BREAKDOWN IN RF CAVITIES*

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Abstract

We present a simple model of breakdown in rf cavities. For most events this involves tensile stress and tensile strength, however other effects can also contribute. We discuss the effects of different materials, fatigue, high pressure gas, primary and secondary emission sites, local field enhancements, dark currents, secondary emission, work functions, magnetic fields, macro and microscopic fracture mechanisms high current densities, surface and subsurface defects, and astronomical power densities. While primarily devoted to normal conductors, this work also has consequences for superconducting rf surfaces.

INTRODUCTION

We have been studying the causes of breakdown in rf systems primarily with reference to high gradient, low frequency structures for the Muon Collaboration and the Muon Ionization Cooling Experiment (MICE)[1][2]. Although this problem has been studied for a long time, and it is related to DC vacuum breakdown, which has been studied for an even longer time, there is no standard model or mechanism or model which explains the data. While we feel that our model fills this need, there are many loose ends and a need for considerable experimental data.

The primary problem with breakdown triggers is that the trigger phase of the breakdown seems to take place very rapidly, (perhaps <0.1 nsec), and with very minute energies, (we estimate <1 nJ), and this phase of the discharge is followed rapidly by a discharge which converts on the order of 1–100 J of electromagnetic energy into heat, much of which is locally deposited in the walls. The discharge itself also takes place in an rf system which, by its nature, is not optimized for instrumentation, so very little has be learned from the discharge itself.

Our effort has grown out of the study of x rays and dark current emission in low frequency (805 MHz) rf systems undertaken by the Muon Collaboration for the Muon Ionization Cooling Experiment (MICE). We have found that the Fowler-Nordheim field emission model described our results when we assumed that the local fields on asperities were on the order of 6 – 10 GV/m, and the dimensions of these emitters was on the order of 10^{-7} m [3]. These parameters are difficult to produce in a repeatable way in the laboratory, however we have found that the field of Atom Probe Tomography is based on evaporation of single atoms at slightly higher fields and there is thus an enormous volume of relevant data we would like to explore[4].

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HISTORY

Breakdown in gasses was first described by Paschen in 1889, in a avalanche model which considered the transverse but not the longitudinal dimensions of the container. Work by Earhart, Michaelson, Hobbs and Millikan looked at the minimum dimensions of the avalanche and discovered that at micron dimensions, in air, breakdown was dominated by two effects, one dependent on the gas and one dependent on the electrodes [5][6][7]. Their data is shown in Figure 1. The data seems to show that two mechanisms are involved, one being the breakdown of the gas at large gaps, and the other due to breakdown of the surface itself. The surface fields measured in these experiments are the same order of magnitude as those presently seen in high gradient rf structures.

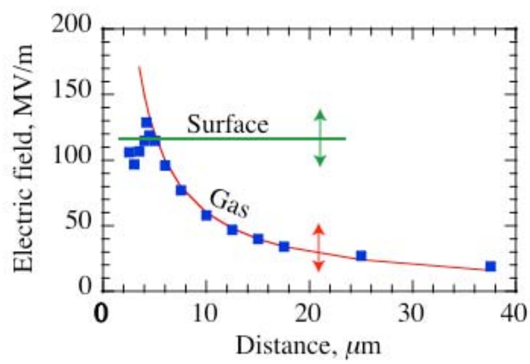

Figure 1, Data on breakdown in air.

While breakdown was aggressively studied in the 1950's and 1960's, there was no agreement on the nature of the trigger mechanisms, although many models and experiments were considered[8][9]. This work is summarized in many places. Recent interest in breakdown is due to the development of the NLC option for the linear collider and flat panel plasma display screens. Our model, based primarily on measurements of 805 MHz cavities done for the Muon Ionization Cooling Experiment (MICE) seem to show that the local fields at asperities are sufficiently high so that the tensile stress exerted by the field is comparable to the tensile strength of the material. This model assumes that fragments or clusters are field emitted from the surface of a material and the fragments are subsequently heated by field emitted electron beams

THE MODEL

We have described our model in a number of recent papers [10][11]. The essential element is that the high surface fields compatible with field emission and x ray production are associated with large, $\varepsilon_0 E^2/2$, tensile stresses, where ε_0 is the permittivity of free space and E is the electric field in volts/m. This stress can be comparable to the macroscopic tensile stress of the material. (Very small samples, in fact, can support much higher stresses.) The primary constraints on the model are that it predict breakdown at the correct local surface field, that it is generally compatible with the data, and that the power densities involved are high enough so that the trigger mechanism can take place in times on the order of 10^{-10} sec or less. There is a considerable literature on breakdown under a wide variety of different conditions and the model should be applicable to much of this literature.

An interesting feature of this study is that we believe our model of rf breakdown also may be a useful explanation of the DC vacuum breakdown, which makes fairly definite predictions about breakdown under a variety of conditions, in a field which has been under study for over 105 years..

Cluster / Fragment Emission

We have modelled the field emission of clusters using a Molecular Dynamics model [12]. While it is unclear what the size of emitted particles will be, the emission of clusters with a "reasonably large" number of atoms can be modelled and understood numerically, and this result should be relevant to a wider range of particle sizes.

To simulate field evaporation at the atomic scale, we have used a classical MD method that is capable of revealing temperature effects. In this MD method, the equations of motion of interacting particles are solved numerically and appropriate initial and boundary conditions are applied.

To simulate field evaporation of a metal tip on an rf-cavity surface, all tip atoms and a "reasonably large" number of surface atoms are treated in detail as "mobile," while the rest of the target is represented by a thermostat. The mobile atoms, with more violent behavior like diffusion, evaporation, or sticking, are studied by solving the set of exact Newton's equations of motion, for which classical forces are obtained from proper interatomic potentials. Two more forces were applied to the charged tip particles: one force was acting on behalf of a periodic rf field and the other was describing the image forces acting on a charge near the metal surface. The thermostat was modelled by using the continuum mechanics elasticity equations and linear thermo-dynamics.

In the MD calculations, we used a Cu (100) surface on the top of which placed a bell-shaped tip that was simply cut of a face centered cubic Cu lattice. The Cu atoms of the "mobile" zone were interacting via a many-bodied Embedded-Atom Method (EAM) potential derived from a second-momentum approximation of the tight binding scheme. The following set of parameters was used for the potential: E_c = 3.50 eV, Z_{nn} = 12, p = 10.08, q = 2.56, where E_c is the lattice cohesion energy, Z_{nn} is the number of nearest neighbors, and p and q are the potential function exponents. This choice of parameters has been devised to attain correct dynamics at room and elevated temperatures [24]. The cylindrical surface model contained $\approx 10^4$ atoms in the central MD zone while the continuum mechanics calculations extended to a volume that was many times larger.

Image forces (Schottky barrier forces) were applied to the charges that were on the top of the tip; the number and location of the charges was obtained from the condition that included the tip's curvature and number of neighbors.

An additional periodic electric field was applied to the charges on the surface of the tip: $\boldsymbol{E}(t) = \boldsymbol{E}_0 \sin(\omega t)$. Here $\boldsymbol{E}_0$ is the maximum value, ω the angular frequency, and t is the time elapsed from the beginning of the evaporation process. Three frequencies of the rf field were modeled: 600 and 800 MHz and 1.2 GHz which correspond to existing linacs. The maximum computation time t_m was then defined as one quarter of the period of rf field oscillation, such as: $t_m = T/4 = 1/4f$, where f is the frequency of the field. Therefore, for f = 600 MHz, $T = 1/f$ = 1.66 ns, and computation time was t_m = 414 ps. This parameter was 312 ps for the frequency of 800 MHz and 200 ps for the frequency of 1.25 GHz. Our computations started at a zero phase and continued to $\pi/2$.

The Cu tip was modelled by 200-1000 Cu atoms built as a bell, with bottom diameters of approximately 54-125Å and heights of 15-30 Å above a Cu (100) surface. Bigger tips were also modelled for comparison. The geometry of the system is shown in Figure 2.

The observed temperature dependence is shown in Figure 3. The model predicts that cluster emission is weakly dependent on the temperature of the cavity, in accordance with measurements made by the CERN/CLIC group. Recent, very preliminary, measurements using an atom probe system at room temperature also shown that the behavior of copper samples does not seem to depend strongly on temperature in the range of 20 – 300 K.

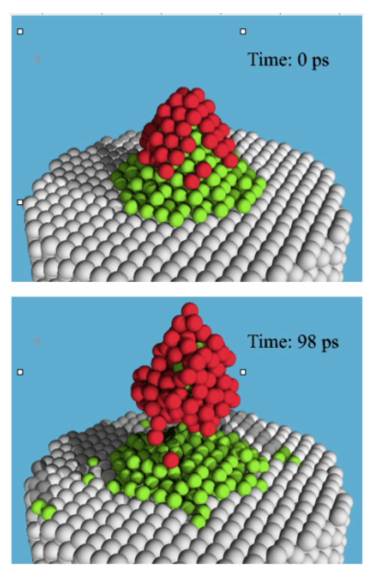

Fig. 2, Field evaporation of clusters

The fields required to produce this cluster evaporation are lower than the 30 – 50 GV/m fields necessary to

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produce single atom evaporation so there may be a tendency to evaporate clusters. This effect could also be due to the force produced by the high charge present in a cluster that might be focused on a particular mechanical defect, starting a fracture process. These mechanisms are accessible in the atom probe microscope and we expect to be able to obtain relevant information on breakdown mechanisms in these devices.

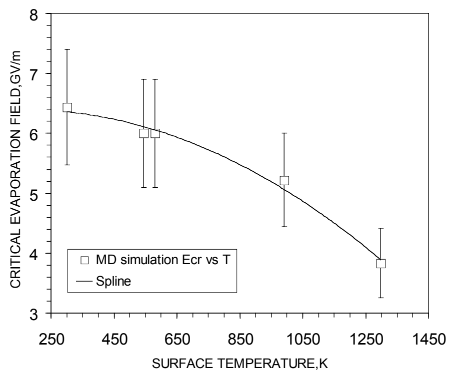

Fig. 3, Temperature dependence of the field evaporation of clusters.

Field Emission Heating

According to measurements from x rays, the surface fields at field emission sites in rf cavities are 5 – 10 GV/m, within a factor of 3 or 4 of the fields at which field evaporation would occur, and the material itself would be unstable. The current densities present at these high fields can and do approach the space charge limit, the highest currents compatible with these fields. An order of magnitude for the power density at which electromagnetic energy is converted to heat can thus be obtained from the dimensions of the emitters, electric fields and the current densities involved. The result shows that fields of 10 GV/m operating over 0.1 μm, producing 1 – 10 mA, would produce powers on the order of 1 – 10 W. The emitter dimensions require that this process occurs in a volume comparable to the linear dimensions of the emitter (0.1 μm)^3, which is equal to roughly10^{-21} m^3, giving a total power density of 10^{21} -10^{22} W/m^3. This power density is comparable to that produced in pulsars, nuclear weapons and supernovae. Gamma Ray Bursters (GRB's) have higher power densities, if the final dimensions after collapse, are used, however the pre-collapse dimensions may be larger.

Comparison with Atom Probe Data

We are trying to check the details of this model experimentally using data from an Atom Probe Field Ion Microscope [12]. We have been able to produce behavior with room temperature copper that seems to show uneven emission which would be characteristic of the processes we are describing here.

The most persuasive test of this model would be detailed and systematic experimental studies of fragment and cluster emission from different materials under a variety of different conditions.

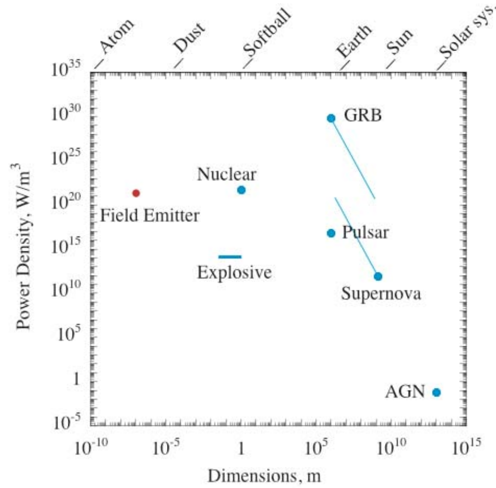

Fig. 4, Power densities.

CONCLUSIONS

The model we describe here is generally in agreement with much of the data taken in rf breakdown. It describes breakdown as due to fracture which occurs at around 5 – 7 GV/m and is primarily independent of the temperature of the material. We intend to extend this model to other materials and a wider class of breakdown events when resources are available. Although primarily relevant to vacuum breakdown a high surface fields, the model should be widely relevant.

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