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Report of Abstracts

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First principles calculations of field emission from a defected metal surface

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Small surface defects are thought to affect field emission through the field enhancement and modification of the work function. We combined density functional theory and quantum transport calculations to study the influence of atomic-scale defects on the work function and field emission characteristics of copper surfaces. A newly developed general methodology for the calculation of the field emitted current density from nano-featured surfaces is used to study specific defects on a Cu(111) surface. Our results show that the inclusion of a defect can significantly locally enhance the field emitted current density. However, this increase is attributed solely to the decrease of the work function due to the defect, with the effective field enhancement being minute. Finally, the Fowler–Nordheim equation is found to be valid when the modified value for the work function is used, with only an approximately constant factor separating the computed currents from those predicted by the Fowler–Nordheim equation

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Suggestions about the role of carbon nanowhiskers in electrical breakdown

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This paper brings together various pieces of theoretical argument and experimental evidence to support the idea that, in some cases, electrical breakdown may be associated with the growth of carbon nanowhiskers. An introduction provides two reminders. (a) That effects of this kind are driven by electrical thermodynamics and by the rule that systems evolve in a direction such that the electrical Gibbs function becomes more negative—possibly/probably with both an electrical surface term and a field-energy (or “capacitance”) term contributing, at least in some circumstances. And (b) that (for so-called “ideal” field electron emitters) it is possible to use a Fowler-Nordheim plot (or a Murphy-Good plot) to measure—with an accuracy estimated as 30%—a characteristic value of local electric field or (better) a characteristic value f_C of scaled field f . Possible mechanisms for the formation and growth of carbon nanowhiskers will be discussed. In this, an important role is played by the results in papers written by a group of French authors, but there is much other evidence. Also of interest is the long established work on so-called “low-macroscopic-field (LMF) electron emission” from carbon, particularly in the Russian literature. Up till now there has been

some tendency to look for “special explanations”, such as resonance tunnelling. However, FN-plot techniques have recently been used to measure the local fields involved, and these have been found to have normal values (of a few V/nm). This suggests that a highly plausible alternative explanation of LMF emission is that carbon-based emitters are capable of exhibiting unexpectedly high (one might say “anomalously high”) field enhancement factors.

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Consideration of the origin of enhanced field emission

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Everyone measuring field emission in macroscopic systems observes larger than expected values. Various mechanisms for the enhancement have been postulated but there is rarely independent confirmation. Commonly considered mechanisms are summarized and a new one is proposed.

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Field electron emission in an external magnetic field parallel to the surface

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The work concerns relativistic effects and the influence of an external magnetic field on the transmission coefficient. The Fowler-Nordheim equation has been relativistically generalized and effect of the Lorentz contraction of a potential barrier at the metal-vacuum interface has been found. Influence of the magnetic field parallel to a metal surface on the transmission coefficient is taken into account when $cB < E$.

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Observations on the link between cathode plastic activity and arc nucleation

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The hypothesis that arc nucleation is related to plastic activity due to collective motion of dislocation in the cathode is examined via experiments and theoretical efforts over the last few years. I will summarise current theoretical and experimental observations indicating specific dislocation activity related to the applied high field. In addition I will discuss the challenges that lie ahead in trying to confirm this hypothesis as well as put it to use.

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Investigations of the transition from field electron emission to plasma discharges (glow discharges and micro-arcs) with extended use of the Fowler-Nordheim plot

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The commonest method of characterising a cold field electron emitter is to measure its current-voltage characteristics, and the commonest method of analysing these characteristics is by means of a Fowler-Nordheim (FN) plot [1]. For example, the field enhancement factor can be calculated. But for novel investigations of the transition from field emission to plasma discharges an extended use of FN plot is proposed. For this, the inverse voltage (x-axis of the FN plot) was extended with factor $1 = (I \cdot t)/(I \cdot t)$:

$$1/V = (I \cdot t)/(V I \cdot t) = Q/E \quad [1/V = A_s/W_s] \quad (1),$$

where V is the Voltage, I the current, t the time, Q the sum of all transported charges (cathode - anode) and E the energy required for this. The relation Q/E is a possible option for energetic evaluation. Fig. 1 shows an example of the energetic evaluation with FN plot (see attachment). It can be seen that the micro-arc discharge has a charge transfer with the least energy input. This energetic evaluation, further and improved measurements, an illustrative “energy compass” for a simple FN plot analysis and novel approaches for comparative energetic evaluations of charge transfers (electrons, ions) will be presented and discussed.

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Does field emission from ‘real’ surfaces affect the high-pressure air breakdown in electric power equipment?

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Field emission from cold cathodes, with electric field enhanced by roughness of (micro-protrusions on) the cathode surface, may play a role in breakdown of the high-pressure air under conditions relevant to electric power equipment. Two examples are considered in this contribution. The first one concerns the breakdown in conditions of the experiment [1]: a concentric cylinder discharge in synthetic air in the pressure range 5-100 bar, with an interelectrode gap of 5 mm and the outer cylinder diameter of 190 mm. Numerical modelling was performed by means of the numerical model of low-current discharges in air [2]. At pressures up to 10 bar, both the experimental breakdown voltage and the computed discharge inception voltage, computed without account of the field emission, grow linearly with the pressure and are close to each other. For higher pressures, the experimental breakdown voltage saturates which is actually a well-known effect, while the computed voltage continues to grow linearly. This striking difference between the modelling and the experiment was removed by introducing in the numerical model the effect of field emission with account of amplification of electric field due to roughness of (micro-protrusions on) the cathode surface. The electron emission current was determined by means of the code [3], based on the straightforward evaluation of the Murphy-Good formalism, protrusions were taken into account by means of a field enhancement factor β introduced on the entire cathode surface. With $\beta = 50$, which is standard in the literature and corresponds to protrusions with aspect ratio of 10, the computed discharge inception voltage indeed reveals a saturation in the dependence of the breakdown voltage with pressure, similar to the one observed in the experiment [1].

Another example considered in this contribution concerns the effect of field emission during the ignition of an arc at separation of contacts of low-voltage contactors or circuit breakers. Note that this topic is related to the effect of field emission in breakdown in micrometer gaps, which is currently under an intensive investigation; e.g., [4] and references therein.

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The Breakdown Induced by Rupture of Dielectric layer (BIRD) model: insights and future developments

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Recently a new model for the cathodic emission at high voltage and high vacuum has been proposed. It is a classical model that assumes the existence of a dielectric layer (oxides mainly) on the cathodic surface and assumes that the cold emission current is due to polarization electrons stripped from the dielectric layer. The application of this model to an experimental case has highlighted its potential to describe the start of the electric current as well as its capability to take into account the experimental random current bursts. Moreover, in the same work it has been showed that an electric current amplification factor, which depends on the voltage difference between the electrodes, is needed to fit the experimental data. In this work we want to clarify some theoretical aspects of the model in greater detail and extend its application to a wider range of experimental cases. Furthermore, it seems worthwhile to look for a quantum model that can describe the cathodic emission process from a dielectric layer. As a preliminary step we will discuss some points in order to check the consistency between classical and quantum theory.

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A "nearly semi-quantitative" explanation of electrical breakdown effects reported by Julius Caesar and Pliny the Elder

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Over the last 2000 years or so, the atmospheric phenomenon now known as "St Elmo's fire" (see Wikipedia) has been reported by very many authors in very many contexts, with the earliest known reports being associated with the names of Julius Caesar and Pliny the Elder (who both reported observations of its appearance on the tips of their soldiers' javelins). Pliny also noted its appearance on the masts of ships. It is now well established that the effect is a form of Corona discharge, and is most prominently observed on dark, wet, stormy nights. The effect is also very often associated with objects that are either relatively tall or relatively sharp, or both. As always, the scientific questions are: what initiates/sustains the discharge, what is the underlying physics, and can we model it? But, as far as I am aware, there has been no successful attempt to date to develop a quantitative model. Recently, the electrostatic phenomena that occur with carbon nanotube field electron emitters have received much attention, as these things affect the design of large-area electron sources. It has become clear that many aspects of nanoscale electrostatics are a consequence of underlying electron thermodynamics, and hence are of general applicability. By putting some of the scientific lessons learnt in nanoscale electrostatics together with the results (now available on-line) of Stephen Grey's reliable 18th-Century experiments on "Gilbert-Grey cone-jets" (often called "Taylor cones"), and other experimental evidence, one can begin to build a possible "nearly semi-quantitative" explanation for the occurrence of St Elmo's fire in various specific contexts. Interestingly, at a high level, this has some elements of resemblance with the recent Helsinki work on the origins of vacuum breakdown. The work may also be of relevance to the issue of how lightning (protection) rods work, though other factors very probably play the dominant role in this case. Finally, one should not forget that dispelling superstition remains part of the role of science.

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3D Modeling of field electron emission from a micro/nano structured surface

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Abstract:

In future Tokamak reactors such as ITER and DEMO, the initiation of fusion reactions in hot plasmas is highly dependent on the capacity to heat the plasma heavy species. To do this, high power beams of energetic neutral D atoms are injected by Neutral Beam Injectors (NBIs) which accelerate the negative D^- ions by applying very high DC voltages ($V \sim 10$ MV). The DC power line feeding the acceleration grids passes the voltage from high pressure (10 bar) to vacuum via the so-called bushing system. Its reliability requires avoiding non predictable breakdown or arcing and the reduction of leakage currents - called dark currents. Among other possible phenomena, the dark current could originate from natural protrusions distributed on the non perfectly flat surface of metal parts. To correctly gauge this phenomenon, deeper fundamental studies on field electron emissions (FEE) from protrusions are necessary. In particular, in the case of real surfaces, protrusions are randomly distributed in terms of size and sharpness, but also locations. Hence, in addition to their own shape, the vicinity of main protrusions can be a parameter of major importance as well, requiring 3D considerations.

The present work exposes modelling results of 3D simulations for two close protrusions, aiming to study such FEE phenomena. The model couples time-dependent equations of heat transfer and current conservation inside the cathode protrusions. Thanks to 3D solving, it takes into account the electrostatic screening and possible thermal interactions between emissive sites. This offers precise insights on how protrusions proximity can influence electron emission and cathode heating, both enabling breakdown or arcing. A dimension reduction approach to reduce the huge computation time spent for 3D calculations is also explored.

The results focus on the effect of interactions between neighbour protrusions depending on their size, material, separating distance and macroscopic electric field. 3D and simplified 3D modeling results will be compared and discussed in the light of the forementioned challenge, predicting possible arcing from (idealized) rough surfaces.

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Field Emission and Multipactor Simulations in High Gradient RF Accelerators

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Field emitted electrons play an important role in the operation of high gradient RF accelerating structures, by generating so-called dark currents, and acting as the initiators of RF Breakdown, which limits the performance in such devices. Another kind of vacuum discharge that commonly affects to the operation of lower-field RF components, for example in space applications, is the Multipactor effect. Theoretical simulations are under development for analyzing both processes in the context of HG accelerators. Mainly using CST Particle Studio, but also additional programs such as Spark3D,

and a homemade multipacting simulation tool developed using MatLAB.

The results show that field emitted electrons generated in the high field regions of the accelerating cavities produce longitudinal and transversal dark currents. In the longitudinal case, the electrons are captured by the RF field and gain energy enough to produce ionizing radiation. In the transversal dark current, we observe how these electrons migrate from the iris to low field regions, pushed by the ponderomotive force, and trigger multipactor there. This phenomenon is a unique interplay between high field and low field processes which may have as a consequence that multipactor actually affects to the performance of high gradient cavities, as field emission electron seeding can reduce the timescales for the onset of multipactor.

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COMSOL simulation of the surface flashover in a MEMS insulator

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This research is on the COMSOL simulation of flashover occurring in a MEMS (Micro-Electro-Mechanical System) insulator and electrode unit, both of the electric field at triple point and of electron trajectories in several practical geometries. In some applications of MEMS technology, electrostatic field up to 5-20kV/mm is of interest. One of these applications is using MEMS components for manufacturing compact electrostatic lenses or apertures to be used in Scanning Electron Microscopes. High voltage insulation is still one of the challenges, as it is in a conventional construction using metal and ceramic to make lenses and apertures. The field strength at triple points is assessed first, and a glass sphere is added as a dielectric particle later to check the effect of particles in a system. Moreover, a secondary electron emission avalanche (SEEA) model is utilized in the simulation. Electrons are assumed to be emitted from the sphere by the mechanism of cold field emission or ionisation. The secondary electrons generated by electrons hitting on the surface of a glass insulator are simulated in COMSOL, the total electrons collected by the electrode on the positive side are recorded, and the multiplication factor is compared for these geometries. Among these geometries, a two-step structure seems to contradict experimental results published before. We try to explain the differences.

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

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We are developing a stochastic, micron-scale field emission model 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 a micron-scale probability density distribution 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 work function and other surface characteristics. Some effort has been made to match emission rates for the coarsened model

to equivalent current densities from atomic scale measurements over intermediate-scale surface areas. 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.

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Simulations of material surface modifications due to combined influence of femtosecond laser irradiation and applied electric fields

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Extreme field enhancement factor of 50-100 is commonly measured in CLIC accelerator design. Such field enhancement values are often associated with high aspect ratio surface irregularities appearing under applied electric fields. Recently, femtosecond laser experiments with tungsten tip under applied electric field demonstrated spontaneous formation of such field emitting modification in time range of minutes due to repeated laser pulsing [1].

Under such conditions, several time and length scales are combined, starting from the application of single laser pulse, towards formation of steady state thermal profile in tip in tens of nanoseconds while incorporating atomic diffusion time scales in order of magnitude of microseconds and finally, ending with formation of the tip in range of minutes. Thus, application of conventional simulation methods becomes extremely challenging, as available tools like molecular dynamics or atomistic kinetic Monte-Carlo succeed in capturing accurately only up to microsecond scale, while standard finite element analysis tools tend to introduce excessive homogenization and either lose the accuracy at the nanoscale or extendability to macroscopic time scales.

In current study we present the outcomes of extensive multi-physics and multi scale simulations, including reproduction of femtosecond laser pulsing using two-temperature model and nanoscale electro-mechanical material response analyses.

To overcome the limitations of extendability of models with the respect of time scales, we utilize the surface stress model [2] in the framework of topology optimization, coupled with electric field and two-temperature approach motivated tip temperature calculations. The topology optimization relies on Lagrangian formalism and moving mesh approaches, leading to continuous surface changes of the system in every optimization step. Thus, allowing successful relaxation of structure due to combined influence of femtosecond laser heating, applied electric field and nanoscale surface stresses. As a result, we successfully overstep the time scale limitations accurate atomistic scale stress calculations while being able to observe physics motivated surface modifications. In combined simulations, we observe significant influence of applied electric field to the surface behavior. For example, tested Cu tip successfully relaxed to {111} dominated pyramidal shape of minimal surface energy, often observed in kMC simulations as well. However, in case of applied electric field, fast flattening of the top of tip similarly to the results in [1] was observed. Moreover, the simulation setup, relying on the energy minimization of the sample and combining the influence of surface stress, thermal stress and

electric field caused stress opens several possible mechanisms for explaining observed spontaneous surface modifications.

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Breakdown-loaded electric field as a high gradient limit

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A novel quantity for predicting the ultimate performance of high-gradient radiofrequency accelerating structures is presented and compared with earlier quantities that it builds on such as the modified Poynting vector. This new method models a nascent RF breakdown as a current-carrying antenna and calculates the coupling of the antenna to the RF power source. Along with a simple emission model fitted to experimental data, an equilibrium breakdown-loaded surface electric field distribution is calculated and found to be well-correlated with spatial breakdown distributions.

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RF Breakdowns in the SPIDER experiment during its first operational phase

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SPIDER is the full-size prototype of ITER Neutral Beam Injector ion source, in operation since June 2018

as part of the ITER Neutral Beam Test Facility located in Padova, Italy. The ion source of SPIDER is composed of eight Radio Frequency drivers operated in low hydrogen gas pressure, 0.3 Pa, driven at

1 MHz with a total power of 800 kW, an extraction and acceleration system is the used to produce a negative ion beam with an energy up to 100 keV.

RF breakdowns outside the ion source beset the SPIDER experimentation since the beginning of the operations. Such breakdowns could be sustained by the power supplies but in many cases cause the plasma pulses to stop and might cause of source damages. Scope of this work is to summarize the experimental evidences, to classify the type of breakdowns and to identify the operational scenarios which seem to be free from this problem.

Three classes of diagnostics have been used to investigate the RF breakdowns: electrical measurements

from the Ion Source and Extraction Power Supply, visible cameras (both fast and slow) and optical fibers

which collect lights from the rear of the SPIDER experiment. Each of these signals is somehow affected by the RF breakdowns; their comparative analysis allows improving the understanding of this issue and helped the identifications of different types of breakdowns that can occur outside the SPIDER Ion Source. A statistical analysis of the pulses performed so far concludes the work; it gives an overview RF breakdowns in the SPIDER experiment and tries to assess the breakdown probability in the conditions relevant for normal plasma operations.

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Why Murphy-Good plots are better than Fowler-Nordheim plots

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This Poster reports a small part of a multi-stage project to improve the interpretation of measured field electron emission (FE) current-voltage [$I_m(V_m)$] data. The first stage of the project involves five or so proposals that aim to improve data interpretation within the framework of the almost universally used (but not physically realistic) *planar emitter approximation*. This models a real emitter, which is usually needle-shaped or post-shaped, as if it were a smooth, planar structureless surface, with constant emission area. In the past, this has been thought an adequate approximation if the emitter apex radius of curvature is sufficiently large. It seems procedurally important to first establish best practice in the context of this approximation (whilst also working in parallel on better procedures for interpreting data from post-shaped and needle-shaped emitters). This Poster reports one of these five or so proposals. Measured FE $I_m(V_m)$ data are traditionally analysed via Fowler-Nordheim (FN) plots, as $\ln\{I_m/(V_m)^2\}$ vs $1/V_m$. These have been used since 1929, because in 1928 FN predicted they would be linear. In the 1950s, a mistake in FN's thinking was found. Corrected theory by Murphy and Good (MG) made theoretical FN plots slightly curved. This causes difficulties when attempting to extract precise values of emission characterization parameters from straight lines fitted to experimental FN plots. Improved mathematical understanding, from 2006 onwards, has now enabled a new FE data-plot form, the "Murphy-Good plot". This plot has the following form $\ln\{I_m/(V_m)^{(2-\eta/6)}\}$ vs $1/V_m$, where η depends only on local work function. Modern ("21st century") MG theory predicts that a theoretical MG plot should be "almost exactly" straight. This makes *precise* extraction of well-defined characterization parameters from ideal $I_m(V_m)$ data much easier. This Poster gives the theory needed to extract characterization parameters from MG plots, and discusses why this extraction procedure is better and easier than the FN-plot procedure. Careful use of MG plots could also help remedy other problems in FE technological literature. It is argued that MG plots should now supersede FN plots.

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Modeling the Role of Effective β on Vacuum Breakdown Initiation: Scaling from Micro to Macro Dimensions

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We are modeling the effects of a field enhancement factor (β) on the generated Fowler-Nordheim current using the Particle-in-Cell Direct Simulation Monte Carlo (PIC-DSMC) method for a vacuum environment. In the present work, we vary the DC voltage, and hence electric field, between two parallel Pt plates in which the modeled electrode surface elements are given a local work function and β by sampling probability density functions that are themselves functions of electrode material, preparation and conditioning, and surface topology. PhotoEmission Electron Microscopy (PEEM) and the combination of Atomic Force Microscopy (AFM) and Scanning Tunneling Microscopy (STM) measurements are used to infer work function and β distributions, respectively. Note that a model utilizing a fully resolved (nano- scale) topology would result in $\beta=1$ everywhere (assuming beta is solely a geometric enhancement factor). A coarsened scale (not nano-scale) β value is derived from the AFM/STM data by actually meshing the surface topology data and simulating an applied electric field to obtain local surface enhanced fields. We show that as the element size of our model grows, comparable field emission yields are obtained through the application of this effective β , rendering such an approach relevant to physical macroscopic dimensions that can be realistically meshed.

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Using Fowler-Nordheim plots to measure characteristic local field values

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An *ideal* field electron emission (FE) device/system is one in which: (a) the measured current I_m equals the emission current I_e ; (b) the characteristic local barrier field F_C is related to the measured voltage V_m by the formula $F_C = V_m/\zeta_C$ where the *voltage conversion length* ζ_C is effectively constant; and (c) the work-function is constant. An orthodox FE device/system is an ideal system where it is adequate to assume, further, that FE can be treated as tunnelling through a Schottky-Nordheim ("planar image rounded") barrier, well below the top of the barrier, that the work-function value is adequately known, and that the pre-exponential correction factor λ in the so-called extended Murphy-Good FE equation can be treated as constant. The purpose of this Poster is: (a) to remind people that it has been known since the 1950s that, for orthodox FE devices/systems, a Fowler-Nordheim plot can be used to measure the characteristic local barrier field, subject to a systematic "calibration discrepancy" of around 30%; and (b) to put this measurement procedure into a useful modern form involving the characteristic scaled field f_C . The mathematical basis of the procedure (which is now based on the extended Murphy-Good FE equation) will be described, the issue of precisely what is being measured will be discussed, and a reminder will be given of the 1950s experiments undertaken in order to check/calibrate the procedure. As illustration, the procedure will be applied to several carbon-based emitters that exhibit low-macroscopic-field (LMF) emission, in order to demonstrate that actual local barrier field values are in the normal range of a few V/nm and are not anomalously low (as hitherto assumed by some authors). Rather, characteristic field enhancement factors must be anomalously high.

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Field-emission investigations of micro-structured stainless steel 1.4301 (ASTM 304) for application of vacuum components as very large FE cathode arrays

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Highly-alloyed chrome-nickel stainless steel is the most important material in vacuum technology. Especially in high and ultra-high vacuum technology it is used for vacuum chambers and components. One of the main research focuses for 2005 [1] was the study of parasitic field emission of specially treated stainless-steel surfaces for applications in accelerator technology. The measured threshold field strength is about 25...30 V/ μm for 1 nA [2], [3]. An important cause of field emission enhancement is the grain boundary structure. And so stainless steel (1.4301 or ASTM 304) was wet-chemical micro-structured and investigated with respect to field-emission properties, as shown in Figure 1. A) and B).

Some selected results are:

- Threshold field strengths of micro-structured stainless steel are in the range of 6.5...7.0 V/ μm , comparable with 7.5 V/ μm in [4] (cf. CNT-Buckypaper field emitter has 1.0...2.0 V/ μm [5]).
- For application as FE cathodes in vacuum components, in particular in cylindrical component surfaces [1], very large cathode arrays of a few cm^2 can be produced cost efficiently.
- Very large cathode arrays with lower current density are field emitter with long-term stability.

In the contribution further measurements and results of field emission investigations will be presented.

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Negative ion beam extraction in an RF hydrogen plasma with Cs seeding

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The development of a negative ion beam source has been in progress in KOREA as part of ITER technology R&D programme. The RF negative ion beam source is one of the key parts of ITER neutral beam injection (NBI) system. In particular, the use of Cs leads to a remarkable enhancement of negative ion production and thus enables the extraction of high current negative ion beams. The final performance goal of our source is 200 keV / 0.5 A (the current density of 13 mA/ cm^2) negative ion beam extraction. To achieve such high current density negative ion beams, the optimization of the use of Cs is necessary. In this regard, the preliminary beam extraction experiment with Cs seeding has been started recently.

The beam source can be divided mainly into three parts: an RF inductively coupled plasma (ICP) source, an expansion chamber and a three-grid beam acceleration system. Firstly, the 2 MHz RF ICP source is a typical AlN dielectric cylinder surrounded by a 6-turn helical antenna. Inside the AlN cylinder, a thin Cu Faraday shield is located for the protection of AlN from the heat load by plasma. Secondly, the expansion chamber is equipped with a permanent magnet filter to prevent the high energy electrons from destroying the negative ions in the extraction region. The Cs delivery system

is also installed in the upper part of the expansion chamber, composed of a Cs dispenser oven and the Surface Ionization Detector (SID) for the Cs evaporation rate measurement. The Cs dispenser containing 20 mg of Cs manufactured by SAES Getters S.p.A. is utilized. Lastly, the three-grid beam extraction and acceleration system consists of a plasma grid (PG) facing the plasma, an extraction grid (EG) and an acceleration grid (AG). Each grid has 5 x 5 apertures of 14 mm diameter. The total beam extraction area is about 38.5 cm².

In the experiment, it was confirmed that higher beam currents could be obtained by using the Cs than those of without Cs. However, the beam optics were not so good than expected. The negative ion production from the Cs-deposited PG surfaces seems not fully optimized yet. The performance characteristics of the beam source based on the experimental data are presented and the issues are discussed.

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Dark current fluctuation measurements the pulsed DC system

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The dynamics of dislocation activity under intense electric fields has been proposed as a potential nucleation mechanism of breakdowns. Results of searches for high-frequency fluctuations in field-emitted current in the pulsed DC system at CERN, that could arise as a consequence of changes in the surface geometry as a result of dislocation motion.

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Commissioning of IFIC High Gradient RF Laboratory to test S-band accelerating structures for hadron-therapy accelerators.

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The IFIC RF laboratory will perform the conditioning and high power tests of S-band accelerating structures designed for hadron-therapy with the purpose of investigate their high gradient behaviour. The facility is based on the scheme of the Xbox-3, a X-band test facility at CERN, adapted to operate in S-band. Two medium peak-power (7.5 MW) and high repetition rate (400 Hz) S-band klystrons have been combined to generated the required power on two testing lines. The test stands installation has been finished and commissioning of the laboratory equipment is progressing. This document will present the latest results and progresses of the IFIC RF laboratory.

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Combined Field Emission and Multipactor Simulation in High-Gradient RF Accelerating Structures

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Field emitted electrons have important consequences in the operation of high-gradient RF accelerating structures both by generating so-called dark currents and initiating RF breakdown. The latter is an important limitation of the performance in such devices. Another kind of vacuum discharge that primarily affects the operation of lower-field RF components, for example those used in space applications, is multipactor. Theoretical simulations using CST Particle Studio, show that field emitted electrons generated in the high field regions of high-gradient accelerating cavities migrate to low field regions under ponderomotive forces potentially triggering multipactor there. This phenomenon is an interplay between high field and low field processes which may have as a consequence that multipactor actually affects to the performance of high-gradient cavities because field emitted electrons might reduce the timescales for the onset of multipactor.

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The smooth transition from field electron emission to glow discharge (as a pre-stage of glow-to-arc transition) - a novel approach for the detection

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An underestimated phenomenon in the operation of field electron emission is the smooth transition to glow discharge as a significant pre-stage of vacuum arcs, which usually occur more frequently at higher operation vacuum pressures and higher emission currents in the range of normal glow discharge (> 0.1 mA). This phenomenon can be understood by investigating the transition from field electron emission (FE) to glow discharge (GD). It is important to note that the detection of the transition using the electrical parameters is not easy, because field electron emission and glow discharge have the same voltage range during a transition (in contrast to arc transition with sudden voltage breakdown). In order to confirm this transition from field electron emission to glow discharge a graphical four-step evaluation method was developed and proposed for detection with electrical parameters [1, 2]. These four steps are:

- 1st step: I-V semi-logarithmic diagram (typical of the FE diagram with many current decades),
- 2nd step: I-V linear diagram with linearity test for measurements of $V = f(I)$ and calculation of serial R ($I > 0.1$ mA),
- 3rd step: I-V linear diagram with R voltage correction, and for glow discharge is $V = \text{constant!}$
- 4th step: V-I linear diagram (typical of the GD diagram in plasma physics).

A detailed description and explanation of this evaluation method is a topic of this contribution. Additionally, we present different optical observations of the cathode-anode distance with typical blue

luminous effects of glow discharges and change of color and brightness during the glow-to-arc transition.

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Recent technical improvements to and plans for ArcPIC

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ArcPIC is a 2D electrostatic particle-in-cell code for simulating vacuum arc discharge plasmas. It is meant to be flexible, making it easy to modify with new surface boundary conditions, external circuits, and more.

ArcPIC was open-sourced 2014, and has since then gone through a technical development and started to be used by a larger community.

Especially, the build system has been rewritten and the output files can optionally be given as HDF5 instead of ASCII.

Furthermore, the arrays for storing the particles and the mesh for the electromagnetic solver was previously defined at compile-time, but is now defined during start-up and re-sized on demand.

Finally, the internal configuration and state data is moved into appropriate classes instead of being stored in the global context.

These improvements aim at making the code faster and more efficient to run, and easier to modify. Further development is foreseen based on this, especially to restore the checkpoint/restart functionality, capability of handling more particle species, and to implement a parallel/full-wave EM solver.

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RF Breakdowns in the SPIDER experiment during its first operational phase

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SPIDER is the full-size prototype of ITER Neutral Beam Injector ion source, in operation since June 2018

as part of the ITER Neutral Beam Test Facility located in Padova, Italy. The ion source of SPIDER is composed of eight Radio Frequency drivers operated in low hydrogen gas pressure, 0.3 Pa, driven at 1

MHz with a total power of 800 kW, an extraction and acceleration system is the used to produce a negative ion beam with an energy up to 100 keV.

RF breakdowns outside the ion source beset the SPIDER experimentation since the beginning of the operations. Such breakdowns could be sustained by the power supplies but in many cases cause the plasma pulses to stop and might cause of source damages. Scope of this work is to summarize the experimental evidences, to classify the type of breakdowns and to identify the operational scenarios which seem to be free from this problem.

Three classes of diagnostics have been used to investigate the RF breakdowns: electrical measurements from the Ion Source and Extraction Power Supply, visible cameras (both fast and slow) and optical fibers which collect lights from the rear of the SPIDER experiment. Each of these signals is somehow affected by the RF breakdowns; their comparative analysis allows improving the understanding of this issue and helped the identifications of different types of breakdowns that can occur outside the SPIDER Ion Source.

A statistical analysis of the pulses performed so far concludes the work; it gives an overview RF breakdowns in the SPIDER experiment and tries to assess the breakdown probability in the conditions relevant for normal plasma operations.

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Field electron emission in an external magnetic field parallel to the surface

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The work concerns relativistic effects and the influence of an external magnetic field on the transmission coefficient. The Fowler-Nordheim equation has been relativistically generalized and effect of the Lorentz contraction of a potential barrier at the metal-vacuum interface has been found. Influence of the magnetic field parallel to a metal surface on the transmission coefficient is taken into account when $cB < E$.

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Investigations of the transition from field electron emission to plasma discharges (glow discharges and micro-arcs) with extended use of the Fowler-Nordheim plot

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The commonest method of characterising a cold field electron emitter is to measure its current-voltage characteristics, and the commonest method of analysing these characteristics is by means of a Fowler-Nordheim (FN) plot [1]. For example, the field enhancement factor can be calculated. But for novel investigations of the transition from field emission to plasma discharges an extended use

of FN plot is proposed. For this, the inverse voltage (x-axis of the FN plot) was extended with factor $1 = (I \cdot t)/(I \cdot t)$:

$$1/V = (I \cdot t)/(V I \cdot t) = Q/E \quad [1/V = As/Ws] \quad (1),$$

where V is the Voltage, I the current, t the time, Q the sum of all transported charges (cathode - anode) and E the energy required for this. The relation Q/E is a possible option for energetic evaluation. Fig. 1 shows an example of the energetic evaluation with FN plot (see attachment). It can be seen that the micro-arc discharge has a charge transfer with the least energy input. This energetic evaluation, further and improved measurements, an illustrative “energy compass” for a simple FN plot analysis and novel approaches for comparative energetic evaluations of charge transfers (electrons, ions) will be presented and discussed.

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Direct Field Ionisation

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Direct field ionisation of neutral atoms may happen when they are immersed in an external electric field of magnitude comparable to the atomic electric field seen by the outer electron shells. The resulting ionisation probability may have a magnitude comparable to the usual electron impact ionisation probability, and thus this process should not be neglected in plasma simulation codes. In particular direct field ionisation may play an important role in the first triggering phase of a breakdown.

This poster presents the basic underlying physics and formulas, and some simple comparison with electron impact ionisation cross-sections.

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COMSOL simulation of the surface flashover in a MEMS insulator

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This research is on the COMSOL simulation of flashover occurring in a MEMS (Micro-Electro-Mechanical System) insulator and electrode unit, both of the electric field at triple point and of electron trajectories in several practical geometries. In some applications of MEMS technology, electrostatic field up to 5-20kV/mm is of interest. One of these applications is using MEMS components for manufacturing compact electrostatic lenses or apertures to be used in Scanning Electron Microscopes. High voltage insulation is still one of the challenges, as it is in a conventional construction using metal and

ceramic to make lenses and apertures. The field strength at triple points is assessed first, and a glass sphere is added as a dielectric particle later to check the effect of particles in a system. Moreover, a secondary electron emission avalanche (SEEA) model is utilized in the simulation. Electrons are assumed to be emitted from the sphere by the mechanism of cold field emission or ionisation. The secondary electrons generated by electrons hitting on the surface of a glass insulator are simulated in COMSOL, the total electrons collected by the electrode on the positive side are recorded, and the multiplication factor is compared for these geometries. Among these geometries, a two-step structure seems to contradict experimental results published before. We try to explain the differences.

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Diagnostics of hot anode surface by optical methods

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Development of vacuum circuit breakers for medium- and high-voltage applications leads to continuous basic research in the field of vacuum arcs. The diagnostics of the electrode surface plays an important role for understanding of basic phenomena and parameter optimization for corresponding applications since the electrodes provide the material for the arc plasma. It is well known that the anode activity has a distinct impact on contact erosion and interrupting capability, because it leads to injection of atomic vapour into the inter-electrode gap causing the lowering of dielectric strength. Therefore, the knowledge about spatiotemporal distribution of the anode surface temperature is of high interest for qualification of electrode materials.

The contribution presents the results for temperature distribution on the anode surface made of CuCr alloy obtained by optical measurements. Several methods, which are applicable during the arcing and after the current interruption, have been applied for quantitative characterisation: NIR spectroscopy, pyrometry and high-speed camera techniques enhanced by narrow-band filters. Advantages and drawbacks of each method will be discussed. The arc was ignited by contact separation during the current flow. The driving current pulse was supplied by a high-current generator that produces an AC waveform at 50 Hz at several kA magnitude. The temporal evolution of the surface temperature for different anode modes will be presented and discussed.

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Field estimation and the statistical analysis of dark currents

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The prevailing way of analyzing dark currents is by looking only at the mean current. While there have been some work to extract useful information from that, there's a lot of data being ignored by neglecting the inherently statistical nature of the current.

In this talk, I will present a novel method for field estimation and its advantages as opposed to the current method of beta estimation from the FN curve.

Experiment and Diagnostics - Applications / 65**Spectroscopic and Microscopic Observations of Anode Behaviors in Vacuum Breakdown****Authors:** Zhipeng Zhou¹ ; Andreas Kyritsakis^{None} ; Zhenxing Wang² ; Flyura Djurabekova¹ ; Yingsan Geng²¹ *University of Helsinki*² *Xi'an Jiaotong University***Corresponding Author:** zhouzhipeng77@stu.xjtu.edu.cn

Under sufficient high electric field, a breakdown process will be triggered in a vacuum insulation system, influencing the efficiency, reliability and even safety of the system. The transition to a vacuum arc, which is indicated by the formation of a conductive channel in the initial vacuum gap, is an important process for a deeper understanding of the vacuum breakdown. According to our previous work, the anodic glow has no dominant contribution to the conductive path formation, and it is only a secondary effect of the cathode events. In this paper, we investigated the anodic glow in more detail, in order to reveal some nature of the cathode events and the conductive channel formation from this related secondary phenomenon. Spectroscopic and microscopic observations were conducted for a tip-cathode-plane-anode system. Based on the analyses of the result, both the cathode and the anode provide atoms for the anodic glow region in every shot of breakdown. The atoms from the burning cathode spot can reach the anodic glow region at the very beginning of the appearance of the anodic glow, and there should be some concentration process for these cathode atoms at the anode surface, which makes the light intensity in the vicinity of the anode higher than that in the middle of the gap. The material transfer from the cathode to the anode during the entire breakdown can form a contamination layer on the anode surface, which provides atoms to the anodic glow in the following breakdowns. The contamination layer on the anode surface has a "covering effect" on the bulk of the anode. The former usually contributes more atoms to the anodic glow than the bulk of the anode, and sometimes even blocks the atom supply from the bulk of the anode.

Experiment and Diagnostics - Applications / 82**Vacuum breakdown voltage distributions between different contact arrangements and materials****Author:** Erik Taylor¹**Co-authors:** Andreas Lawall ; Jörg Genzmer¹ ; Andreas Schulz¹¹ *Siemens AG***Corresponding Author:** erik-d.taylor@siemens.com

Although electrical breakdowns are often reported as a single value, in general breakdowns for both vacuum and gases are in fact a distribution of values. This work measures the breakdown voltage distribution for two general contact arrangements (floating and fixed shield) using Cu-Cr contact material. Tests were performed using the lightning impulse voltage pulse, with a 1.2/50 μ s rise/decay time. The breakdown distributions were acquired by the always breakdown method. In the always breakdown method, the voltage is set to a high enough level that the contact gap always breaks down, providing a datapoint for each voltage application. Breakdown rates were measured from a few percent up to 100%. The data was compared to an empirical model based on the Weibull distribution and a model taken from work on linear accelerators. The Weibull distribution with a high shape parameter gave good agreement with the data across a wide range of measurements. A model taken from linear accelerator data at very low breakdown rates also successfully matched the data and the calculated Weibull distribution for breakdown rates <10%, using similar parameters in both models. The extremely steep dependence of the breakdown rate on the voltage necessitates a vacuum breakdown model that can explain both the occurrence of the breakdown and the dramatic

change in the frequency of the breakdowns. A comparison with a broad range of other published data demonstrates that detailed comparisons benefit from determining the breakdown distribution and/or a clear choice of the breakdown rate being compared. Comparisons focusing on general trends and broad ranges of parameters can be more flexible.

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Precision high voltage platform for ion mass analysis

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High voltage platform are of widespread use in nuclear physics accelerator in order to provide the initial acceleration of ion. The ion source environment is particular challenging for high voltage holding, since discharge can be energized from source radiation or secondary particle generated by the ion beam.

Moreover spectrometers for charge to mass ratio of exotic nuclei requires a well defined beam energy, which poses challenging requests to high voltage design, rising the question of which electrode design rules are necessary for quiet voltage operation, with typically tolerable energy rms fluctuation in the 10^{-5} order, including contributions from all devices in a beamline (spanning a 10 m size). Need for thick plate ground is discussed and compared to existing installation

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Roles and Physical Processes of Anodes in the Initial Stage of Vacuum Breakdowns

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Vacuum breakdowns are common phenomena in nature and gain their important role in modern technologies. Although a lot of effort has been done to reveal the nature of the breakdown, the dispute over the roles and physical processes of anodes in the initial stage is not over. The objective of the paper is to experimentally investigate prerequisites for appearing anodic glow and its role in a vacuum breakdown. By employing a streak camera with high-time resolution up to several pico-seconds, we observed anodic glow during vacuum breakdowns accurately. Combined with analysis of I-V behaviors, it is found that different anode materials did not affect the delay times between the cathodic and anodic glow obviously as well as the breakdown voltages, and both the energy and charge deposited on anode surfaces are the necessary conditions for triggering anodic glow. Moreover, anodic glow is generated by the combined effect of evaporated atoms from the anode surface and the incident electrons from the cathode. Only the electron with low-energy can excite the atoms efficiently, so the effect of electron sheath, which can control and decelerate the incident electrons, is critical in the physical processes of the anodic glow. In addition, the low-energy electrons drift back to the cathode, changing the emission on it, leading to a final equilibrium of vacuum discharge. In the end, we reaffirm that a fully conductive channel after a vacuum breakdown triggered can be established without contributions from the anode.

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HVDC insulation between shaped electrodes separated by large vacuum gaps

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The contribute describes and analyses some recent experimental results obtained at the High Voltage Padova Test Facility (HVPTF)

The results of four voltage hold -off experiments adopting stainless steel electrodes are presented and discussed. The conditioning histories in high vacuum, obtained by a fully automatic procedure, have been compared and analysed. A marked total voltage effect has been observed for gap lengths longer than 70 mm. The best hold -off performances in medium vacuum, up to 800kV, the limit of the system, were obtained by the stationary injection of Ar.

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Progress of the ITER Neutral Beam Test Facility project

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This paper gives an overview of the progress of the Neutral Beam Test Facility realization, including the experimental status of SPIDER.

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First year of operation of SPIDER, prototype source of ITER neutral beam injectors

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To reach fusion conditions and to control the plasma configuration in ITER, the next step in thermonuclear fusion research, two heating and current-drive neutral beam injectors (NBIs), each supplying 17MW, by accelerating negative hydrogen or deuterium ions to 1MeV. The requirements of ITER NBIs (40A negative H or D ions for 1 hour) have never been simultaneously attained. So in the dedicated Neutral Beam Test Facility (NBTF) at Consorzio RFX (Italy) the performances of the ITER NBI (divergence <7mrad, aiming <2mrad) will be studied and optimised. The NBTF includes two experiments: MITICA, full-scale ITER NBI prototype, and SPIDER, full-scale prototype of the ITER NBI source with 100keV particle energy. SPIDER aim is to investigate source uniformity (over a 1m×2m area), negative ion current density and beam optics.

The present contribution will briefly outline the activities and the experiments carried out in the SPIDER beam source during its first year of operation with volume generation of negative ions. First a description will be given of the preparation activities in view of the start of the operations and of the improvements that were found necessary to guarantee reliable operational capabilities. In order to extend the source pressure range and to provide a thorough investigation of the properties of the early SPIDER beams, a mask was installed in the accelerator, leaving only isolated beamlets (for a total number of 80 beamlets out of 1280). The detailed investigation of the plasma properties, to assess the efficiency of RF coupling to the plasma in different configurations of the RF circuits, are presented. During the first extraction of negative particles from the source, the features of the co-extracted electrons were studied and correlated with the plasma parameters. Particularly, the magnetic filter field effectiveness in reducing the co-extracted electron current was verified; correspondingly, the decrease of the plasma emissivity was studied as well as the influence on the negative ion current. Finally the first characterisation of the SPIDER beam, in terms of beamlet divergence and deflection, is proposed and compared with numerical models while varying the source parameters. The negative ion beam is found to exhibit values of current density and optics similar to those expected in volume operation.

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Design of the first vacuum and low-pressure gas insulation tests for the MITICA 1 MV electrostatic Accelerator

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MITICA is the prototype of the ITER Heating Neutral Beam Injector (NBI), which is designed to generate a 40 A beam of Hydrogen/Deuterium negative ions, to accelerate the ions up to an energy of 1MeV and then to neutralize them, producing a neutral beam of about 16.6 MW power. The design of MITICA is as far as possible identical to the design of the ITER HNB, except that in the ITER NBI, the neutral beam will be directed to the plasma in the Tokamak vessel via a duct, whereas in MITICA the neutral beam will be directed to a water-cooled calorimeter. The NBI system will consist of a Vacuum Vessel (AISI304L, overall dimensions 15 × 5 × 5 m³), where the negative ion Beam Source, which is the most complex component of the NBI system, will be installed, together with other components (i.e. gas-cell Neutralizer, residual Ion Dump and Cryo-Pumps). The negative ion Beam Source includes a Plasma Chamber (with a gas injection system and auxiliaries for the production of negative Hydrogen/Deuterium ions) and a multi-stage Electrostatic Accelerator, constituted by a series of 7 metallic grids each having 1280 apertures. The Plasma Chamber and the metallic grids of the multistage electrostatic Accelerator will be kept at different electric potentials ranging from about - 1MV (Plasma Chamber, Plasma Grid and Extraction Grid) to ground potential (Grounded Grid) in steps of 200 kV. The Vacuum Vessel will be grounded. The insulation between electrodes having different electric potential will be provided by gaps in vacuum (filled with low pressure Hydrogen during operation) and by alumina post insulators. The voltage holding capability of the MITICA Beam Source at 1 MV is a very challenging issue, which could not be fully addressed so far on the basis of the theoretical models and experimental results available in literature. This paper describes a specific HV test campaign to be implemented in the MITICA Vacuum Vessel using a mock-up of the Beam Source. The tests have been designed with the aim of reducing the insulation problem

to its most essential configuration (just 2 electrodes, possibly with an intermediate shield), so as to obtain reliable data on voltage holding at 1 MV and, if necessary, to focus on the most effective solutions. The tests shall be performed in the MITICA Vessel (already available in the NBTf site) both in vacuum and in low-pressure gas, using a specific 1.3 MV Test Power Supply, in parallel with the construction and assembly of the MITICA Beam Source.

In the paper, the test objectives and requirements are first introduced. Then the test configurations and procedures are defined. Finally, some design solutions for the electrode realization are described and preliminary plan together with a list of test equipment is given.

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Surface coatings for arc prevention between plasma facing components

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The design of the RFX-mod device upgrade requires a 3 mm copper shell close to the plasma to achieve improved plasma confinement properties. Although a continuous conductive structure would be preferred as a passive plasma stabilizer, such a conductive structure shall have an electrical discontinuity in both the poloidal and toroidal directions, in order to allow the penetration of electromagnetic fields into the plasma region. These gaps prevent the formation of net poloidal and toroidal currents. Moreover, the shell has been designed with an overlapping region at the poloidal gap in order to reduce the induced field errors.

During Reversed Field Pinch operations, the loop voltage, externally induced to sustain the plasma current, can reach values up to 400 V. These values can rapidly increase up to 2 kV during fast plasma current terminations. Therefore, intense electric fields can develop between the shell flaps, only a few millimetres apart, along the overlapping region. Furthermore, taking into consideration that the copper shell is located inside the vacuum chamber and is therefore exposed to the low temperature plasma of the scrape off layer, the formation probability of harmful electric arcs is high.

In order to avoid arc formation, different types of insulation coating on the copper, able to withstand the applied electric fields in the presence of plasma, are under investigation.

The electrical insulation performances of an alumina coating on a copper substrate are investigated. Several deposition methods have been evaluated, including magnetron sputtering, atmospheric plasma spray and detonation gun spray, which differ in the adhesion to the substrate, compactness, porosity and mechanical strength of the deposited material. The last two methods have the advantage of being conducted in air at atmospheric pressure, without the aid of complex vacuum systems.

In order to validate the process, an experimental apparatus was set up in the laboratory aimed to reproduce the expected conditions at the shell gap. It consists of a vacuum chamber in which a helium plasma was generated by the use of a hot filament and a DC power supply. A bias voltage was applied between a copper plate and a cylindrical electrode (\varnothing 4 mm). The plate side facing the electrode was covered with alumina. The two electrodes are floating and biased by a small capacitor bank ($0.3 \div 2 \mu\text{F}$). The voltage on the electrodes was applied for 200ms, with a repetition rate of 1Hz. In this contribution, the results of the experiments, with the aim of studying the conditions for the arc formation in presence of a weakly ionized plasma ($n_e \sim 10^{16} \text{ m}^{-3}$), are presented. In particular, voltage pulses up to 2.5 kV were applied, with a background gas pressure between 10^{-3} and 10 mbar. Furthermore, the electrodes were kept both in contact and spaced up to 5 mm. The analysis of alumina degradation, after dielectric cracking in the presence of arc, is also presented.

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Study on the post-arc sheath and the post-arc current in vacuum

interrupters

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Post arc dielectric recovery process is an important stage when vacuum circuit breakers interrupt current, which has decisive effect on the whole interrupting process and causes much concern. much concern. The post arc dielectric recovery process, which contains the physical processes, e.g., the dissipation of residual plasma and metal vapor, begins at the moment of current zero and lasts until the gap recovers its dielectric strength. After current zero, the residual plasma forms an ion sheath in front of the post arc cathode and develops to the post arc anode under the effect of transient recovery voltage, then forms the so called post-arc current.

In order to obtain an in-depth understanding of the post-arc sheath, a one-dimensional particle in cell (PIC) model has been developed to study the basic characteristics of the post-arc sheath expansion process. Firstly, the influence of plasma temperature on the post-arc sheath expansion has been studied. Then the theory of ion rarefaction wave. Then simulations of different residual plasma drift velocity also have been carried out. Because the collisions between electrons and metal vapor and the collisions between ions and metal vapor exist during the post arc sheath expansion process, a PIC-MCC model has been developed to study the influence of metal vapor. Moreover, a two-dimensional cylindrical PIC model has been developed to study the influence of plasma motion in radial direction on post arc sheath expansion.

Then the influences on the characteristics of post-arc current by some factors, e.g., residual plasma density, the rising rate of transient recovery voltage, the plasma temperature and the contacts stroke, have been studied with the one-dimensional PIC model. Because ions can enter the post arc anode, the influence on the proportion of ions and electrons entering the post arc anode of the above factors also have been studied. Besides, the influences on the post arc current density of different factors also have been studied.

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Simulations of vacuum arcs with liquid-metal cathodes

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Operation of vacuum arcs involves multi-phase processes associated with melting, evaporation and ionization of electrode materials. In this paper, we will present simulations of vacuum arc ignition from the tip of a Taylor cone on the surface of liquid cathode made of GaIn. The formation of Taylor cone on liquid metal surface is simulated using the volume-of-fluid approach with adaptive Cartesian mesh. We analyze the conditions of the Taylor cone formation and the ejection of liquid droplets from the Taylor cone tip in electric fields. The ignition of an arc discharge starts with the electron field emission and continues until the explosion of the cathode tip due to its heating by the current occurs. We investigate the transition from the field emission to the explosive electron emission (EEE). In this work, we also analyze how the plasma generation and ejection of droplets influence the dynamics of the liquid electrode. The focus on simulations of single ecton on tip of Taylor cones formed on liquid cathodes. EEE results in the formation of plasma jets expanding from the cathode. During jet expansions, a non-ideal plasma turns into an ideal plasma. We use hybrid fluid-kinetic models to analyze effects of ambient gas pressure on the dynamics of EEE-induced plasma processes. The results of our simulations are compared with the available experimental data Acknowledgments This work is supported by the DOE SBIR Project DE-SC0015746.

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Study on breakdown phenomenon of high energy ions bombarding electrode

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In the ion accelerator or film deposition instruments, the ion beam may induce breakdown under the high voltage. In order to explain this phenomenon, a typical model of protons impacting the electrode is analyzed with the help of a PIC-DSMC code. The temporal and spatial distribution evolution of electrons, ions and neutrals with different electrode conditions are present. The critical value of local gas density to induce breakdown is 1025 m^{-3} . According to the discussion of the form of the electrons avalanche, it is evident that the electrons ionization gas is the key reaction affecting the form of breakdown, and the form of sheath near the electrode is available to the electrons avalanche. Finally, the physical mechanism of the breakdown induced by ions bombarding the electrode is explained.

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Generalizing Models of Vacuum Arcs

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Useful models of arcing capable of predicting operating gradients in limited environments are beginning to be produced, but generalizing these models to many applications is coming very slowly. We will show how each stage of the arcing process can be explained by many possible mechanisms, each with its own parameter space and peculiarities, and outline how a general model, applicable to many applications such as fusion, power transmission and accelerators, might be produced. The system must consider mechanisms able to cope with a wide range of environments, (plasma/surface, solid/liquid surfaces, wide ranges of temperatures, pressures and densities, classical/non-Debye plasmas. .), over many different timescales, in a consistent way. We prioritize the outstanding questions and suggest some simplifying assumptions.

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Theory of electric field breakdown nucleation: mobile dislocation population dynamics and atomic simulations

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We present a model in which electrical breakdown in high-voltage systems is caused by a critical transition, due to stochastic fluctuations of the mobile dislocation population in the cathode. Recent developments of the model, due to comparison with experiment and microscopic observations, are described. We propose a number of additional experiments to validate the model, and discuss its applications. Additionally, we describe atomic simulations of the experimental scenarios and their implications for the model.

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Numerical Simulation of the Initial Phase of Unipolar Arcing in Fusion Relevant Conditions

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NUMERICAL SIMULATION OF THE INITIAL PHASE OF UNIPOLAR ARCING IN FUSION RELEVANT CONDITIONS

The results of experimental works on unipolar arcs, e.g. [1], suggest that there are two phases of unipolar arcing. An intense external energy flux, i.e., the laser pulse (or ELM), causes significant heating of a wide region of the surface of an isolated plate, current transfer is initiated and the potential difference between the plasma and the plate is reduced. The laser beam is then switched off, however the potential difference remains the same and small bright spots are seen moving away from the impact site; the second phase.

A model for the initial phase of unipolar arcing has been developed on the basis of the detailed numerical model of plasma-cathode interaction in vacuum arcs [2]. The model takes into account an external heating which triggers the arc spot, the vaporization of the atoms from the heated surface, the ions and electrons produced by ionization of the vapor, the electron emission from the metal surface, and relevant hydrodynamic phenomena, including convection and surface deformation. Current transfer outside the arc attachment is taken into account and the potential difference between the plasma and the metal surface (the plate) is evaluated from the condition that the net current transferred to the plate is zero at each moment.

The developed model is used for simulation of the interaction of an external energy load (laser beam) with and current transfer to a tungsten plate immersed in a helium background plasma in conditions similar to those of the experiment [1]. Simulations were performed for different dimensions of the plate and laser beam radii. The results revealed the formation of a crater, but no jet formation or droplet detachment. If the plate is large ($R = 100\text{mm}$), the peak temperature attained is 5200K , and the plate potential remains below the plasma potential. If the plate is small ($R = 10\text{mm}$), a peak temperature of 7500K is reached, the potential of the plate surpasses the plasma potential, circulation of the melt at the pool periphery occurs, and the erosion (which is mainly due to the vaporization of the metal atoms in the spot) reaches the value of 37 micrograms.

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Diffusion on metal surfaces under high electric fields

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Combining classical electrodynamics and density functional theory (DFT) calculations, we develop a general and rigorous theoretical framework that describes the energetics of metal surfaces under high electric fields. We show that the behavior of a surface atom in the presence of an electric field can be described by the polarization characteristics of the permanent and field-induced charges in its vicinity. We use DFT calculations for the case of a W adatom on a W{110} surface to confirm the predictions of our theory and quantify its system-specific parameters. Our quantitative predictions for the diffusion of W-on-W{110} under field are in good agreement with experimental measurements. This work is a crucial step towards developing atomistic computational models of such systems for long-term simulations.

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Direct Field Ionisation

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Direct field ionisation of neutral atoms may happen when they are immersed in an external electric field of magnitude comparable to the atomic electric field seen by the outer electron shells. The resulting ionisation probability may have a magnitude comparable to the usual electron impact ionisation probability, and thus this process should not be neglected in plasma simulation codes. In particular direct field ionisation may play an important role in the first triggering phase of a breakdown.

This poster presents the basic underlying physics and formulas, and some simple comparison with electron impact ionisation cross-sections.

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Collective motion of large number of cathode spots

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The purpose of the present paper is to investigate numerically the movement of many cathode spots in interaction through their self-magnetic field. The movement of the spots is assumed to be controlled by a combination of stochastic random motion and a drift in the retrograde direction. It is shown that the cathode spots randomly nucleate near the center and then move towards the edge of the electrode. Many spots move collectively in the form of alignments of 3 to 7 spots. For large applied currents, the spots form a cloud that expands periodically in an anisotropic way. We show that under some conditions, the spots form a cloud that rotate regularly over the surface of the electrode.

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Machine learning for Cu surface kinetic Monte Carlo

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Kinetic Monte Carlo (KMC) is among the most efficient methods for modelling diffusion. In the context of CLIC, we're interested in the diffusion processes on the Cu surface - especially under high electric fields that are present prior to electric breakdown events.

The accuracy of a KMC model relies on the comprehensiveness of the catalogue of different migration events that are available for the simulated system, and on the accuracy of the energy barriers associated with those events. The heavy calculations required to find the energy barriers are typically the bottleneck of KMC simulations.

We are improving the KMC model earlier developed in our group, by adding nuance to the way we describe the atomic environments of the migration events, with the aid of machine learning. At the moment the machine learning model has reached performance level comparable to the currently existing one, but we hope that we can eventually capture physical processes more realistically. In this talk, we will present some of the newest simulation results obtained with the machine learning KMC model, as well as some outlook on future work.

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Electrical Design and Voltage Holding Analyses of the MITICA Beam Source Mock-up and its Intermediate Electrostatic Shield

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The high-Q operation of the ITER tokamak will require two Neutral Beam Injectors (NBIs) for plasma heating and current drive. Each beam will be generated by a 40A current of Deuterium negative ions, accelerated up to the specific energy of 1MeV and then neutralized. The power delivered to the plasma by each NBI shall reach 16 MW with duration up to 1h. The beam source will be constituted by an RF-driven negative ion source at -1 MV potential, by a Multi-Aperture, Multi-Grid (MAMuG) electrostatic accelerator (consisting of 5 stages at intermediate potentials), and a gas-box neutralizer at ground potential. All components will be installed in a vacuum vessel (also at ground potential), together with a high-capacity cryo-pumping system which controls of the background gas pressure. In order to validate the ITER NBI design and address all the outstanding issues related to these demanding requirements, a full-scale prototype Injector called MITICA is under construction in Padova at Consorzio RFX in the Neutral Beam Test facility (NBTF). Single-gap insulation at 1 MV in vacuum and/or very low-pressure gas is indeed one of the expected issues which MITICA will have to deal with and that could not be fully addressed so far on the basis of the theoretical models and experimental results available in literature. Recent numerical analyses indicate that an intermediate additional electrostatic shield, biased at -600kV, surrounding the Beam Source might be necessary to guarantee the required voltage holding capability.

For this reasons, before the assembly and installation of the real Beam Source, dedicated voltage holding tests up to 1 MV are planned to be performed in the MITICA VV, using a mockup of the Beam Source and, if necessary, also a mockup of the intermediate electrostatic shield.

In this work the design of this experimental setup from the electrical point of view has been performed by means a new 3D numerical tool, called Voltage Holding Prediction Model (VHPM), based on the clumps theory in vacuum. In particular the electrical design of the Mock-up of the Beam Source, its shield and the mobile anode (needed to adjust the gap length) is presented as well as the expected voltage holding performances of the system

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Dynamic coupling between particle-in-cell and atomistic simulations

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We propose a method to directly couple molecular dynamics, finite element method and particle-in-cell techniques, to simulate response of a metal surface to high electric fields. We use this method to simulate the evolution of a field emitting tip under thermal runaway, by fully including the 3D space-charge effects. We also present a comparison of the runaway process between two tip geometries of different widths. The results show with high statistical significance, that in case of sufficiently narrow field emitters, the thermal runaway occurs in cycles where intensive neutral evaporation alternates with cooling periods. The comparison with previous works shows, that the evaporation rate in the regime of intensive evaporation is sufficient to ignite a plasma arc above the simulated field emitters.

The proposed method, which is under constant development, forms the basis for fully simulating the processes that lead from thermal runaway of intensively field emitting nanotips tips to full arc plasma onset. By introducing and handling new particle species such as neutrals and ions, we aspire to bridge the gap of understanding between the dark current and the vacuum arc ignition. This understanding is becoming increasingly important, in view of recent developments in the analysis of the dependence of the breakdown rate to the available electromagnetic power.

Modeling and Simulations - Applications / 78**Mutual exchange of charged particles in high voltage dc devices insulated by high vacuum**

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The mutual exchange of charged particles is a phenomenon which could justify the onset and the temporal evolution of microdischarges during the high voltage conditioning in high vacuum. Localized heating has been observed in unexpected positions on anodic surfaces at the High Voltage Padova Test Facility. Experimental evidences concerning the existence of accumulation points during occurrence of micro-discharges have been observed and simulated numerically by ray tracing method. The position of the accumulation points depends only on electrode shape and the ratios of applied voltages. It has been demonstrated in a double polarity configuration that a perturbation of the trajectories position by altering the voltage distribution has been sufficient to initiate the micro discharge occurrence.

Modeling and Simulations - Applications / 75**Electric field devices for the EDM prototype ring**

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In the framework of the Physics Beyond Colliders (PBC) study at CERN, the Electric Dipole Moment (EDM) working group is investigating the feasibility of building a storage ring to precisely measure the permanent electric dipole moment of the proton. As a preparation for this main ring, a prototype ring (PTR) is proposed to demonstrate the feasibility of technologies that are not yet operationally confirmed. The PTR is to be small and simple to contain the cost, and will therefore have a circumference of < 100 m. The power supply voltages of the PTR will be limited to 200 kV. The mainly electric field ring will store protons at an energy of 30 MeV for stage 1 and 45 MeV for stage 2 (where frozen spin optics will be pursued). This article describes the challenges related to the electric field quadrupoles of the PTR as well as to the injection elements. The feasibility of the each element will be discussed and the outstanding issues will be highlighted.

Modeling and Simulations - Applications / 159**Development of the design technique with empirical scaling of vacuum insulation for electrostatic accelerators with large surface area and locally concentrated electric field for fusion application**

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A design technique with empirical scaling has been developed in order to design a robust vacuum insulation on the 5-stage electrostatic accelerator with large surface area and locally concentrated electric field, aiming for the acceleration of 1 MeV, 40 A deuterium beams for fusion application. So far, there was no practical design technique and no applicable database of the voltage holding capability of electrodes whose surface area was several m², which was one of critical issues on accelerators for fusion. Recently, the voltage holding capabilities of plane and coaxial electrodes have been widely investigated by the electrodes with the surface area up to 10 m² which is directly applicable to the accelerator for fusion. In addition, voltage holding capability of electrodes with locally concentrated electric field has also been investigated by adjusting electrodes setup so that breakdowns occur at the corner where relatively strong electric field is generated. Based on the Clump theory showing a breakdown is triggered by $EV = \text{const}$, these experimental results have been integrated into the empirical scaling of allowable EV , such as $EV \propto S^{-0.33}$ for plane and coaxial electrodes, $EV \propto \exp(-2 \times 10^{-3} R)$ for the corner, where E and S are the electric field and surface area on the cathode, V is the sustainable voltage and R is the radius of the electrode. By taking into account the empirical scaling, the design technique has been developed in order to optimize the combination of the gap lengths and the surface area in multi-stage electrodes to maximize the voltage holding capability within the given boundary conditions of the geometry. By applying the design technique with the empirical scaling, the vacuum insulation of the 5-stage accelerator and its 5-stage high voltage busings have been designed and experimentally tested. As a result, the design voltage of 1 MV has been successfully satisfied in both cases, which shows the credibility of the technique. Moreover, these are easily applicable to not only the accelerator for fusion application but also general configuration of high voltage components in vacuum.

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Recent progress at pulsed dc systems

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Pulsed DC systems dedicated to the study of electrical breakdown phenomenon and the conditioning process are part of the CLIC (Compact Linear Collider) project. There are two pulsed DC systems operational at CERN, as well as similar systems at Helsinki and Uppsala Universities. In the systems, two plane electrodes with large surface areas are placed parallel to each other with a separation of tens of micrometers, under a high vacuum. The experimental results from the field emission current measurements, conditioning of different materials and the effect of different factors to the breakdown rate and the material state are presented.

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Preliminary results from the cryogenic pulsed dc system

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Field emissions and vacuum breakdowns are major limiting factors for the development of the compact particle accelerators. An extensive program of developing high-gradient X-band accelerating structures has been carried out at CERN. To complement these RF tests, a high repetition rate, pulsed DC system with large planar electrodes has been also operated. It proved that high-field behaviors in RF and pulsed DC are similar, thus validating the use of such systems for in depth studies of the fundamental physics and for development of the high-gradient accelerator technology.

The vacuum breakdown process is dependent upon surface electron emission which inherently depends on the surface material. By studying a range of materials under a range of temperature conditions we can improve the fundamental understanding of the process and promote a better and wider test of the present theoretical models, even widening the understanding to materials used for superconducting accelerating cavities. We report here on a further development with a first DC setup where temperature can be controlled through a wide range, from room temperatures all the way down to 4 K.

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STATISTICAL ANALYSIS OF CURRENT AND X-RAYS SIGNALS FOR A VACUUM HIGH VOLTAGE HOLDING EXPERIMENT

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The High Voltage Padova Test Facility (HVPTF) is an experimental device for investigating HV insulation in vacuum, in support of the realization of MITICA, the prototype of a neutral beam injector for ITER. The facility investigates the physical phenomena underlying voltage holding in vacuum, such as the mechanisms causing breakdowns and the electrode conditioning process, along with testing technical solutions to increase the breakdown threshold. Inside a high vacuum chamber, two stainless steel electrodes, separated by a few centimeters gap, can achieve HV values up to 400 kV each. The conditioning process (typically) consists in the gradual increase of the breakdown voltage in time, until the system achieves a saturation value. Between two consecutive breakdown events, current micro-discharges involving the electrodes are observed in correspondence of high energy X-rays. A global increase of gas emission is measured too, in particular H₂ and CO₂.

In this contribution we present a statistical analysis of micro-discharges events during the conditioning phase, in terms of frequency, amplitude and their occurrence with respect to the applied voltage. The highly time resolved X-ray diagnostics (single events are detected) and the precise timing with the current signal allow a deep characterization of the events occurring during high voltage conditioning.

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X-rays spectrum characterization during high voltage conditioning in vacuum insulated system using high rate detectors

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The characterization of the X-ray energy spectrum during the high voltage conditioning of a multi electrode vacuum insulated system (such as the MITICA electrostatic accelerator) could be useful to understand which stage is causing the micro discharge onset. This technique seems particularly promising for measuring small dark currents ($I < 10\mu\text{A}$), which are generally difficult to be measured with standard techniques. The X-rays produced during HV experiments are mainly due to bremsstrahlung interaction between the electrons escaping from the HV electrodes (field emission effect) and the background gas or the chamber walls. The X-rays spectrum extends from low energy ($\sim \text{keV}$) up to several hundreds of keV depending on the maximum potential difference applied to the electrodes. During these events high photon flux (about 1 MHz) has been measured in the last years using standard NaI detectors that are not able to cope with high rates. In order to measure this wide spectrum at high rate in single photon counting mode, a diagnostic system that combines a Gas Electron Multiplier (GEM) detector (active area $10 \times 10 \text{cm}^2$) and a LaBr3 scintillator ($3'' \times 3''$ active volume) coupled to standard photomultiplier (PMT) is under development. Both are able to stand very high rate ($> \text{MHz}$) in single photon counting mode and results to be complementary with respect to the X-rays energy: GEM is optimized to cover the energy range from 2 up to 50 keV, while LaBr3 extends from 50 keV up to 500 keV. The GEM detector is equipped with anodic pads ($256 \text{ pads } 6 \times 6 \text{ mm}^2$), readout with a new data acquisition system called GEMINI, which gives the possibility to obtain information about the energy deposited in the detector by the incoming radiation using the so called Time-Over-Threshold technique on each detector channel, allowing also a spatial reconstruction of the X-rays footprint. This measurement can be performed at several MHz counting rate, due to the very high rate capability of GEM detector (MHz/mm^2). The LaBr3+PMT detector has a single readout channel that is routed to a 500 Msample/s ADC. This configuration allows getting a few percent energy resolution at 500 keV at MHz counting rate. This paper describes the system construction and shows preliminary measurements using laboratory source.

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Micromachined Surface-Flashover Ion Source Based on MEMS Technology

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The surface flashover ion source based on MEMS technology is the component of the chip type neutron generator. In this paper, patterned titanium films are prepared on polished ceramic substrates and surface flashover ion source samples are obtained. The stability of the surface flashover ion source is studied by analyzing the extraction ion current. The relative standard deviation of ion current is 10.0%, which shows that the arc discharge operates stably. The ratio of ion current to arc current is 3.6%. The electrode ablation characteristics of the surface flashover ion source are obtained

by laser confocal microscope. Finally, based on the experimental results, the discharge mechanism of surface flashover ion source is revealed.

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Plasma cleaning of Cu surfaces before and after conditioning with DC pulses

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Oxidation and other kinds of surface contaminants are one of the biggest unknowns in understanding the breakdown resistance and conditioning behaviour of Cu electrodes under frequent DC voltage pulsing.

Argon can be used to clean the electrode surfaces in situ under vacuum. In the process, Ar gas is inserted into the chamber and a constant DC voltage is used to ionize the gas in order to form plasma arcs that clean the surface.

The plasma cleaning process has been experimented with the Larger Electrode Pulsed DC System in Helsinki. Latest findings show the effect of the cleaning for pristine electrodes both before and after the conditioning process, as well as during flat mode runs. The released contaminants are additionally studied with a mass spectrometer.

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Breakdown Measurements in High-Gradient RF Test Stands

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The CLIC project aims to establish an accelerating gradient of 100MV/m within novel high gradient X-band accelerating structures, this leads to surface electric fields on the order of 220MV/m. In this context, CERN have developed high power X-band RF test stands (Xboxes) to test the prototype structures for CLIC at high power. A summary and analysis of recent RF results from the test stands will be presented.

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Dark Current Analysis at CERN's X-band Facility

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Dark current is particularly relevant during operation in high-gradient linear accelerators. Resulting from the capture of field emitted electrons, dark current produces additional radiation that needs to be accounted for in experiments. In this paper, an analysis of dark current is presented for four accelerating structures that were tested and conditioned in CERN's X-band test facility for CLIC. The dependence on power, and therefore on accelerating gradient, of the dark current signals is presented. The Fowler-Nordheim equation for field emission seems to be in accordance with the experimental data. Moreover, the analysis shows that the current intensity decreases as a function of time due to conditioning, but discrete jumps in the dark current signals are present, probably caused by breakdown events that change the emitters' location and intensity.

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Development of the design technique with empirical scaling of vacuum insulation for electrostatic accelerators with large surface area and locally concentrated electric field for fusion application

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A design technique with empirical scaling has been developed in order to design a robust vacuum insulation on the 5-stage electrostatic accelerator with large surface area and locally concentrated electric field, aiming for the acceleration of 1 MeV, 40 A deuterium beams for fusion application. So far, there was no practical design technique and no applicable database of the voltage holding capability of electrodes whose surface area was several m², which was one of critical issues on accelerators for fusion. Recently, the voltage holding capabilities of plane and coaxial electrodes have been widely investigated by the electrodes with the surface area up to 10 m² which is directly applicable to the accelerator for fusion. In addition, voltage holding capability of electrodes with locally concentrated electric field has also been investigated by adjusting electrodes setup so that breakdowns occur at the corner where relatively strong electric field is generated. Based on the Clump theory showing a breakdown is triggered by $EV = \text{const}$, these experimental results have been integrated into the empirical scaling of allowable EV, such as $EV \propto S^{-0.33}$ for plane and coaxial electrodes, $EV \propto \exp(-2 \times 10^{-3} R)$ for the corner, where E and S are the electric field and surface area on the cathode, V is the sustainable voltage and R is the radius of the electrode. By taking into account the empirical scaling, the design technique has been developed in order to optimize the combination of the gap lengths and the surface area in multi-stage electrodes to maximize the voltage holding capability within the given boundary conditions of the geometry. By applying the design technique with the empirical scaling, the vacuum insulation of the 5-stage accelerator and its 5-stage high voltage busings have been designed and experimentally tested. As a result, the design

voltage of 1 MV has been successfully satisfied in both cases, which shows the credibility of the technique. Moreover, these are easily applicable to not only the accelerator for fusion application but also general configuration of high voltage components in vacuum.

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Electrode conditioning for prevention of DC arc formation in presence of a cold plasma background.

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In RFX-mod2, an experiment for the magnetic confinement of fusion relevant plasmas presently under construction, the in-vessel conductive plasma facing components are expected to be subjected during transient plasma current phases (start-up and termination) to significant electric fields, in the kV/mm range. While such electric fields are of no concern for components in vacuum, the presence of the scrape-off plasma (electron density n_e $1E16 \div 1E18$ m⁻³, electron temperature T_e of few eV) can create the appropriate conditions for dangerous arc formation. For this reason part of the plasma facing components require a proper conditioning technique capable of maintaining the insulation between conductive components even in presence of the scrape-off plasma.

To this purpose an experimental apparatus has been developed where to test the conditions for the arc formation and prevention between two electrodes immersed in a plasma generated by a hot filament. The results of an extensive experimental campaign will be discussed, aimed at demonstrating the possibility of gaining a good electrical conditioning by applying the standard conditioning technique usually employed for higher voltage ranges. It consists of a repetitive sequence of pulses with voltage applied to the pair of electrodes with current limitation, in the presence of the background plasma. The voltage is then slightly increased when arcing ceases, until the final desired voltage level is achieved (2.5 kV). In order to validate the procedure, different electrode materials have been tested in a variety of plasma conditions in terms of electron density and working gas pressure.

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Limiting BD Power in a Pulsed DC System

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Breakdowns generated with pulsed DC systems between large and fixed Cu electrodes are typically highly localized near the edge of the electrodes. The effect is especially strong on BDs which are generated after the electrode has been conditioned, i.e. when the electric field is near the maximum level. Understanding the reason for this phenomenon can be a key factor in hindering the breakdown rate on a given voltage.

Recent studies hint that the effect is related to the power flow across the electrode surface. Between the contact surfaces of the anode and the cathode, the power travelling from the perimeter to the

center is at its highest near the edges, and slightly decreases as it reaches the center point. Limiting the magnitude of this power flow promises to also limit the BD creation.

A straightforward solution to the problem is to consume the power in high-power resistors, inserted in series in between the pulse generator and the anode. The first results show an 18 % increase in the average breakdown field after adding a 5.7 k Ω resistor in the system.

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Cathodic Arc Expansion in Low-Pressure Helium

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The laser-collision induced fluorescence (LCIF) diagnostic allows quantitative and multidimensional interrogation of electron densities and temperatures. We use this diagnostic to interrogate a cathodic arc expanding in 65 mTorr of Helium. Two-dimensional spatial and time resolved images of electron densities and temperatures within the plasma are shown. Optimization methods were implemented to extract densities up to 10^{16} cm⁻³, and results of this procedure are also presented. These images will be used for verification and validation of models and numerical simulations of the plasma expansion.

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Electrical Design and Voltage Holding Analyses of the MITICA Beam Source Mock-up and its Intermediate Electrostatic Shield

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The high-Q operation of the ITER tokamak will require two Neutral Beam Injectors (NBIs) for plasma heating and current drive. Each beam will be generated by a 40A current of Deuterium negative ions, accelerated up to the specific energy of 1MeV and then neutralized. The power delivered to the plasma by each NBI shall reach 16 MW with duration up to 1h. The beam source will be constituted by an RF-driven negative ion source at -1 MV potential, by a Multi-Aperture, Multi-Grid (MAMuG) electrostatic accelerator (consisting of 5 stages at intermediate potentials), and a gas-box neutralizer at ground potential. All components will be installed in a vacuum vessel (also at ground potential), together with a high-capacity cryo-pumping system which controls of the background gas pressure. In order to validate the ITER NBI design and address all the outstanding issues related to these demanding requirements, a full-scale prototype Injector called MITICA is under construction in Padova at Consorzio RFX in the Neutral Beam Test facility (NBTF). Single-gap insulation at 1 MV in

vacuum and/or very low-pressure gas is indeed one of the expected issues which MITICA will have to deal with and that could not be fully addressed so far on the basis of the theoretical models and experimental results available in literature. Recent numerical analyses indicate that an intermediate additional electrostatic shield, biased at -600kV, surrounding the Beam Source might be necessary to guarantee the required voltage holding capability.

For this reasons, before the assembly and installation of the real Beam Source, dedicated voltage holding tests up to 1 MV are planned to be performed in the MITICA VV, using a mockup of the Beam Source and, if necessary, also a mockup of the intermediate electrostatic shield.

In this work the design of this experimental setup from the electrical point of view has been performed by means a new 3D numerical tool, called Voltage Holding Prediction Model (VHPM), based on the clumps theory in vacuum. In particular the electrical design of the Mock-up of the Beam Source, its shield and the mobile anode (needed to adjust the gap length) is presented as well as the expected voltage holding performances of the system

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Electric field devices for the EDM prototype ring

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In the framework of the Physics Beyond Colliders (PBC) study at CERN, the Electric Dipole Moment (EDM) working group is investigating the feasibility of building a storage ring to precisely measure the permanent electric dipole moment of the proton. As a preparation for this main ring, a prototype ring (PTR) is proposed to demonstrate the feasibility of technologies that are not yet operationally confirmed. The PTR is to be small and simple to contain the cost, and will therefore have a circumference of < 100 m. The power supply voltages of the PTR will be limited to 200 kV. The mainly electric field ring will store protons at an energy of 30 MeV for stage 1 and 45 MeV for stage 2 (where frozen spin optics will be pursued). This article describes the challenges related to the electric field quadrupoles of the PTR as well as to the injection elements. The feasibility of the each element will be discussed and the outstanding issues will be highlighted.

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X-rays spectrum characterization during high voltage conditioning in vacuum insulated system using high rate detectors

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The characterization of the X-ray energy spectrum during the high voltage conditioning of a multi electrode vacuum insulated system (such as the MITICA electrostatic accelerator) could be useful to understand which stage is causing the micro discharge onset. This technique seems particularly

promising for measuring small dark currents ($I < 10\mu\text{A}$), which are generally difficult to be measured with standard techniques. The X-rays produced during HV experiments are mainly due to bremsstrahlung interaction between the electrons escaping from the HV electrodes (field emission effect) and the background gas or the chamber walls. The X-rays spectrum extends from low energy ($\sim \text{keV}$) up to several hundreds of keV depending on the maximum potential difference applied to the electrodes. During these events high photon flux (about 1 MHz) has been measured in the last years using standard NaI detectors that are not able to cope with high rates. In order to measure this wide spectrum at high rate in single photon counting mode, a diagnostic system that combines a Gas Electron Multiplier (GEM) detector (active area $10 \times 10 \text{cm}^2$) and a LaBr3 scintillator ($3'' \times 3''$ active volume) coupled to standard photomultiplier (PMT) is under development. Both are able to stand very high rate ($> \text{MHz}$) in single photon counting mode and results to be complementary with respect to the X-rays energy: GEM is optimized to cover the energy range from 2 up to 50 keV, while LaBr3 extends from 50 keV up to 500 keV. The GEM detector is equipped with anodic pads ($256 \text{ pads } 6 \times 6 \text{ mm}^2$), readout with a new data acquisition system called GEMINI, which gives the possibility to obtain information about the energy deposited in the detector by the incoming radiation using the so called Time-Over-Threshold technique on each detector channel, allowing also a spatial reconstruction of the X-rays footprint. This measurement can be performed at several MHz counting rate, due to the very high rate capability of GEM detector (MHz/mm^2). The LaBr3+PMT detector has a single readout channel that is routed to a 500 Msample/s ADC. This configuration allows getting a few percent energy resolution at 500 keV at MHz counting rate. This paper describes the system construction and shows preliminary measurements using laboratory source.

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Optical Spectroscopy in the Large Electrode System at CERN

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LES (Large Electrode System) is the DC system at CERN, used for observations of the gap between electrodes. This system has view ports that allow for different imaging devices to be set up in parallel to observe the breakdown process. Vacuum arcs can often be seen by eye due to relatively high light intensity, but there are other possible sources of light that may exist before a breakdown. Therefore, integrating a spectrometer with the LES would allow for observations of the spectra to be made. This could be used to extract data relating to field emission, plasma or possible surface processes that occur before and during a breakdown.

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Recent progress at pulsed dc systems

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Pulsed DC systems dedicated to the study of electrical breakdown phenomenon and the conditioning process are part of the CLIC (Compact Linear Collider) project. There are two pulsed DC systems operational at CERN, as well as similar systems at Helsinki and Uppsala Universities. In the systems, two plane electrodes with large surface areas are placed parallel to each other with a separation of tens of micrometers, under a high vacuum. The experimental results from the field emission current measurements, conditioning of different materials and the effect of different factors to the breakdown rate and the material state are presented.

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Generalizing Models of Vacuum Arcs

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Useful models of arcing capable of predicting operating gradients in limited environments are beginning to be produced, but generalizing these models to many applications is coming very slowly. We will show how each stage of the arcing process can be explained by many possible mechanisms, each with its own parameter space and peculiarities, and outline how a general model, applicable to many applications such as fusion, power transmission and accelerators, might be produced. The system must consider mechanisms able to cope with a wide range of environments, (plasma/surface, solid/liquid surfaces, wide ranges of temperatures, pressures and densities, classical/non-Debye plasmas. .), over many different timescales, in a consistent way. We prioritize the outstanding questions and suggest some simplifying assumptions.

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Diffusion on metal surfaces under high electric fields

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Combining classical electrodynamics and density functional theory (DFT) calculations, we develop a general and rigorous theoretical framework that describes the energetics of metal surfaces under high electric fields. We show that the behavior of a surface atom in the presence of an electric field can be described by the polarization characteristics of the permanent and field-induced charges in its vicinity. We use DFT calculations for the case of a W adatom on a W{110} surface to confirm the predictions of our theory and quantify its system-specific parameters. Our quantitative predictions for the diffusion of W-on-W{110} under field are in good agreement with experimental measurements. This work is a crucial step towards developing atomistic computational models of such systems for long-term simulations.

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Machine learning for Cu surface kinetic Monte Carlo

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Kinetic Monte Carlo (KMC) is among the most efficient methods for modelling diffusion. In the context of CLIC, we're interested in the diffusion processes on the Cu surface - especially under high electric fields that are present prior to electric breakdown events.

The accuracy of a KMC model relies on the comprehensiveness of the catalogue of different migration events that are available for the simulated system, and on the accuracy of the energy barriers associated with those events. The heavy calculations required to find the energy barriers are typically the bottleneck of KMC simulations.

We are improving the KMC model earlier developed in our group, by adding nuance to the way we describe the atomic environments of the migration events, with the aid of machine learning. At the moment the machine learning model has reached performance level comparable to the currently existing one, but we hope that we can eventually capture physical processes more realistically. In this talk, we will present some of the newest simulation results obtained with the machine learning KMC model, as well as some outlook on future work.

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STATISTICAL ANALYSIS OF CURRENT AND X-RAYS SIGNALS FOR A VACUUM HIGH VOLTAGE HOLDING EXPERIMENT

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The High Voltage Padova Test Facility (HVPTF) is an experimental device for investigating HV insulation in vacuum, in support of the realization of MITICA, the prototype of a neutral beam injector for ITER. The facility investigates the physical phenomena underlying voltage holding in vacuum, such as the mechanisms causing breakdowns and the electrode conditioning process, along with testing technical solutions to increase the breakdown threshold. Inside a high vacuum chamber, two stainless steel electrodes, separated by a few centimeters gap, can achieve HV values up to 400 kV each. The conditioning process (typically) consists in the gradual increase of the breakdown voltage in time, until the system achieves a saturation value. Between two consecutive breakdown events, current micro-discharges involving the electrodes are observed in correspondence of high energy X-rays. A global increase of gas emission is measured too, in particular H₂ and CO₂.

In this contribution we present a statistical analysis of micro-discharges events during the conditioning phase, in terms of frequency, amplitude and their occurrence with respect to the applied

voltage. The highly time resolved X-ray diagnostics (single events are detected) and the precise timing with the current signal allow a deep characterization of the events occurring during high voltage conditioning.

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Breakdown Measurements in High-Gradient RF Test Stands

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The CLIC project aims to establish an accelerating gradient of 100MV/m within novel high gradient X-band accelerating structures, this leads to surface electric fields on the order of 220MV/m. In this context, CERN have developed high power X-band RF test stands (Xboxes) to test the prototype structures for CLIC at high power. A summary and analysis of recent RF results from the test stands will be presented.

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Precision high voltage platform for ion mass analysis

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High voltage platform are of widespread use in nuclear physics accelerator in order to provide the initial acceleration of ion. The ion source environment is particular challenging for high voltage holding, since discharge can be energized from source radiation or secondary particle generated by the ion beam.

Moreover spectrometers for charge to mass ratio of exotic nuclei requires a well defined beam energy, which poses challenging requests to high voltage design, rising the question of which electrode design rules are necessary for quiet voltage operation, with typically tolerable energy rms fluctuation in the 10^{-5} order, including contributions from all devices in a beamline (spanning a 10 m size). Need for thick plate ground is discussed and compared to existing installation

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Field estimation and the statistical analysis of dark currents

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The prevailing way of analyzing dark currents is by looking only at the mean current. While there have been some work to extract usefull information from that, there's a lot of data being ignored by neglecting the inherently statistical nature of the current. In this talk, I will present a novel method for field estimation and its advantages as opposed to the current method of beta estimation from the FN curve.

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Impact of surface contamination on the initiation of a vacuum arc

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Vacuum arc initiation is sensitive to the initial state of the metal electrodes. Surface roughness, oxide thickness, and other surface contaminants impact the arc initiation. In this poster we present results on the impact on arc initiation of dosing metal electrodes with a variety of common gases, such as CO, H₂O, O₂, Ar, methane, and others. We show results of how the current and voltage stabilities are sometimes impacted via gas dosing. A “first use” phenomena is also always observed in which the arc is more easily initiated. Further, the metal electrodes can be reset via gas dosing to produce a “first use” arc even after many hundreds of arc operations. This observation confirms the important role that surface contamination plays in understanding arc initiation and stability.

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Apokamp discharge: the transient luminous event in physical laboratory

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In 2016 the group of experimentalists led by Eduard Sosnin (Institute of High Current Electronics, Tomsk, Russia) has been discovered a new phenomenon in low-temperature plasma physics: an extended plasma jet developing perpendicular to the bending point of the pulsed arc discharge channel between two electrodes [1]. This phenomenon occurs if the discharge ignites between two electrodes: first one must be under the high pulse-periodic potential, and the other have to be floating potential, i.e. connected via a capacitor to “ground”. The discharge has been entitled an “apokamp” (from Greek $\alpha\pi\omicron$ - “off” and $\kappa\alpha\mu\pi\eta$ - “bend”). As it was found that apokamp represents a single needle

or a conical jet of 6–7 cm length being attached to the bending point of the current channel. This new unusual type of discharge phenomenon is observed at high (atmospheric) and medium pressures in gas mixtures usually containing a small portion of electronegative admixture, e.g. oxygen or chlorine. It was shown experimentally that apokamp does not exist in highly purified non-electronegative gases (argon, krypton, nitrogen). It should be also noted that depending on voltage pulse parameters, the apokamp can turn into more than one plasma jets also directed almost perpendicularly to the current channel [2]. In [3], it was shown that the apokamp in low-pressure air represents an exact tiny analogue of large-scale stratospheric transient luminous events, e.g. “blue jets” or “sprites” depending on the operating pressure.

Here we give first theoretical backgrounds for the apokamp phenomenon in terms of deterministic DC-discharge theory. We use the “two-moment model” [4] of a multicomponent discharge plasma to describe a self-sustained periodic discharge in pure oxygen both in the inter-electrode gap and in the surrounding space above the electrodes. To simplify the consideration of a physical situation the 2D-model is used instead of 3D, so the discharge between two plane electrodes with similar to experimental physical conditions has been considered. In simulations, the high-voltage potential is connected to the pulse voltage source through the 10 kohm ballast load. The floating potential electrode is connected to the ground through the 10 pF capacitance. We also consider a simplified plasma-chemical reactions and species sets for oxygen [5]. Our reduced formulation includes only electrons, neutral molecules O and O₂, positive O₂⁺ and negative O₂⁻ single charged ions. The reactions number are restricted to four most important: electron impact ionization, impact dissociation, electron attachment and ion-ion recombination. We also used non-uniform initial conditions for quasi-neutral plasma density and temperature distribution in the inter-electrode space to perform the simulations in the pre-conditioned medium.

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Growth of electric field enhancing precursors for vacuum high-voltage breakdown

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Quasi-stochastic and sudden formation of plasma in a vacuum gap and subsequent high-voltage discharges between electrodes often limits the reliability of high-voltage vacuum electronic devices. Electronic field emission (FE) from the negatively charged electrode is assumed a precursor for a subsequent explosive electron emission (EEE) discharge of the macroscopic gap. The reason for the sudden development of discharge events after long periods of reliable operation is still matter of debate. This paper postulates a relatively slow growth process of carbon and metal based field enhancing structures, which eventually cause avalanche effects of vacuum breakdown and EEE to occur. The slow growth process explains why the undesired events often occur quasi stochastically, despite of prior conditioning the high voltage gap. Means to improve the reliability of vacuum electronic high voltage devices can be derived from the model.

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Modeling of Vacuum Arc Behavior under Anode Spot and Anode Plume Modes

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In many high current vacuum arc experiments, anode spot and plume phenomena are widely observed, which is related to the anode melting and evaporation under strong heating from vacuum arc. Anode vapor will then have great influence on the arc column through ionization-recombination process and energy exchange process among atoms, ions and electrons. This work aims to investigate the vacuum arc characteristics and its interaction with anode spot or anode plume based on two-dimensional (2D) magneto-hydro-dynamic (MHD) model. Formation mechanism of anode spot and anode plume modes in vacuum arc is studied based on numerical simulation. Different from previous work, friction forces between ions and atoms are also taken into account. Simulation results show that the expansion behavior of anode vapor depends on the pressure balance between anode jet and cathode plasma. Higher anode temperature can lead to larger neutral atom vapor area (NAVA) dominant by neutral atoms. In front of the atom vapor area, there is an ionization layer which can be corresponding to the "shell" observed in experiments. Inside NAVA, ion temperature and electron temperature are lower than 1.1eV during anode spot mode and anode plume mode due to ionization process and energy exchange. Electric conductivity in this area is also so low that the maximal value of current density is inclined to move to the edge of the anode instead of anode center, which can make the anode temperature distribution more uniform. The transition from anode spot mode to anode plume mode is related to the pressure competition between anode plasma and cathode plasma. If the anode plasma pressure is much larger than cathode plasma pressure, anode plume mode will form. The asymmetric appearance of anode plume is mainly caused by asymmetric anode temperature distribution with respect to the anode spot center. Qualitative comparisons between simulation results and experiments verifies the correctness of simulation.

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Measurement of Plasma Parameters in the Plasma Generator of KSTAR NBI during Beam Extraction

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The neutral beam injection (NBI) system in KSTAR (Korea Superconductor Tokamak Advanced Research) provide heating and current drive to KSTAR tokamak plasma. It is composed of a plasma generator, an accelerator, and neutralizers. The plasma generator and the neutralizer decide the plasma chemistry and finally the beam fraction while the accelerator decides the beam optics. In general, the plasma characteristics of the plasma generator is measured without the accelerator activation, but it can be varied during beam extraction due to the ion extraction and the back stream electrons. In this presentation, the plasma parameters during the beam extraction and its time evolution is compared to the quiet plasma (without accelerator activation). The collisional-radiative (CR) modeling based OES is used for plasma measurement.