MECHANISMS LIMITING HIGH GRADIENT RF CAVITIES

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Abstract

The specific mechanisms responsible for breakdown of rf cavities have been widely debated. A large number of different processes are thought to be involved, including field emission, surface contamination, mechanical stresses, plasma effects, explosive electron emission, a variety of heating mechanisms, mechanical imperfections, surface structure and chemical composition. We are attempting to model the surface effects that limit the operation of high gradient rf cavities using the HEIGHTS package. Models of individual processes are being developed and compared, in an attempt to evaluate the relative importance of these effects, specifically for the case of low frequency (200 - 800 MHz.) copper cavities, but probably applicable to other materials and frequencies.

INTRODUCTION

Although breakdown has been studied for many years, the problem seems to be complex and have many causes. In analyzing the data from experiments done by the Muon collaboration in Lab G, we have found that the dark current spectrum can give useful information on the field emitters, and these field emitters can likewise provide useful information on the sources of breakdown. We have begun to model breakdown mechanisms with the ultimate aim of producing predictions that can be compared with experimental measurements.

BREAKDOWN MODELS

An enormous amount of data has been collected on rf and dc breakdown over the past century. This work has been summarized in a number of books and papers[1, 2, 3]. The basic mechanism, described by Dyke and Trolan, who used "lightning rod" shaped probes against ground planes, is that high current densities heat up probe tips and evaporation and ionization then produce breakdown[4]. Additional detail in this model was supplied by Knobloch, who modeled the formation of plasma and the ionization and heating of the surface by the plasma in a high electric field[5].

A number of sources of field emission have been discovered. Dust, inclusions, debris from past breakdown events, voids, grain edges, and distortions of the surface have been seen and identified as possible emission sites. Dust, which is composed of silicon and aluminum oxide, is difficult to completely eliminate from most surfaces. Voids, grain edges and distortions are to some extent the byproduct of the cleaning and annealing process and are being actively studied. In addition the surface of most metals is covered with an oxide layer. The behavior of the oxide layer in an electric field can be complex. Oxides, while normally good insulators, can form conducting paths when exposed to electric fields, and these conducting paths remain after the removal of the electric field[6].

In addition, grain edges and inclusions are found to be the sites of breakdown events, possibly because they contain foreign material and structures. Arcing is seen to take place preferentially at grain boundaries.

While the causes of breakdown events are studied extensively, any breakdown model must explain how very low breakdown rates can exist. Many old linacs with large areas of very damaged copper structures, such as the 50 MeV IPNS system, seem to operate at accelerating gradients where they produce some dark currents and x rays, but do not break down at a significant rate. There is evidence, however, that breakdown rates and dark current production are related[7]. An example of this is shown in Fig. 1.

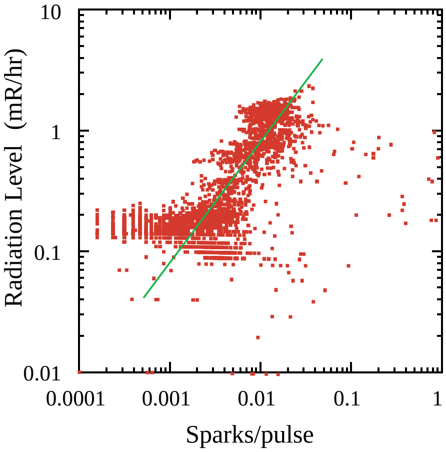

Fig 1. Sparking vs. Field Emission

TENSILE STRESS

Much of this work was heavily influenced by measurements made on 805 MHz open and closed cell copper cavities in Lab G of Fermilab for the Muon Collaboration[8][9].

This work seemed to indicate that the mechanism for breakdown was related to the tensile stress exerted by the electric fields, and the tensile strength of the wall material.

The basic argument is: 1) field emission describes emitter properties, and 2) the properties we infer are very close to mechanical failure of the structure. We assume that dark currents we see produced in the cavity are the

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result of field emission as described by the Fowler Nordheim (FN) expression. We denote this current density by $i_{FN}(E)$, where E is the local electric field. Measured dark currents as a function of electric field can then provide rough estimates of the emitter area and the enhancement factors required to produce the 5 - 10 GV/m gradients required by the FN parameterization of field emission. The argument is shown in Fig. 2, which relates measured dark current production with the FN parameterization. There are basically two variables, the emitter area and the enhancement factors that can be determined from the data. There is a small correction (~0.1) that converts rf field emission values to dc field emission .

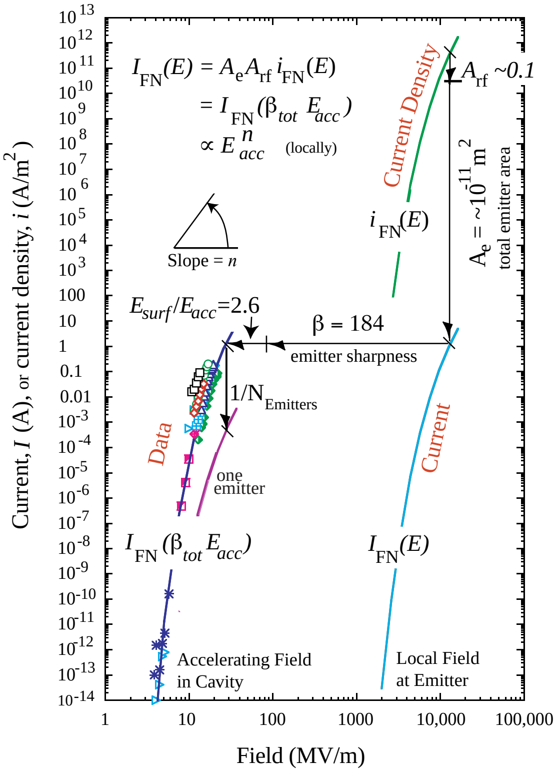

Fig 2. Dark currents and the Fowler-Nordheim model.

The local electric fields inferred from this analysis are very large. These fields are associated with process are very large and the stresses associated with the fields, $p = 0.5\varepsilon_0 E^2$, where E is the electric field and ε_0 is the capacitance of free space, are also very large. This is shown in Fig. 3, for copper. As the field inferred from the dark current measurements increases towards 8 - 10 GV/m, the associated tensile stresses approach 40,000 - 50,000 lb/in^2, which is the tensile strength of hardened copper.

We assume an initial failure of the structure, perhaps on the edge of a crater on a protrusion, might look something like Fig. 4. Such a fragmentation of a crystalline sample would tend to leave sharper corners that could then produce further fragmentation as shown in Fig. 5. We have begun numerical simulation of these processes using the HEIGHTS package[9]. The HEIGHTS package was originally developed for studying plasma-wall interactions in the fusion program, and has been extended to consider a large number of problems where materials are subjected to exotic environments.

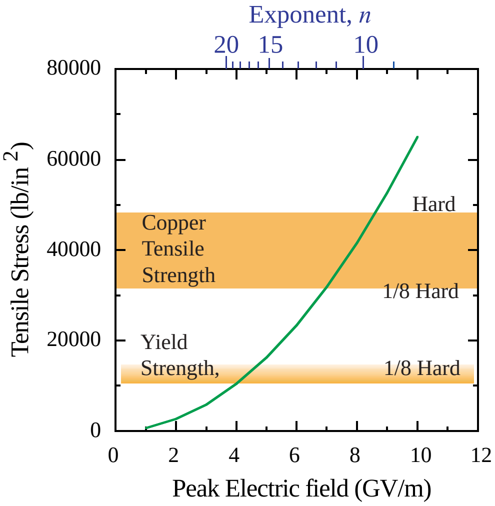

Figure 3. Copper stress

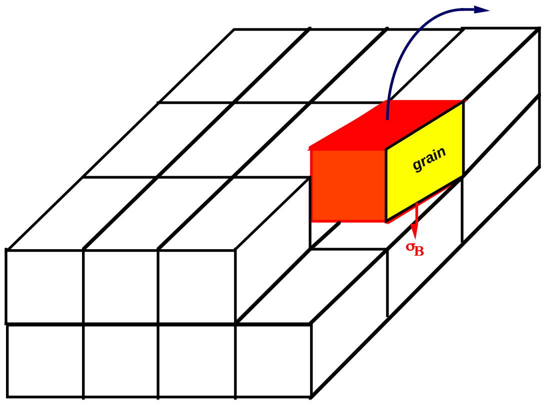

Figure 4. Initial breakup of a copper surface.

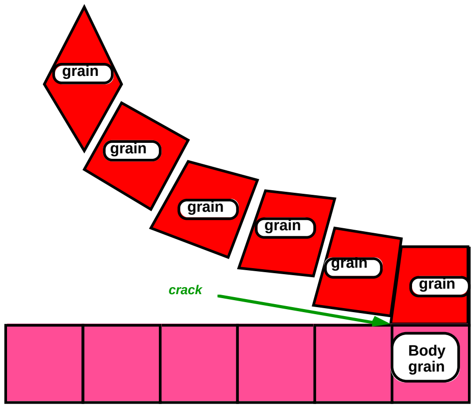

Figure 5. Destruction of surface layer.

Copper grains can be heated ohmically by dark current beams within the structure, or by ionization heating from accelerated dark current beams when the copper grains have detached from the structure. When the grains are coupled to the wall, ohmic heating power increases the temperature. This power is equal to *IV*, where *I* is the dark current and *V* the resistive voltage drop across the grain. On the other hand, when the grains are detached from the wall the absorbed power, *IV*, can be much larger, since the relevant voltage in now the accelerating voltage seen by accelerated electrons, $V = E\mathrm{d}z$ with an electric field *E* and separation dz. This energy, can be many orders of magnitude larger than the ohmic power. Since the grains have lost thermal contact with the wall there will also be no conduction losses. Thus detached grains in space can be heated much faster than grains coupled to the wall. Modeling is underway to determine the rates at which all these processes can occur in real systems to compare with experimental data.

It is also useful to look at the limits of this mechanism in detail to determine how much of the observed behavior is compatible with this mechanism. On the other hand, there are many phenomena that are not obviously explained by the field induced stress on the surface. These include breakdown at inclusions and grain boundaries, repetitive breakdown at similar field conditions and wall damage due to high currents. It is not clear how widely this mechanism applies.

MODELING

Although we are just beginning, we have some initial results on the size limit for grains, frequency dependence of breakdown the motion of electrons in the cavity and the effects of secondary emission. We intend to expand this effort and look at the time development of the breakup, ionization and rf breakdown process in the coming months.

ACKNOWLEDGEMENTS

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