Voltage Holding Prediction in Multi Electrode–multi Voltage Systems Insulated in Vacuum

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ABSTRACT

The voltage holding in the 1 MV ITER Neutral Beam Accelerator is recognized to be one of the most critical issues for long lasting beam operation, due to the complex electrostatic structure formed by differently shaped electrodes biased at different potentials. At present, no model is available to predict the breakdown probability of electrostatic system with a comparable complexity degree. This paper is aimed at proposing an innovative modelling for the voltage breakdown prediction of such complex systems, based on the implementation of the micro particle (clump) induced breakdown Cranberg-Slivkov theory into a statistical approach. After a detailed description, the model is applied to simple geometries and the results are compared to the experiments found in literature; finally, the model is applied to an electrostatic mock-up of the real ITER Neutral Beam accelerator, showing a good agreement with the experiment.

Index Terms- **Fusion reactors, particle beam injection, probability, vacuum insulation.**

LIST OF SYMBOLS

P	Breakdown probability
R_H	Voltage holding probability
N	Number of microparticles for unit surface
A	Electrode surface
q	Microparticle charge
U	Electrode potential
E	Electrode local electric field
B	Magnetic field
g	Gap between electrode
W_c	Clump energy (Cranberg model)
W_s	Sublimation energy
W_{SLVK}	Slivkov breakdown parameter - Weibull shift parameter
W_0	Weibull scale parameter
W	Slivkov breakdown variable
v	Microparticle velocity
m_p	Microparticle mass
m	Weibull shape parameter
p	Pressure
pd_{min}	Paschen minimum voltage pressure-distance product
U_{Pmin}	Minimum Paschen voltage breakdown
M	Mole mass
R	Ideal gas constant
T	Temperature
δ	Mass density
β	Electric field enhancement factor

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1 INTRODUCTION

IN the framework of the International Thermonuclear Experimental Reactor (ITER) project [1] supported by the European Union (EU), Japan, Russian Federation, USA, China, South Korea and India, the realization of a full scale prototype (MITICA- Megavolt ITER Injector & Concept Advancement [2]) of the 40 MW Neutral Beam Injector for Plasma Heating and Current Drive has started in Padova (I).

This system shall produce a 40 A Negative Ion Beam of Deuterium, accelerated by -1 MV_{dc} voltage between the Ion Source biased at negative voltage and the grounded grid; the NIB is then neutralized to obtain an energetic (1 MeV) Deuterium atoms beam. The expected beam power is approx 16 MW deposited in MITICA to a calorimeter. In ITER, this power will heat the thermonuclear plasma and will transfer also momentum to drive the plasma current.

The beam accelerator is composed of five acceleration grids (MAMuG, Multi-Aperture-Multi-Grid structure [2]), each biased at increasing voltages, with steps of 200 kV. Figure 1 shows a view of the Injector with the details of the accelerator.

The voltage holding capability to sustain with adequate safety margin the full voltage with the duty cycle of 1 h on and 3 h off is one of the most challenging issues for the NBI experiment. This is due to a twofold reason: at one side, a complete understanding of the breakdown phenomenon under dc voltage is still lacking, at the other side the NBI electrostatic is extremely complex, being formed by a number of electrodes polarized at different voltages, so that the prediction of voltage breakdown extrapolation from simpler electrode geometries is unreliable.

Nevertheless, for the geometries typical of the NBI injectors [3], i.e. with gap length above few centimetres, there are experimental evidence of the voltage breakdown tendency to saturate with the gap distance (U proportional to g^{α}, with $0.3<\alpha<0.7$), indicating that the breakdown is dominated by the "clump mechanism", proposed first by Cranberg in the fifties [4] or by electron bombardment of the anode when the electron energy exceeds 0.6-0.7 MeV [5].

The clump mechanism, based on the existence of electrically charged micro-particles leaving one electrode and clashing to the electrode with opposite polarity with sufficient energy to vaporize, underlies the presence on the electrode surface of a micro-particle surface density N [m^{-2}] which can provoke the voltage breakdown. Such observation, first proposed by Toya et al [6], which links a physical mechanism (the clump theory) to a statistical property of the electrodes (the N distribution of the micro-particles on the electrode surface) is the basis of the proposed method for voltage holding prediction, necessary for a reliable design of any electrostatic structure.

After a description of the method, the paper discusses its application to simple electrode geometries and comparison with some experimental result.

2 THE METHOD

2.1 THE PROBABILISTIC APPROACH

Let us consider an electrostatic system composed of a number of electrodes E_k polarized at the U_k voltages and define N as the number of micro-particles per surface unit which can be detached by electrostatic forces from sending electrode and clash to the receiving electrode with sufficient energy to vaporize. The breakdown probability associated to the elementary area ΔA_i is expressed by equation (1)

$$p_i = N_i \cdot \Delta A_i \tag{1}$$

Using the same approach followed by the Failure Analysis Theory [7], the voltage holding probability R_H has the following expression:

$$R_H = \prod_{i=1}^{M} \left(1 - N_i \cdot \Delta A_i\right) \tag{2}$$

being M the number of sub areas in which the sending electrodes are divided in. If ΔA_i tends to zero, R_H can be written as:

$$R_H = \prod_{i=1}^{M} \left(e^{-N_i \cdot \Delta A_i}\right) \approx e^{-\sum_{1=1}^{M} N_i \cdot \Delta A_i} \approx e^{-\int_A N \cdot dA} \tag{3}$$

where the integral is extended to the whole sending electrodes area A

The overall breakdown probability has then the following expression:

$$P = 1 - e^{-\int_A N \cdot dA} \tag{4}$$

The point now is to identify the relationship between N and the physical mechanism underlying the clump induced breakdown.

Cranberg conjectures that the breakdown between two electrodes j and k occurs -with nonzero probability- if the energy W_c transferred by the electric potential to a microparticle exceeds its minimum sublimation energy W_s:

$$W_c = q \cdot \left(U_j - U_k\right) = H \cdot E_s \cdot \left(U_j - U_k\right) > W_s \tag{5}$$

H being the ratio of the electric charge transferred to the micro-particle and the local electric field; the vapour produced by the clump sublimation is ionized by the electric field leading to the breakdown. From equation (5), is derived the well known relationship:

$$U_{BD} \propto \sqrt{g} \tag{6}$$

for a gap g between parallel plane geometry (E= constant).

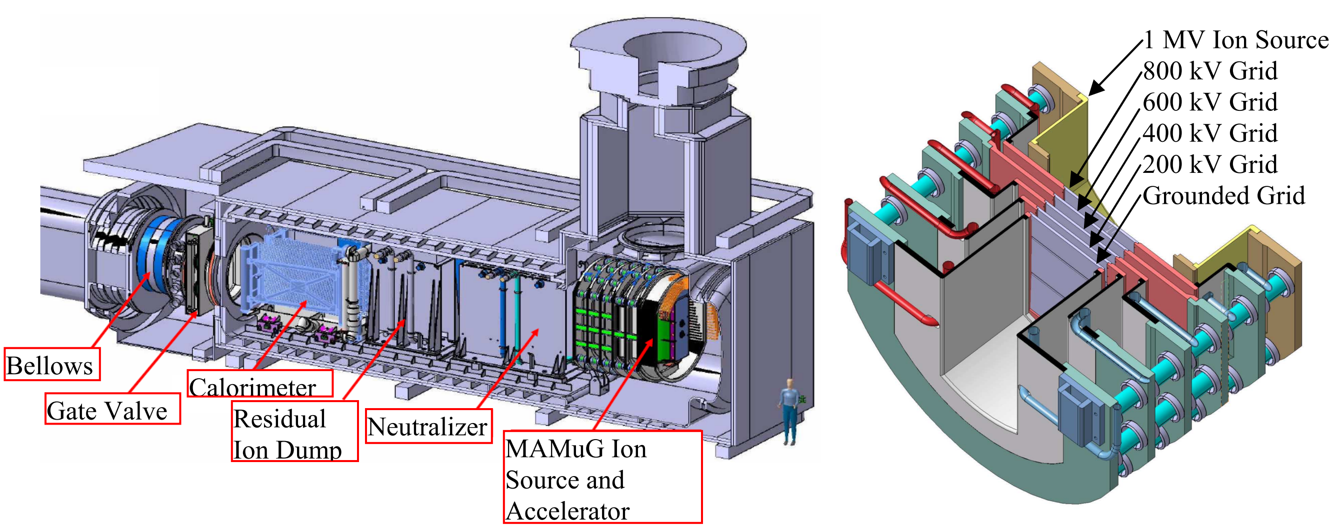


Figure 1. ITER Neutral Beam Injector - left: Neutral Beam Assembly; right: details of the Accelerator (Ion Source missing).

In the Cranberg model there is no difference between anode and cathode (clumps can be either positively or negatively charged), and the effect of the receiving electrode is not considered. Slivkov [8] proposed a modification of the Cranberg criterion, adding the condition that the breakdown can occur if the electric field at the receiving electrode is sufficient to initiate a Paschen discharge across the vapour bubble; furthermore, he conjectures that only negatively charged clumps cause breakdown, because the bubble ionization provokes cathode bombardment, leading to a strong electron emission. The nonzero probability breakdown will occur when W defined in equation (7) exceeds the parameter W_{SLVK}:

$$W = E_C \cdot \left(U_j - U_k\right) \cdot E_A^{\frac{2}{3}} > W_{SLVK} \tag{7}$$

where E_C and E_A are respectively the electric field at the cathode (responsible for clump charging) and at the anode (responsible for the vapour bubble ionization. Appendix I reports new calculation of the W_{SLVK} parameter with respect to the Slivkov model.

The fundamental assumption is that the N number of micro-particles that potentially can produce breakdown is an increasing function of the W parameter; as shown in [6], this functional dependence, which is a cumulative probability, is expressed by the three parameters Weibull distribution:

$$\begin{aligned} N(W) &= N_0 \cdot \left(\frac{W - W_{SLVK}}{W_0}\right)^m & W &> W_{SLVK} \\ N(W) &= 0 & W &\le W_{SLVK} \end{aligned} \tag{8}$$

where W_{SLVK} plays the role of the shift parameter, W_0 is the scale parameter and m is the shape parameter. The N_0 parameter which assures dimensional balancing to equation (8) has the conventional value of 1 $[m]^{-2}$. W_{SH}, W_0 and m depend upon the electrode material, (Cu, Ti, Al, SS etc), its treatment (out gassing, polishing) and probably vacuum quality and do not depend on the electrostatic configuration. In this way, in the assessment of the overall voltage holding capability of a given electrostatic configuration, the electrode physical properties (identified by m, W_0 and W_{SH}) are decoupled from the geometrical properties (upon which the electric field depends). In other words, for a given probability P, the breakdown voltage U_{BD} of a multi-electrode, K-potentials system can be expressed by inverting equation (4):

$$U_{BD} = F\left(P, W_0, W_s, m, k_2, k_3, .. k_K\right) \tag{9}$$

where k_i indicates the ratio between the potential of the i^{th} electrode and the highest potential in the system (referred to the first electrode): $k_i = U_i/U_1$, being $U_1 = U_{BD}$.

By its nature, the probabilistic model is general: for example, it contains, as a special case, the area effect [4] empirical law: the breakdown voltage in parallel plane electrode configuration scales inversely with the electrode area, with the same gap as shown in equation (10).

$$\frac{U_1}{U_2} = \left(\frac{A_2}{A_1}\right)^{\mu} \tag{10}$$

with $0.05<\mu<0.1$. Given, for example, $U=U_{50\%}$ and $W_{SLVK}=0$, being $E=U/d$, the two electrodes configurations with area A_1 and A_1 have the same $U_{50\%}$ breakdown voltage if

$$\int_{A_1} N \cdot dA = \int_{A_2} N \cdot dA \rightarrow \frac{\left(U_1^{\frac{8}{3}} \Big/ d^{\frac{5}{3}}\right)^m \cdot A_1}{\left(U_2^{\frac{8}{3}} \Big/ d^{\frac{5}{3}}\right)^m \cdot A_2} = 1 \rightarrow \frac{U_1}{U_2} = \left(\frac{A_2}{A_1}\right)^{\frac{3}{8 \cdot m}}$$

The corresponding values of m are $3.75<m<7.5$; this result is not conflicting with the, even if scarce, experimental findings (m=18 in [6] and m=5.3÷4.2 in [10])

2.2 TRAJECTORY COMPUTATION

For simple geometries the evaluation of W can be determined analytically (parallel plane or coaxial geometries), but for multi-electrode, multi-potential systems the voltage difference and the anodic electric field experienced by a clump are determined only by calculating its trajectory. In general, the integration of motion equation requires the knowledge of the electrode potentials, the clump initial velocity, its mass m and its electric charge transferred by the microscopic electric field at cathode.

Apparently, this calculation appears unfeasible, due to the impossibility to determine the clump charge q, being unknown the microscopic electric field at the cathode, and its mass m. Nonetheless, it can be demonstrated that the clump trajectory depends only upon the geometry of the electrostatic system, provided that the initial clump velocity is zero and the motion is not relativistic. The other assumption is that q remains constant during the time of flight of the clump. As a matter of fact, some authors [11] state that a number of negative clumps (the smaller ones) can be subjected to field emission (i.e. they lose electrons), but these micro-particles can be disregarded in our model because of their negligible contribution to voltage breakdown.

A concise demonstration of the independence of the trajectory upon mass, charge and even gap voltage can be

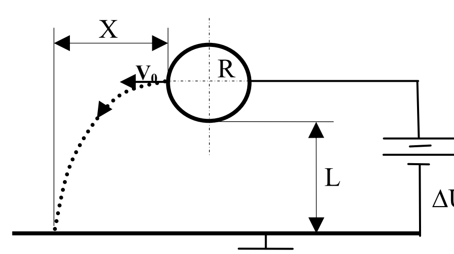


Figure 2. Quantities that determine a characteristic length of a trajectory in a conservative (electric) field.

done by means of the Buckingham Theorem [12]. Referring to Figure 2, the distance X (the variable identifying the ending point of the trajectory, is a function of all the physical parameters governing the system.

$$X = F\left(m_p, q, v_0, L, R, \Delta U\right) \tag{11}$$

Equation (11) is rewritten in terms of dimensional quantities:

$$\frac{X}{L} = f\left(\frac{m_p \cdot v_0^{\,2}}{q \cdot \Delta U}, \frac{L}{R}\right) \tag{12}$$

In case of v_0=0, the trajectory (X/L) depends only by L/R, i.e. the trajectory depends only by the system geometry.

This is valid only if the motion is not relativistic (mass constant), i.e. if the relativistic energy of the clump ($m_p c^2$) is much larger than electrostatic energy (qU). For energy up to 1 MeV this is true, being:

$$\frac{c^2}{1MV} = 10^{11} > \left[\frac{q}{m_p}\right]_{nucleon} = \left(10^8\right) >> \left[\frac{q}{m_p}\right]_{clump} \tag{13}$$

3 APPLICATIONS OF THE METHOD

3.1 COAXIAL GEOMETRY

The first application example deals with the coaxial electrode configuration. In this case the particle trajectory evaluation is not necessary because, due to the radial symmetry of the configuration- the trajectory lines coincide with the electric field lines. As a consequence, equation (9) can be evaluated analytically.

In coaxial geometry, under a potential difference U, the maximum electric field occurs at the internal conductor, and it is expressed by equation (14) as a function of the

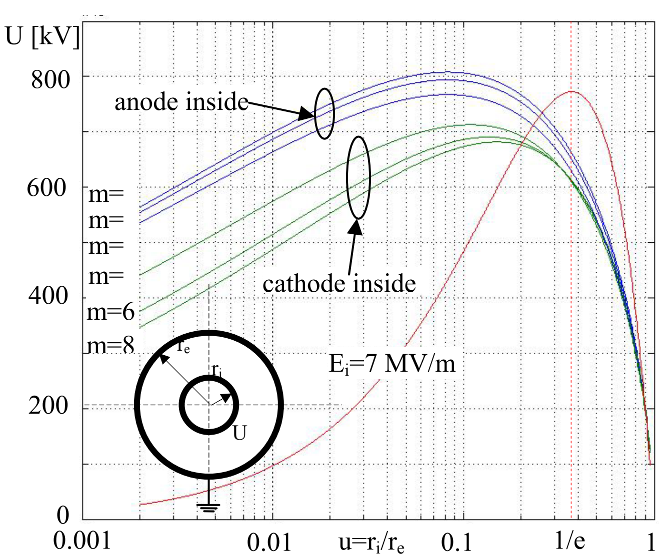


Figure 3 50% breakdown probability for coaxial geometry – r_e=300 mm- as a function of $u=r_i/r_e$ for m=4,6,8, W_s=0 and W_0=5.16x10^{17} [V$^{8/3}$m$^{-5/3}$] The breakdown curve based on electric field criterion is drawn for E_i=7MV/m.

$u=r_i/r_e$ ratio. The electric field at the inner electrode has the following expressions:

$$E_i = \frac{U}{r_e} \frac{1}{u \cdot \ln\left(\frac{1}{u}\right)} \tag{14}$$

For a given external dimension (r_e=const), E_i has a minimum for u=1/e, i.e. for r_e=2.71·r_i, and its value is U/r_i. The breakdown criterion based only on electric field (see Figures 3), shows the maximum voltage holding for u=1/e; the application of the probabilistic model shows instead that the highest voltage breakdown (evaluated for a 50% probability) occurs for r_i smaller than the minimum for the electric field; this results highlights the previous mentioned "area effect", applied to an asymmetric electrode configuration. It is worth noticing that the voltage breakdown increase changing the inner conductor polarity from negative to positive. The influence of the shape parameter is opposite for the two polarities. For u approaching to unity (i.e. the two parallel plane case with small gap) the models converge to the same breakdown voltage, governed by the electric field.

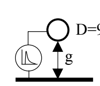
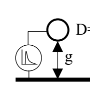
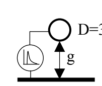
3.2 SPHERE-PLANE GEOMETRY

In this case the computation of the clump trajectories is necessary, so requiring a Finite Element modelling to evaluate the clump trajectory necessary for the calculation of the W parameter. In this case the model results have been compared to the experimental results reported by Slivkov [8].

The experimental campaign was carried out for various electrode configurations and with the application of 1-40 μs (rise time and decay time to half value) voltage waveform, of both polarity; the operating pressure range was from 0.65·10^{-3} to 0.93·10^{-3} Pa. Table I reports the synopsis of the experimental results in terms of voltage breakdown.

To each voltage breakdown value has been associated the 60% breakdown probability as indicated in the Slivkov paper (three breakdown occurrences of five pulses).

Table 1. Synopsis of the Slivkov's results.

 D=9.3 mm g		 D=20 mm g		 D=30 mm g	
U_{BD}-g [kV]-[mm]		U_{BD}-g [kV]-[mm]		U_{BD}-g [kV]-[mm]	
positive	negative	positive	negative	positive	negative
150-1.5	150-2.5	150-1.5	150-2.0	150-2.0	-----
200-2.5	200-3.5	200-3.0	200-3.0	200-3.0	-----
250-4.0	250-5.0	250-4.0	250-4.0	250-3.5	-----
300-5.0	300-7.0	300-5.5	300-5.5	300-5.0	-----
350-6.0	350-10	350-6.5	350-7.0	350-6.5	-----

Being the experimental conditions (pressure, same material of plane and sphere electrode, same degree of surface treatment) unchanged from one experiment to the other, the Weibull parameters W_0 and m would be derived by fitting all the experimental data, reported in Table 1 (W_{SLVK} is assumed to be zero). Implementing in Comsol Multiphysics© v. 3.5 [9] software the trajectory computation, a formulation suitable for data fitting has been derived for equation (9), by using P=63%:

$$U_{BD}(P,W_0,m)=W_0^{\frac{3}{8}}\cdot g^{\frac{5m-6}{8m}}\cdot \chi\left(m,\frac{2g}{D}\right)^{-\frac{3}{8m}}$$
$$\chi\left(m,\frac{2g}{D}\right)=\int_{A_c} f_a^{\frac{2}{3}}\cdot f_c\cdot dA \tag{15}$$

where f_a and f_c are functions of the system geometry (2g/D), the shape parameter m and of the polarity applied. Figure 4 shows the fit of the experimental data.

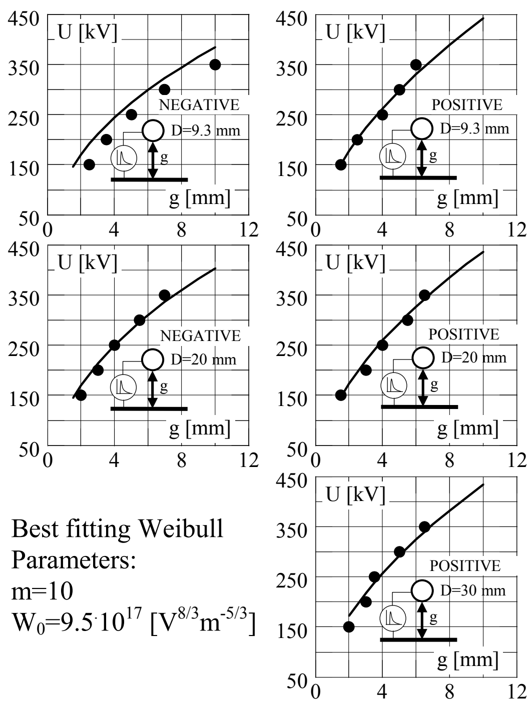


Figure 4 Fit of the experimental results summarized in Table I using the predictive model.

The fit is good for all the cases, apart the 9.3 mm cathode case in which the model gives an overestimation of the voltage breakdown. For both 9.3 mm and 20 mm cases the model reproduces the polarity effect.

3.3 MULTI ELECTRODE – MULTI POTENTIAL CASE

In the experimental work carried out at the MegaVolt Test Facility (MTF) in Naka, Japan the Multi Aperture Multi Gap (MAMuG) and the Single Gap (SinGap) concepts for the ITER Neutral Beam Accelerator have been tested [13]. At this purpose, two different electrostatic configuration for the accelerator have been set up, both characterized by the presence of five potentials (-200, -400, -600, -800 and -1000 kV) and of a complex electrode axial geometry. Figure 5 shows the two configurations.

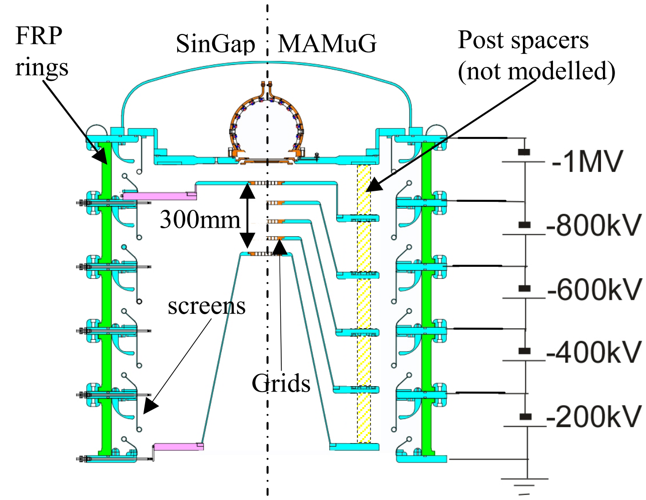


Figure 5 Cross section of the MTF. Left: SinGap configuration; right: MAMuG configuration.

In Figure 6 are reported the results of the electrostatic and of the trajectory analyses. In this last one, each trajectory has been coloured as a function of the W parameters: the warmer the colour, the larger the W.

The analysis method based on the trajectories and the associated W computation highlights the "weak points" of the system much better than the simple electrostatic analysis: for example, referring to the 800 kV screen in the SinGap configuration, its electric field stress is almost equal to the other screens; instead, the trajectories analysis combined to the W parameter (W distribution) evaluation shows that 800 kV screen appears to be critical as far concerns the breakdown initiation, being a source of highly energetic clumps flying to the ground potential electrode. As far the MAMuG configuration is concerned, the higher electric field is concentrated again in the screen region and the calculated W distribution behaves similarly. It is worth noticing that the two configurations do not differ in terms of electrostatic field, whilst they differ greatly in the W distribution and values.

The highest breakdown voltages obtained for the two configurations are 573 kV at 7.2×10^{-4} Pa for the SinGap configuration and 756 kV at 7.2×10^{-4} Pa for the MAMuG configuration.

By associating to the SinGap voltage the 99% breakdown probability, the values of m=8, $W_0=1.15\times10^{16}$ [$V^{8/3}m^{-5/3}$] and $W_{SLVK}=0$ have been determined to match such a breakdown voltage. In Figure 7 are reported the Weibull plot for the two configurations; for the MAMuG one have been adopted the same values m and W_0 derived for SinGap.

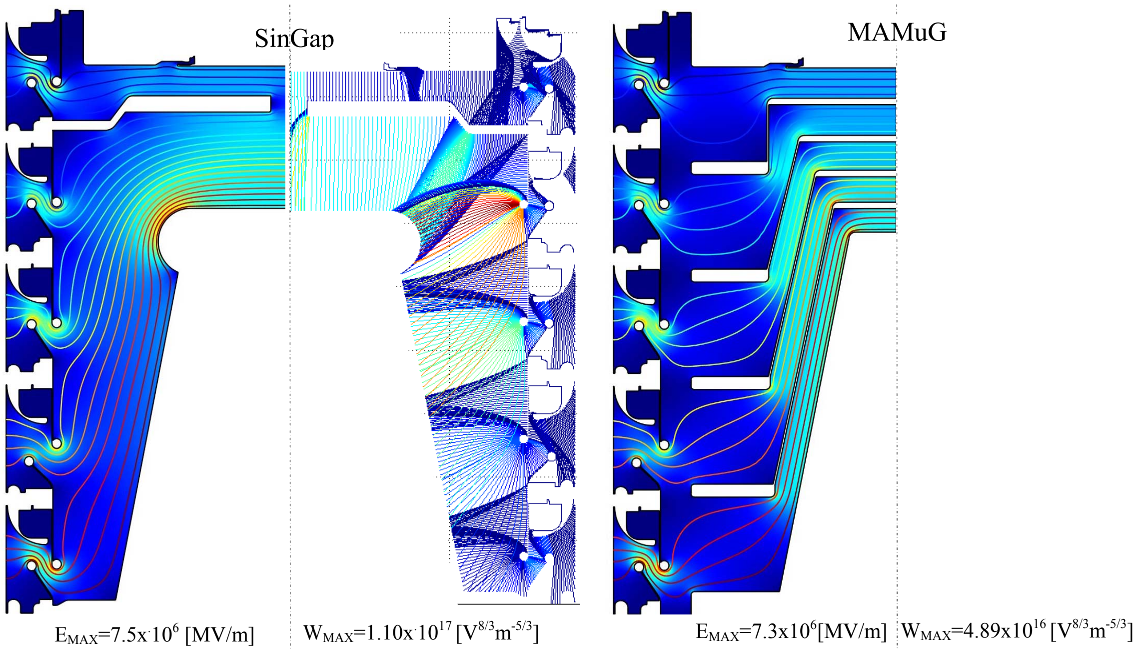


Figure 6 Comparison between the electrostatic field (left) and the particle trajectory (right) analyses for the two configurations.

By considering in the Weibull plots the same breakdown probability of 99%, the corresponding breakdown voltage are for SinGap $U_{99\%}$=541 kV and for MAMuG $U_{99\%}$=789 kV. This last value is in good agreement with the experiment. This result, taking into consideration the complexity of the two electrostatic systems, is an encouraging proof of the predictive model effectiveness.

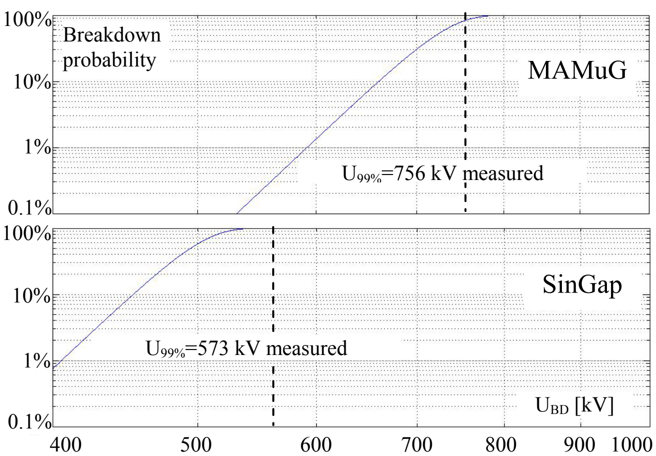


Figure 7. Weibull plot for the SinGap and MAMuG configurations of the MTF.

4 CONCLUSIONS

The presented predictive model of breakdown voltage gives a comprehensive evaluation of the breakdown risk for a given electrostatic configuration, as it includes electrode material properties (through the three Weibull parameters), geometry and breakdown mechanism, this one based on the Slivkov clump theory.

The breakdown voltage evaluation in terms of probability makes this model suitable for an engineering approach to the insulation design; in particular, the electrode profile design would be no longer based upon the electric field minimization but upon the minimization of the new "breakdown driver" parameter W, and the optimization procedure of the electrode profiles shall be aimed at its reduction.

The benchmarking with experiment have been done using data kept from literature, from which was not possible to derive with precision the Weibull distribution parameters m, W_{SLVK} and W_0. Nevertheless, the model showed to behave correctly even in very complicated electrode geometries.

Anyway, further, extensive experimental work is required for the model validation. For example, it is necessary to identify what actually influences the Weibull, distribution parameters: in particular, it would be of great interest to verify if the pressure effect (the voltage breakdown increase for long gap cases when the pressure ranges from 0.01 to 0.1 Pa [14]), whose physical reason is still unclear, can be included in the model.

APPENDIX I

Assuming that the microparticle can be approximated as sphere with radius r connected to the cathode by a "thin wire" of length h (droplet model), the electric charge q transferred to the clump is expressed by:

$$q = \beta^* \cdot E_C \cdot r^2 \tag{A-1}$$

where E_c is the average electric field at the cathode and β^* is the charge transfer coefficient. This coefficient shows a linear dependence, as expressed by equation (A-2), upon the electric field enhancing factor $\beta = E_{Cmax}/E_C$, evaluated by several Finite Element Analyses carried out for different values of r and h, as shown in Figure AI-1.

$$\beta^*(\beta) = A \cdot \beta + B$$
$$A = 1.139 \cdot 10^{-10}\left[\frac{F}{m}\right]; \quad B = -3.557 \cdot 10^{-10}\left[\frac{F}{m}\right] \qquad \text{(A-2)}$$

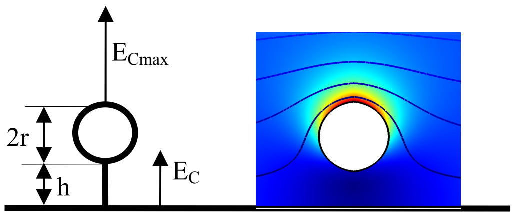


Figure A-1 Droplet model electric field distribution

The breakdown mechanism conjectured by Slivkov consist in the following steps.

- The energy W_c gained by the metal clump (density material δ [kg/m^3], unit mass M [kg/mol]) exceeds its sublimation work L_S [J/mol] after the impact to the anode:

$$W_c = q \cdot U = \beta^* \cdot E_C \cdot r^2 \cdot U \geq \frac{4}{3}\pi \cdot r^3 \cdot \frac{\delta}{M} \cdot L_S \qquad \text{(A-3)}$$

- The number of moles N contained in the clump is:

$$n = \frac{4}{3}\pi \cdot r^3 \cdot \frac{\delta}{M} \qquad \text{(A-4)}$$

- The metal vapour bubble of diameter d [m] expands following the perfect gas law:

$$p \cdot V = n \cdot R \cdot T \rightarrow pd = 8 \cdot \frac{r^3}{d^2} \cdot \frac{\delta}{M} R \cdot T \qquad \text{(A-5)}$$

- across the vapour bubble is applied the anode electric field E_A. The breakdown occurs once the voltage across the diameter d of the bubble exceeds the Paschen breakdown voltage U_P:

$$E_A \cdot d \geq U_P = \frac{\frac{U_{P\min}}{pd_{\min}} \cdot p \cdot d}{1 + \ln \frac{p \cdot d}{pd_{\min}}} \qquad \text{(A-6)}$$

where pd_{min} and U_{Pmin} depend on the clump material.

Substitutig equations (A-3) and (A-4) into equation (A-6), the following inequality follows:

$$E_C \cdot U \cdot E_A^{\frac{2}{3}} \geq W_{SLVK}\left[V^{\frac{8}{3}} \cdot m^{-\frac{5}{3}}\right]$$
$$W_{SLVK} = 1.966 \cdot \frac{L_S}{\beta^*} \cdot \sqrt[3]{pd_{\min} \cdot \left(\frac{\delta}{M}\right)^2 \cdot \frac{U_{P\min}^2}{R \cdot T}} \qquad \text{(A-7)}$$

The coefficient 1.966 results slightly different from that calculated by Slivkov (2.094). Equation (A-7) defines the Slivkov's breakdown criterion.

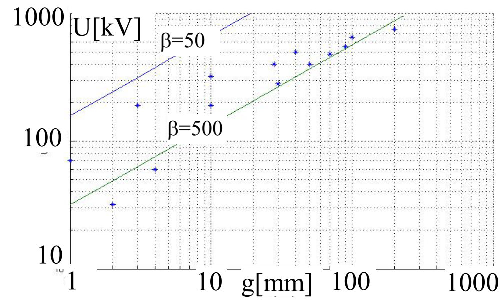


Figure A-2 Experimental result in [14] compared with Slivkov criterion.
pd_{min}=0.665 [N/m], L_S=0.37 [MJ/mol], M=0.056 [kg/mol], δ=8000 [kg/m^3], U_{Pmin}=300 [V], T=300 [K], R=8.31 [J/mol·K].

The criterion is compared with experiment in Figure A-2, showing the results of the breakdown voltage U against gap length g reported in [14], carried out in different experiments but in the same conditions: geometry (parallel disk 200 mm diameter electrodes), electrode material (stainless steel) and pressure (10^{-4} Pa). Ranging 50<β<500 [15] most of the experimental data are included. This observation suggests that the stochastic behaviour of the discharge is mainly due to the distribution of the β value.

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