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Investigation of Vacuum Breakdown in Pulsed DC Systems

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

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

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

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

[1] H. T. C. Kaufmann, M. D. Cunha, M. S. Benilov, W. Hartmann, and N. Wenzel, "Detailed numerical simulation of cathode spots in vacuum arcs: interplay of different mechanisms and ejection of droplets", J. Appl. Phys., vol. 122, p. 163303, 2017.
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[3] A. Kyritsakis, M. Veske, K. Eimre, V. Zadin, and F. Djurabekova, "Thermal runaway of metal nano-tips during intense electron emission", J. Phys. D: Appl. Phys., vol. 51, p. 225203, 2018.

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