed DC experiment at CERN was investigated by means of electrical measurements, SEM and STEM imaging of the surface and cross sections of the copper electrodes, and numerical modeling. The breakdown sites comprise one or more craters. There is plastic deformation beneath the craters.

The crater(s) represent the epicenter of the breakdown, where electron emission and vaporization of the metal occur, and the plasma ball is formed. The only possible mechanism of ionization of neutral vapor seems to be ionization by the emitted electrons. The pressure exerted by the plasma ball is responsible for the formation of the crater. This physical picture is generally similar to what was seen in simulations of formation of cathode spots in vacuum arcs under conditions typical for, e.g., circuit breakers and unipolar arcs in fusion devices. There is, however, a very important difference. There are external factors provoking the formation of cathode spots in vacuum arcs (the plasma cloud left over from an (extinct) spot that previously existed in the vicinity of the (new) spot being ignited) [1], and the ignition of unipolar arcs (plasma instabilities which deliver high energy and particle fluxes to the plasma-facing components) [2]. There is no such external agent which would facilitate the breakdown in the CERN experiment. Therefore, the breakdown voltage is by orders of magnitude higher than in vacuum and unipolar arcs. Moreover, the breakdown is dominated by field electron emission, which is irrelevant in vacuum and unipolar arcs and enhancement of the field on cathode microprotrusions must be a decisive effect.

Simulations have been started with the aim to describe the mechanisms of vacuum breakdown on copper cathodes with protrusions of different geometries. The numerical model used in these simulations is based on that of works [1, 2]. At the present stage of the work, simulations of the initial phase of breakdown were performed for copper electrodes with a 20 μm gap between them. Different geometries of field-enhancing protrusions have been modeled: an ellipsoidal protrusion with a height of 5 μm and a base radius of 0.5 μm; a conical protrusion with a height of 5 μm, a 60° full aperture angle and a spherical tip (various values of the radius R of this tip were used). It should be stressed that while the ellipsoidal protrusion is slender and in line with protrusions usually considered in the modelling of vacuum breakdown (e.g., [3]), the conical protrusion is not slender, and the electric field amplification is due to high values of the ratio of the height of the protrusion to the tip radius.

First results show that, while Joule heating is initially a minor effect, together with the Nottingham effect, it may lead to a rapid increase of the protrusion temperatures up to the critical temperature, which may be indicative of a microexplosion. Very thin protrusions are not critical for the initiation of a microexplosion and subsequent breakdown; rather, the breakdown may be initiated by significantly wider ridge-like structures. The numerical model will be further developed so as to describe the whole evolution of the breakdown in vacuum.

[1] H. T. C. Kaufmann, M. D. Cunha, M. S. Benilov, W. Hartmann, and N. Wenzel, "Detailed numerical simulation of cathode spots in vacuum arcs: interplay of different mechanisms and ejection of droplets", J. Appl. Phys., vol. 122, p. 163303, 2017.
[2] H. T. C. Kaufmann, C. Silva, and M. S. Benilov, "Numerical simulation of the initial stage of unipolar arcing in fusion-relevant conditions", Plasma Phys. Control. Fusion, vol. 61, p. 095001, 2019.
[3] A. Kyritsakis, M. Veske, K. Eimre, V. Zadin, and F. Djurabekova, "Thermal runaway of metal nano-tips during intense electron emission", J. Phys. D: Appl. Phys., vol. 51, p. 225203, 2018.

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Session Classification: Modelling and simulations

Contribution ID: **36** Type: **Virtual Poster**

Quantum oscillations as a possible way of the increasing pre-breakdown field emission current

Thursday, 11 March 2021 15:45 (20 minutes)

The quantum-mechanical problem of the motion of electrons through a potential barrier with an additional near-surface dipole layer is considered. An analytical generalization of the Fowler-Nordheim formula, for such potential barriers, was made. Using such a model is a way to consider the influence of vacancies and pores existing in the surface layer of a metal on the field emission current density. A new effect in the theory of field emission current was discovered: quantum oscillations of the current depending on the thickness of the covering layer on the metal surface or voids inside the metal surface.

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Session Classification: Poster Session

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

ANALYZING EXPERIMENTAL DATA ON INGINITION OF CORONA DISCHARGES AND BREAKDOWN ON POSITIVE ELECTRODES IN HIGH-PRESSURE AIR FOR DIAGNOSTICS OF SURFACE MICROPROTRUSIONS

Thursday, 11 March 2021 14:00 (30 minutes)

Analysis of deviations from the similarity law, observed at high and very high pressures in experiments on discharge ignition and breakdown in corona-like configurations, can serve as a useful, albeit inevitably indirect, source of information about microprotrusions on the surface of electrodes.

Current-voltage characteristics of field electron emission from cold cathodes in vacuum follow approximately the Fowler-Nordheim formula with the applied electric field being multiplied by the so-called field enhancement factor β, which is of the order of 100 or higher. Various mechanisms for the enhancement have been postulated, among them an enhancement of the applied (average) electric field by microprotrusions present on the cathode surface, a local reduction of the work function of the cathode material caused by, e.g., lattice defects or adsorbed atoms, 'nonmetallic' electron emission mechanism, and enhancement of field emission by waves confined to the metal surface (plasmons). There is still no widely accepted understanding, despite several decades of active research.

The effect of enhanced field emission from the cathode surface was considered also in gas discharge physics in connection with deviations of measured breakdown voltage of plane-parallel gaps from Paschen's law. Deviations occurring at atmospheric pressure in microgaps, conventionally described by introducing a field enhancement factor into the Fowler-Nordheim field emission equation, are important for operation of microelectromechanical and nanoelectromechanical systems and are under intensive investigation; e.g., [1] and references therein. Deviations from the Paschen law occurring at very high pressures, starting from pressures of the order of 10 atm, have been known for several decades and a recent surge of interest in this topic is motivated by the possibility to use high-pressure air as a replacement for SF_6 for high-voltage insulation. It was hypothesized that the reason of these deviations is the field emission from the negative electrode enhanced by micrononuniformities as in the case of microgaps. Another hypothesis is that the deviations are not due to field emission (or at least not only), but rather due to enhanced ionization of neutral gas molecules in regions of increased electric field near the protrusions on the surface of the electrodes [2, 3].

In this work, analysis of deviations from the similarity law observed at very high pressures in experiments on corona inception and breakdown for discharges on positive cylindrical electrodes of small radii [2, 4] was performed by means of 2D numerical modelling. Cathodic phenomena are irrelevant and enhanced ionization of neutral gas in regions near protrusions on the anode surface appears to be the only possible explanation. The modelling has shown that the deviations from the similarity law, observed in the experiment, may indeed be attributed to enhanced ionization of air molecules in regions of enhanced electric field near the microprotrusions. A qualitative agreement with the experiments is achieved for protrusion heights of the order of 50μm. Such values appear rather high, however there is no other explanation in sight at present. The enhancement of the field electron emission from the surface of the negative electrode was estimated and found insignificant in the range of values of the protrusion aspect ratio where the enhanced ionization of air molecules in the gas phase comes into play.

[1] Y. Fu, P. Zhang, J. P. Verboncoeur, and X. Wang, Plasma Res. Express 2, 013001 (2020).
[2] A. H. Howell, Electrical Engineering 58, 193 (1939).

[3] M. Seeger, P. Stoller, and A. Garyfallos, IEEE Trans. Dielectr. Electr. Insul. 24, 1582 (2017).
[4] M. Robinson, J. Appl. Phys. 40, 5107 (1969).

Acknowledgments
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Session Classification: Field emission

Contribution ID: **38** Type: **Oral**

Microscopy investigation of the surface behaviour of different materials after H- irradiation in different conditions

Monday, 8 March 2021 14:45 (30 minutes)

The Advanced Electron Microscopy team at CERN uses advanced material characterization techniques, such as Scanning Electron Microscope –Focused Ion Beam (SEM-FIB), Electron Backscattered Diffraction (EBSD), or 3D FIB tomography in order to evaluate production techniques, help to optimize fabrication processes, and to analyse materials used in accelerator facility (e.g. as collimators, radio-frequency cavities, beam screens, magnets, detectors).
In the current study, various microscopy techniques are being employed to characterize near surface features equivalent to those observed in the surface of the copper Radio Frequency Quadrupole (RFQ) of the LINAC 4 at CERN after operation.
At this aim, samples of copper, and alternative materials that can be potentially used for future RFQ with better performance, are being inspected before and after H- irradiation in different conditions (energy, dose, rate…) paying special attention to blistering and breakdown phenomena as well as to the role of metallurgical and manufacturing aspects in the features density and appearance.

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Session Classification: Experiments & Diagnostics

Contribution ID: **39** Type: **Virtual Poster**

Diffusion on Cu Surface under Electric Field with Collective Variable -accelerated Molecular Dynamics

Thursday, 11 March 2021 15:45 (20 minutes)

Atomic diffusion on metallic surfaces under electric field is known to be biased towards higher field values. In the vicinity of a field-enhancing protrusion, stochastically hopping surface atoms are hypothesized to contribute to the growth of the protrusion by this bias mechanism.

In the context of the Compact Linear Collider (CLIC), field-enhancer growth by diffusion is one of the mechanisms proposed to play a role in the build-up of electrical breakdowns that disrupt the operation of the collider. The events immediately preceding a breakdown are difficult to observe experimentally, and thus simulation methods can often greatly assist in the study of these phenomena.

In this work, we have studied the Cu surface under electric field by Molecular Dynamics (MD). The electric field is implemented with the Femocs library [1]. To overcome the timescale limitation of MD, we have used Collective Variable -driven Hyperdynamics (CVHD) acceleration [2]. This way, the long timescale diffusion events can be simulated more efficiently.

In this presentation, we will give a short overview of the methodology, and discuss the results of our work in progress.

[1] Veske, Mihkel, et al. Journal of Computational Physics 367 (2018): 279-294.

[2] Bal, Kristof M., and Erik C. Neyts. Journal of chemical theory and computation 11.10 (2015): 4545-4554.

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Session Classification: Poster Session

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

Mo/Cu Multilayers by Bias HiPIMS for X-Band technology

Friday, 12 March 2021 14:30 (30 minutes)

Feasibility of the production with ionized sputtering of Mo/Cu multilayers with nanometer periodicity inside compact X-band radio-frequency cavities is studied. High gradients require high electromagnetic fields and power flows, which pose serious issues with the materials. Pulsed stress at surface could be responsible of the surface breakup by cyclic fatigue. Nanometer periodicity metallic multilayers might be able to reduce or prevent the device RF-breakdown due, in the final analysis, to the surface material transformation induced by the high power pulsed-microwave electric and magnetic fields, which, in turn, promote destructive electrical discharge.
Deposition of multiple Mo/Cu nano-layers obtained by the ionized sputtering HiPIMS technique in a dual closed field magnetron system is presented. The key aspects of the process are presented and interpreted using time-resolved optical emission spectroscopy and electrical measurements. Electron microscopy and α-particles EBS are used to characterize the multiple nano-layers.

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Session Classification: Experiments & Diagnostics

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

Low-energy H- irradiation of accelerators components: influence of material and material properties on the breakdown resistance at high electric fields

Monday, 8 March 2021 14:15 (30 minutes)

The LINAC 4 is a negative hydrogen linear ion injector, scheduled to become the next proton bream source for the Large Hadron Collider (LHC) at CERN. A Radio Frequency Quadrupole (RFQ) is the first stage of acceleration in LINAC 4, capturing a 70mA, 45keV beam from the ion source and accelerating it to 3MeV. After one year of test operation the RFQ was inspected with an endoscope and surface modification was observed on the copper RFQ vanes. This surface modification appears to be a combination of blistering due to H- beam loss and vacuum arcing, which raises the possibility of beam-loss induced vacuum arcing. A study was launched with goals of investigating and understanding this phenomenon and identifying potential alternative materials (copper alloys or transition metals) with a combined better resilience to blistering and breakdowns. This talk presents a general overview and motivation of this study, while other talks will focus on the first experiments of ion irradiation and the related metallurgical analyses and breakdown resistance characterization.

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Session Classification: Experiments & Diagnostics

Contribution ID: **42** Type: **Virtual Poster**

Comments on the presentation of field emission theory in the SLAC report

Thursday, 11 March 2021 16:25 (20 minutes)

This Poster forms part of a quiet campaign by the author to bring the theory of field electron emission (FE), as used in technological contexts, into a common form based on: (a) the "new" rules for writing scientific equations introduced as part of the 1970s reforms associated with the introduction of SI units; and (b) modern formulations [1,2] of the 1956 FE theory of Murphy and Good (MG) [3]. Murphy-Good FE theory is based on an underlying physical model—the "smooth planar metal-like emitter" (SPME) model" that disregards the effects of atomic-level structure and models the emitter as if it had a smooth planar surface of large lateral extent. Better models and formulations do now exist (e.g., [4]), but the author's view is that it will be easier for technological FE
to move on to using a better underlying approach (if desired, in due course) if we first move to a common modern method of formulating and using MG FE theory.
As of 2021, the author's preferred method (in the context of modern MG theory) of writing an expression for the local emission current density J in terms of the local work function φ and the magnitude F of the local barrier field is
$J = \lambda a \varphi^{-1} F^2 \exp[-v(f) \cdot b\varphi^{3/2}/F]$, (1)
where a [≅ 1.541434 μA eV V^{-2}] and b [≅ 6.830890 $eV^{3/2}$ V nm^{-1}] are the Fowler-Nordheim constants. The exponent correction factor v(f) is a particular value of the principal field emission special mathematical function v(x) [5], and is obtained by setting x equal to the scaled field f (for a barrier of zero-field height equal to the local work function) given by
$f \equiv (e^3/4\pi\varepsilon_0)\, \varphi^{-2} F \cong (1.439965\ eV^2\ V^{-1}\ nm)\, \varphi^{-2} F = (1.439965\times10^{-9}\ eV^2\ V^{-1}\ m)\, \varphi^{-2} F$. (2)
An exact series expansion is now known for v(x), but many different algebraic approximations for v(x) have been used in the literature. Approximation (5) below was in fact suggested by Charbonnier
and Martin in 1962 [6]. The pre-exponential correction factor λ formally takes into account physical
effects disregarded in the SPME model, and is regarded as an "uncertainty factor", whose functional
form and values are not currently known (and are unlikely to be accurately known for many years to
come). In MG 1956 theory a correction factor that I would now write as $t^{-2}(f)$ appears instead of λ, but
this difference between eq. (1) and the 1956 formulation is not of major interest for this Poster.
In a 1997 report [7] from the Stanford Linear Accelerator Centre, sometimes referred to as the "SLAC Report" and often cited, the following expression is given for local emission current density
(J =) $j_F = [1.54\times10^{-6} E^2/t^2(s)\, \varphi] \exp[-6.83\times10^9\, \varphi^{1.5}\, v(s)/E]$ (A/m^2) , (3)
where E is stated to be the surface electric field measured in V/m, φ is stated to be in eV, and
$s = 3.79 \times10^{-5}\, E^{0.5}/\varphi$, (4)
$v(s) = 0.956 - 1.062\, s^2$. (5)
By substituting these into (3) and letting $t^2(s) \approx 1$, the SLAC report derives (after some further algebraic manipulation) the "all-in-one" approximate formula
$j_F = [1.54\times10^{-6} \times 10^{(4.52/\sqrt{\varphi})}\, E^2/\varphi] \exp[-6.53\times10^9\, \varphi^{1.5}/E]$ (A/m^2) . (6)

This Poster will comment on the format differences between eq. (1) and the SLAC report equations, suggest that format (1) has advantages, and assess the accuracy of approximation (5).

[1] R.G. Forbes & J.H.B. Deane, Proc. R. Soc. Lond. A 463, 2907–2927 (2007).
[2] R.G. Forbes, R. Soc. Open Sci. 6, 190912 (2019).
[3] E.L. Murphy & R.H. Good., Phys. Rev. 102, 1464–1473 (1956).
[4] A. Kyritsakis & F. Djurabekova, Computational Materials Sci. 128, 15–21 (2017).
[5] R.G. Forbes, Chap. 9 in: Modern Developments in Vacuum Electron Sources (Eds. G. Gaertner et al.)
(Springer, 2020).
[6] F.M. Charbonnier & E.E. Martin, J. Appl. Phys. 33, 1897–1898 (1962).
[7] J.W. Wang & G.A. Loew, SLAC-PUB-7684, October 1997.

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Session Classification: Poster Session

Contribution ID: **43** Type: **Virtual Poster**

A tutorial commentary on the Schottky constant

Thursday, 11 March 2021 16:05 (20 minutes)

An electron within a piece of condensed matter is held into the material by a surface barrier. In simple basic models, the force preventing electron escape is attributed to an image attraction between
the electron and the material surface. This gives rise to an energy barrier of zero-field height H that
prevents classical escape. The application of a classical electrostatic field of appropriate polarity and
magnitude lowers this barrier, and can reduce it to zero if the field magnitude is sufficiently large.
Effects of this general kind were discussed by Kelvin and by Maxwell, in the context of
conducting spheres. J. J. Thomson, when discussing (in his 1903 book [1]) electrical discharge effects
between closely spaced planar surfaces, suggested that a barrier lowering effect of this kind might
enable electron emission to cause the observed phenomena. However, relevant planar-geometry
equations were first clearly formulated by Schottky in 1913 [2], and hence the effect is known as the
(classical) Schottky effect.
Schottky's original treatment was in terms of "electric potentials", and used the Gaussian equation
system. Modern treatments involve the component of electron total energy in the direction (z) normal
to the material surface, and use the modern international equation system that has the vacuum electric
permittivity ε0 in Coulomb's Law [3]. For a good conductor, such as a metal, the energy barrier is
described by an energy-like quantity M(z) given (for a planar surface) by
$M(z) = H -eFz -e2/16\pi\varepsilon0z$, (1)
where e is the elementary positive charge and F is the magnitude of the linear field outside the planar
conductor surface. (My term for M(z) is the motive energy.) This barrier is often now called the
Schottky-Nordheim barrier. It can be shown that the maximum height of the barrier is lowered by an
energy ΔS called the Schottky reduction (or Schottky lowering) and given by
$\Delta S = c\ F1/2$, (2)
where c is a universal constant given by:
$c \equiv (e3/4\pi\varepsilon0)1/2 \simeq 1.199985$ eV V−1/2 nm1/2 = 3.794686×10−5 eV V−1/2 m1/2 . (3)
Clearly, the so-called zero-barrier field F0(H) needed to reduce a barrier of zero-field height H to
zero, via the Schottky effect, is
$F0(H) = c-2H2$. (4)
where $c-2 \simeq 0.6944615$ eV−2 V nm−1 = 6.944615×108 eV−2 V m−1 . (5)
This universal constant c (alternatively denoted by cS) has been called the Schottky constant. The
numerical value of c (when fields are measured in V/cm) was first given by Schottky in 1914 (see
eq. (6) in [2]), with the numerical value of c−2 given in his 1923 paper [4] (see Table 1, on p. 83).
Although the Schottky constant plays a central role in the theories of field electron emission, thermal
electron emission and ionic field evaporation, particularly since the 1970s reforms in the interna-

tional
system of measurement, it is not widely recognised as a useful universal constant.
This Poster provides a brief "tutorial" introduction to the Schottky constant, primarily for those not familiar with it. It will include: a proof of equations (2) and (3); a demonstration of how the equations need to be modified when the escaping entity is an ion of charge ne (where the chargenumber
n is a small integer); statements identifying the scientific contexts and equations in which the Schottky constant is most commonly used; and a demonstration that the Schottky constant is a "property of the world" that is represented by technically different physical quantities in different equation systems (strictly, what is discussed above is the "ISQ Schottky constant" [3]).

[1] J.J. Thomson, Conduction of Electricity through Gases (1st ed., Cambridge Univ. Press, 1903), see p. 386.
[2] W. Schottky, Physik. Zeitschr. 15, 872–878 (1914).
[3] Since 2009, the modern equation system that uses ε0 has been called the "International System of
Quantities" (ISQ).
[4] W. Schottky, Z. Phys. 14, 63–106 (1923).

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Session Classification: Poster Session

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

Electrostatic discharges on very large spacecrafts solar panels: coupled model of a cathode spot and flash-over expansion in vacuum

Tuesday, 9 March 2021 14:00 (30 minutes)

The increase of the onboarded power on Spacecraft is actually still limited by the charging issue due to the plasma natural environment. The charging of the external dielectrics is due to the complex geometry, the number of different materials and the presence of biased conductor. It leads to a high potential difference on solar cells edges that can reach several kilo-volts. In this conditions, an electrostatic discharge (ESD) may appear. The ESD emits a current called a flash-over that will expand on the surface of the solar panel. It takes the form of a plasma bubble i.e. a conductor environment in which secondary arcs may appear. Our objective is to identify the duration and extinction conditions of the flash-over. Indeed, it has been shown that the plasma bubble can cover panels a few meters long but there is no clue about bigger ones (some dozen of meters long). Based on known literature, we tailored cathode spot and plasma expansion in vacuum models to our specific case and coupled them. Both models are developed in parallel to create a closed system without free parameters other than the ESD initial position and the initial charging state of the solar panel surface (obtained from the known environment).

We present the coupled cathode spot-plasma expansion model, detailing the physical assumptions made to fit to our particular environment and close our system. The cathode spot model is developed for different materials and we focus on the impact of the cathode spot on the extinction of the flash-over. The results of the coupled model are compared to experimental measurements of flash-over expansion on large solar panel area performed at ONERA's facilities. Those measurements reveal that the extinction occurs before the complete neutralization of the charge. We show that, even-though the cathode spot has a direct impact on the plasma bubble lifetime, the characteristics of the solar panel also have its influence on the flash-over extinction.

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Session Classification: Modelling and simulations