THE INTERACTIONS OF SURFACE DAMAGE AND RF CAVITY OPERATION*

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Abstract

Studies of low frequency RF systems for muon cooling has led to a variety of new techniques for looking at dark currents, a new model of breakdown, and, ultimately, a model of RF cavity operation based on surface damage. We find that cavity behavior is strongly influenced by the spectrum of enhancement factors on field emission sites. Three different spectra are involved: one defining the initial state of the cavity, the second determined by the breakdown events, and the third defining the equilibrium produced as a cavity operates at its maximum field. We have been able to measure these functions and use them to derive a wide variety of cavity parameters: conditioning behavior, material, pulse length, temperature, vacuum, magnetic field, pressure, gas dependence. In addition we can calculate the dependence of breakdown rate on surface field and pulse length. This work correlates with data from Atom Probe Tomography. We will describe this model and new experimental data.

INTRODUCTION

We are looking at the interactions between the cavity rf parameters and the cavity operation, in the combined results of an experimental program, some modeling and initial studies of the material science of surfaces under high electric stress. At the most basic level this effort should explain how multi-cell structures cannot achieve the operating fields of single cell structures, and how structures with long pulses generally require lower fields than those with short pulses.

We work with a breakdown model where the breakdown trigger is caused by tensile stress due to 5 - 10 GV/m local electric fields combined with field emission produce and ionize small lossy plasmas which discharge the stored electromagnetic energy of the cavity into the walls.

THE BREAKDOWN MODEL

Our experimental program has shown that field emitted electron beams can be used to understand asperities that exist on the surface of rf structures. The trigger mechanism is described in detail in a number of recent papers [1-5] . Here we describe how the cavity parameters and the morphology of the surface interact to define the operating limits of the structure. Guided by measurements in Ref [4], we see that if the spectrum of damage produced in a breakdown event is , $s_2(\beta) = Ue^{-a\beta}$, where we assume a proportionality to the energy, U, in the discharge, and define $\beta = E_{local}/E_{surf}$, and a a constant. We also assume that the constraint that fewer hot emitters are produced then demolished in an breakdown event, defines the maximum β_{eq} in the cavity. This is derived in Ref. [5].

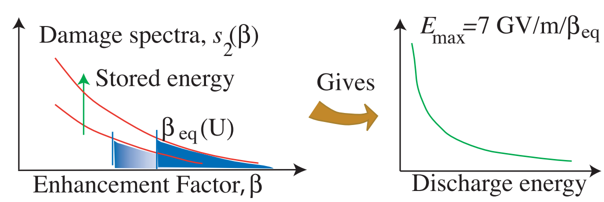

Figure 1: Breakdown causes damage, which limits E_{max}.

The limit to the maximum field in the cavity is then of the form $E_{max} = \sqrt{2\sigma/\epsilon_0}/\beta_{eq}$, where σ, ϵ_0 and β_{eq} are, respectively, the tensile strength of the material, the permittivity constant and the equilibrium value of the enhancement factor determined from the model. Although the value of β_{eq} can, in principle, be calculated theoretically, the procedure is somewhat complicated and it is more useful to interpolate or extrapolate from the parameters of existing systems.

USING THE MODEL

This model can produce a detailed picture of the operation of rf structures at their operating limits. The assumptions above can be used to produce predictions of an extremely large range of parameters. We hope this work will be useful in improving the understanding of these phenomena and in suggesting experiments which can increase the precision of the model. The simple model shown in Fig. 1 can be used to explain all aspects of high gradient rf and DC operation. We present a number of examples most of which have been covered in more detail in Ref [5]

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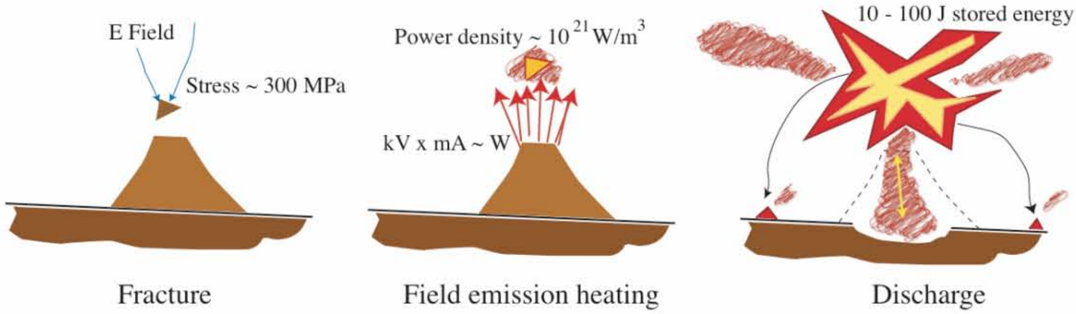

Figure 2: The breakdown model. The initial fracture can be influenced by temperature, magnetic field, material and electric field, the field emission heating stage can be influenced by the gas pressure and type, and the discharge phase is influenced by the stored energy, pulse length, geometry and frequency.

Conditioning Data in Refs. [1] and [7] show that during the conditioning process, the product $\beta E_{surf} = E_{local}$ is constant. During initial operation, the high β field enhancement sites are burned off and the accelerating field rises.

Although most structures are not operated for long periods of time at their maximum operating field, we believe that this operation mode will result in a configuration where the spectrum of field emitters in the structure will experience a sharp cutoff at β_{eq}. This will result in a very narrow range in field emission intensities. We have seen this behavior in our open cell cavity in 2001[1, 5]. The experimental structures used by Dolgashev and Tantawi may be a practical technique for comparative studies of materials at the maximum field [8].

Materials Substituting different materials into structures, without changing the geometry, shows that the breakdown fields increase like $\sqrt{\sigma}$, however some uncertainty remains, due to fluctuations in β_{eq}, which are not well understood [5, 8]. Systematic studies of different materials have never been made, partially because of the complexity of comparing materials with many different properties.

Breakdown rate vs E, Pulse length & emitter lifetime Since the model argues that the dependence of operating conditions should be determined by the dependence of β_{eq} on the stored energy U. The dependence of structure performance on pulse length and time within the pulse are comparatively simple predictions [5].

It is also interesting to look at the correlations between breakdown events, assuming that the first breakdown event produces a secondary breakdown site, and the time at which the second breakdown event occurs is a measure of the lifetime of breakdown sites. Existing data from continuing studies of conditioning the Fermilab linac seem to show that the time between breakdown events is inversely proportional to the frequency of breakdown events. This implies that the simplest model, where the distribution of lifetimes of a breakdown site goes like an exponental, is not correct. When we assume the Manson-Coffin rule of fatigue limited failure, we find that existing data on correlated breakdown events seems to imply that failure of these breakdown sites is related to structural defects in the physical breakdown site, and the distribution of breakdown lifetimes is related to the distribution of these defects in the site [12]. This is discussed in more detail in Ref [5].

Scaling predictions A natural application of this model is to generate scaling laws for maximum gradient as a function of frequency, to compare with the well known Kilpatrick limit. Unfortunately, because the model is sensitive to many aspects of the operating parameters a simple one parameter model is less useful than one would like. The geometry, pulse length, tolerable breakdown rate, power systems and controls can have a significant influence both on the structure and the model. Nevertheless, the logarithmic dependence of the maximum gradient is consistent with experimental data. It is interesting to note that this model assumes that above some frequency, there will not be sufficient stored energy to produce significant damage.

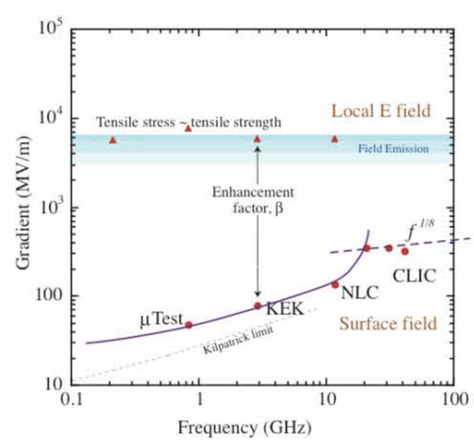

Figure 3: The model predicts that the stored energy and dimensions of the structure strongly influence the operating conditions. Lower frequency structures and longer pulses produce more damage, lowering E_{max}.

Magnetic Field & Temperature Dependence Magnetic field and temperature of the material could influence the initial fracture of the material [3, 4]. While the effects of temperature seem to be small, the effects of magnetic field seem to be somewhat dependent on the cavity geometry, and measurements made with different structures are not entirely consistent.

DC breakdown, Light switches (V below 300 V) There has always been a question about the similarity between DC and rf breakdown. We argue that the first two stages of the process (see Fig. 1) are very similar and there may also be some similarity in the discharge phase. In air, below 300 V, the breakdown process occurs as it does at high fields in vacuum [10].

Gas type & pressure This model assumes that the primary effect of gas in cavities is to reduce the energy of the field emitted electrons hitting the detached fragment (Fig. 1). The retarding force produced by the gas on electrons with energy $E_[eV]$ greater than 100 eV, is roughly $dE/dx = min(20, 13E_{[keV]}^{-0.77})$ GV/m for unit density, while the density of gasses at STP is roughly (molecular wt) $\times$ 0.05 g/l [11]. (The dE/dx for hydrogen is more than other elements because all nucleons are charged.) Thus one would thus expect heavy molecules, like SF_6, and high pressures, would be the most successful at suppressing breakdown.

Atom probe samples We have found that samples in Atom Probe Tomography, (which are roughly the same size as we measure for cavity field emitters, 100 nm dia.), frequently fail at fields of a few GV/m before they reach their operating fields of 10-30 GV/m [9, 6].

Superconducting rf While superconducing rf is subject to different constraints than normal rf, it is still possible to see field emission where local fields reach 4 GV/m, and it is frequently useful to subject these to "high power processing", which seems to use the same breakdown mechanisms to remove these sites.

Disappearance of emitters during breakdown We assume that breakdown triggers caused by high local fields. The local fields also produce field emission, which can be used to measure the properties of these sites. Trivially, when breakdown events occur, we expect that the field emission sites should be destroyed. We have recorded this behavior [4]

Open issues

There are a number of issues that require further effort. Some of these are mentioned below.

Field emission heating Although the failure of emitters occurs when the electrostatic stresses reach the tensile strength of the surface material, it is not clear at what level field emission heating contributes to this failure. The primary factor determining the temperature of the field emitting surface is the geometry of the field emitter.

Geometrical effects While there has been one measurement of the damage spectrum produced in breakdown events, we have seen that the damage spectrum is highly geometry dependent and damage can occur in a number of forms, both at the source of the discharge, and distributed around the inside of the structure.

FUTURE WORK

We believe that it is essential refine to this model to increase the precision and reliability of the results. This work seems to require at least four separate efforts: 1) modeling of the breakdown process, 2) RF experiments on a wide variety of systems, 3) systematic Atom Probe Tomography measurements of a variety of surfaces under high electric fields, and 4) studies of high current density phenomena in the laboratory.

SUMMARY

We are attempting to apply this model to a variety of rf data with some success.

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