Phenomenological description of vacuum breakdown and detailed modelling of cathode spots

Camila Cró[1,2], Helena Kaufmann[3], Nelson Almeida[1,2], Pedro Almeida[1,2] , Mikhail Benilov[(*)1,2]

[1] *Departamento de Física, FCEE, Universidade da Madeira, Largo do Município, 9000 Funchal, Portugal*

[2] *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Univ. de Lisboa, 1041 Lisboa, Portugal*

[3]*SE GT PRM D AIS VI, Siemens Energy Global GmbH & Co. KG, Berlin, Germany*

[(*)] benilov@staff.uma.pt

1. Introduction

Field electron emission is a necessary mechanism for the development of vacuum breakdown and is generally accepted that the field on the surface of the cathode is locally enhanced to values that lead to breakdown. In [1], the field enhancement is attributed to imperfections microprotrusions on the cathode surface, though these have not yet been observed experimentally. Alternatively, it has been suggested (e.g. [2], [3]) that breakdown could be attributed to the motion of dislocations on the metal surface as the electrodes are subjected to an electric field. A phenomenological approach was taken when considering the local enhancement of the field - a field enhancement factor, β, based on high-field measurements in high-voltage cryosystems [4] was introduced as a means of describing the enhancement of the field.

Simulations of vacuum breakdown initiated by field emission due to the enhanced electric field have been performed for axially symmetric planar copper cathodes and prove that that field emission is sufficient to cause a thermal instability underneath the surface that leads to a fast increase of the temperature and current density at the cathode's surface. The onset of a hot spot below the surface of the cathode that rapidly reaches the critical temperature of the cathode material was observed. This means that, in principle, no other mechanism in addition to field emission is necessary to cause vacuum breakdown. Preliminary work regarding other relevant physical mechanisms, such as the motion and deformation of the melt and contributions to current and energy transfers from the plasma has also been conducted.

2. The model

Simulations of the temperature and current distributions were made for an axially symmetric cylindrical copper cathode with a radius and height of $10\,\mu$m. The model consists of the heat conduction equation (supplemented with Joule heating) and the current continuity equation,

$$\begin{gathered} \rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + \sigma \left(\nabla \varphi\right)^2 , \\ \nabla \cdot \mathbf{j} = 0, \quad \mathbf{j} = -\sigma \nabla \varphi, \end{gathered} \tag{1}$$

respectively, where T is the temperature, $\mathbf{j}$ is the current density, ρ is the mass density of the metal, c_p is the effective specific heat of the metal (which takes into account the change of phase from solid to liquid), κ and σ are the thermal and electric conductivities of the metal, respectively, and φ is the electric potential. The boundary conditions at the bottom and front-facing surface of the cathode were

$$\begin{aligned} z = 0: &\quad \kappa \frac{\partial T}{\partial z} = q_{\text{rad}_0} , \quad \varphi = 0, \\ z = h: &\quad \kappa \frac{\partial T}{\partial z} + q_{\text{rad}_h} = -q_{\text{em}} , \quad \sigma \frac{\partial \varphi}{\partial z} = -j_{\text{em}}, \end{aligned} \tag{2}$$

where $q_{em} = (j_{em}/e)(2k_B T + A_{\text{eff}})$ is the energy flux due to field emission, j_{em} is the field emission current density, and A_{eff} is an effective work function. q_{rad} is the energy flux due to the radiation emitted by the cathode in terms of its temperature. The field emission current density was calculated in terms of the effective electric field $E_{\text{eff}} = \beta E_w$, where $\beta(T)$ is the temperature-dependent enhancement factor. Finally, thermally and electrically insulating boundary conditions were considered for the lateral surface of the cathode.

3. Results and discussion

For a cathode initially at a temperature of 300 K to which a perturbation of 40 K on a $1\,\mu$m scale is introduced, the results are as follows: for an applied electric field of $E_w = 1.9 \times 10^7$ V/m, we initially have gradual heating of the surface. A region of subsurface heating appears at $t = 14.8$ ns; from here, a very rapid increase in temperature underneath the surface is observed - at $t = 15$ ns, a thermal instability region is well-developed, and the cathode reaches a maximum temperature exceeding the critical temperature of copper, located at a depth of about 60 nm from the surface, as shown in Figure 1. The region of melted metal has a maximum depth of $0.5\,\mu$m. It can be concluded that field electron emission on its own is sufficient to induce vacuum breakdown, and that the enhancement of the surface electric field need not be due to surface microprotrusions, but can be described by a temperature-dependent enhancement factor, $\beta(T)$, which may relate to dislocations.

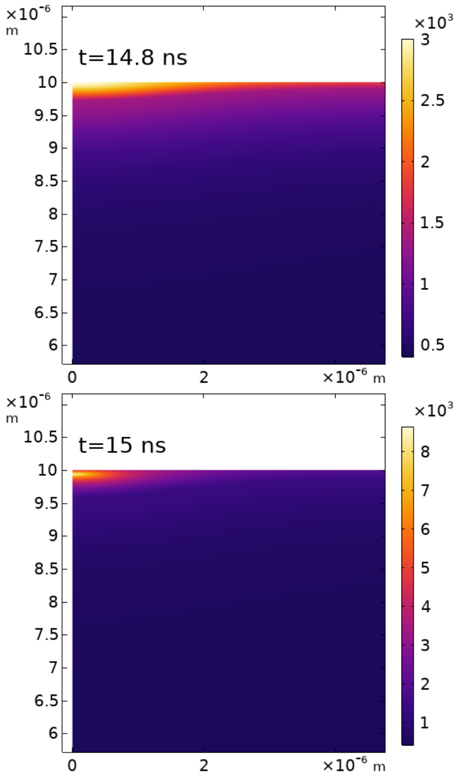

Fig. 1: Temperature (K) of the cathode for $E_w = 1.9 \times 10^7$ V/m, as a function of time.

From here, it is logical to consider what happens next. The results reported above concern the initial stage of breakdown. However, as the temperature increases, plasma contributions will have to be taken into account, similarly to the work presented in [5]. The goal is therefore to produce a thorough description of vacuum breakdown that takes into consideration all relevant physical mechanisms. At this stage, preliminary work has been completed regarding the implementation of the continuity and Navier-Stokes equations (which include the Lorentz force due to the self-induced magnetic field) to account for the motion of the melt, the current and energy contributions from the plasma to the cathode surface, and the deformation of the cathode surface. The final results are to be presented at the conference.

IPFN activities were supported by FCT - Fundação para a Ciência e Tecnologia, I.P. by project references UIDB/50010/2020, UIDP/50010/2020 and LA/P/0061/2020 and by European Regional Development Fund through the Operational Program of the Autonomous Region of Madeira 2014-2020 under project PlasMaM1420-01-0145-FEDER-000016.

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