A GENERAL MODEL OF HIGH GRADIENT LIMITS*

J. Norem, ANL, Argonne, IL, 60439, USA
D. Huang, IIT, Chicago, IL, 60616, USA
P, Stoltz, S. Veitzer, Tech-X Corp., Boulder, CO, 80303, USA

Abstract

Recent experimental work done to develop high gradient, low frequency cavities for muon cooling has led to a model of rf breakdown and high gradient limits in warm structures. We have recently been extending this model to try to explain some superconducting rf quench mechanisms, as well as DC and dielectric breakdown. The model assumes that the dominant mechanisms in warm metal systems are fractures caused by the electric tensile stress, and surface micro-topography that is strongly determined by the cavity design and history. We describe how these processes can determine all measurable parameters in warm systems. With superconducting systems, these mechanisms also apply, however field emission, impurities and temperature produce a somewhat different picture of quenching and pulsed power processing. We describe the model and some recent extensions and improvements.

OUTLINE OF MODEL

Although accelerating gradients on the order of ~500 GeV/m have been seen with small copper samples, this paper is concerned with the physical mechanisms that limit high power accelerator structures. Over the past five years a model has been developed which seems to explain the operation of warm rf accelerating structures [1]. This model has four parts.

Field Emission

The local environment of field emitters in rf cavities can be easily described using fairly crude measurements of radiation levels or dark currents, as the Fowler-Nordheim field emission expression can be locally fitted by $I = E^n$ [1- 3]. Many measurements have been made, all are consistent with E_{local} = 7- 8 GV/m for operating copper cavities [4].

Surface Morphology

The internal surface of cavities is affected by a number of surface defects, which cause enhanced electric and magnetic fields. The spectra of these enhancement factors, β, have been measured, before and after operation in cavities, in a number of papers. The data are consistent with an exponential distribution $n(\beta) = A\exp(-B\beta)$, where the constants A and B depend on the surface history [5, 6].

Trigger

The 7-8 GV/m electrostatic fields seen in field emission measurements imply $\sigma = 0.5\varepsilon_0 E^2$ tensile stresses on the surface on the order of the macroscopic tensile strength of the material. We assume that these stresses, applied at two times the frequency of the rf, can cause the material to fracture, and any fragments produced would be immediately ionized by field emitted electrons [2].

Equilibrium between EM Fields and Surface

Breakdown events will preferentially destroy field emission sites with high enhancement factors. Discharges will produce secondary breakdown sites, however, and we assume the density of these sites is proportional to the energy in the discharge. An enhancement spectrum of the form $n(\beta) \sim e^{-B\beta}$, implies a maximum field that depends on the discharge energy, U, like $E_{surf} \sim 1/\ln(U)$ [1].

OPEN ISSUES

The open issues we are pursuing are relevant to muon cooling and basic physics of cavity operation.

Initiation of Discharge

Although discharges have been studied for over 100 years, little modeling of this process has been done for a variety of reasons, including the lack of a consensus about the trigger mechanism. We are starting to model the tensile stress induced fracture trigger, specifically the fragment ionization stage, in order to understand the energetics of this process. We assume that there is a fragment very close to a very intense source of ~1 keV field emitted electrons. This produces a small plasma gaining energy from electron impact.

Magnetic Field Effects

Muon cooling requires high accelerating electric fields in the presence of high solenoidal magnetic fields. The data on the maximum field produced in cavities in high magnetic fields are somewhat ambiguous. An open cell cavity conditioned to equal accelerating fields with and without 4 T fields, however a simple pillbox cavity was not able to reach comparable electric fields in the presence of a magnetic field [6]. A high-pressure gas cavity quickly conditioned to equal fields with and without 3 T solenoidal fields [7]. Since the plasma parameters would be strongly affected by a magnetic field, one might expect that the geometry of the cavity and the relative orientation of ***E*** and ***B*** fields at the surface would be relevant, however there is little data to help understand this problem and an incomplete model.

High Pressure Gas and Dielectrics

High pressure gas cavities have been proposed as an elegant way of combining the beam acceleration and

*Work supported by DOE / HEP
#norem@ anl.gov

absorption functions of muon cooling in a single component [7]. The behavior of high-pressure cavities at high gradients seems to be due both to mechanisms that operate on the surface and ones that operate in the gas. Fragment heating from field emission implies that the primary effect of the gas is to attenuate field-emitted electrons before they interact with fragments, which occurs preferentially with small emitters that would have compact high field regions.

Ionization of high density gas by high power beams could be significant. The energy loss of low energy electrons in gas and plastic has been measured by Cole [8]. The dE/dx energy loss is dominated at low energies by atomic properties, and Bethe-Bloch ($1/\beta^2$) effects at somewhat higher energies. We assume that the maximum gradient a gas will support would be given by the condition that the accelerating field would be roughly equal to the drag exerted by the gas for essentially zero energy electrons. In this model, at δ-ray energies where the drag term on electrons was larger, electrons would slow down and recombine; at energies where the accelerating field was larger, the electrons would run away. The plot below implies that if secondary electrons (δ-rays) were produced with more than ~1 keV, they would not recombine. This argument is supported using GEANT4 modeling by Yonahara [9]. The total number of δ-rays produced is ~(2 MeV/g/cm^2)/(20 eV) or 10^5 /g/cm^2. According to Sauli, the fraction of secondaries with energies > 1 keV is about 10^{-3}[10]. These electrons would be detectable as an increased loss tangent at high fields, in a radiation environment.

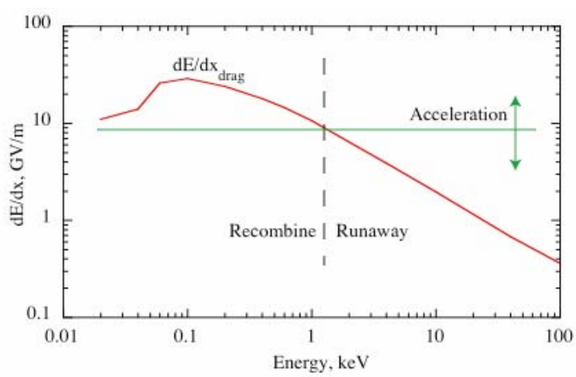

Figure 1: Drag and acceleration terms as a function of particle energy for a 1 g/cm^3 material.

Solid dielectrics should be subject to the same mechanisms, although they seem to be vulnerable to a variety of other effects that may prevent reaching these limits. Goulding, et. al., have shown that the loss tangent of both solids and gasses increased during transient ionizing radiation exposure due to increased conductivity, $\sigma_{[S/m]} \sim 10^{-9} R_{[Gy/s]}$ [11]. The resulting increase in the loss tangent would most likely make beam loss or beam halo responsible for any operational gradient limits in dielectric in an accelerator environment.

Arc Parameters

The nature of discharges in cavities is not well understood. Very high power levels (10's of MW), short timescales (sub μsec), small physical dimensions (~100 μm damage spots), and the almost random timing of events make experimental measurements difficult. The discharge can lose energy by conduction to the nearby wall, to runaway electrons that produce x-rays, and to radiation. In addition to the dimensions of the discharge, ion and electron temperatures, etc., the energy balance of these discharges and the overall power flow of a discharge have never been systematically explored. An understanding of how these plasma parameters interact with many aspects of cavity operation seems essential.

Interactions with Superconducting RF

While superconducting systems have some failure modes unique to the superconductivity, many of the limitations of normal rf also apply to superconducting systems. Superconducting systems are more sensitive to local thermal effects (field emission) than warm rf because of local heating can cause quenches. The behavior of field emitters and high power pulsed processing seems to have direct analogues to normal rf.

The surface of superconducting structures is very similar to that of normal structures, for example radiation levels during conditioning of the SNS cavities were similar to those of seen in the MUCOOL pillbox cavity at similar accelerating fields. Conditioning of supercon-ducting cavities is difficult because, 1) field emission seems to cause quenching at local fields that are too low to produce breakdowns, and 2) niobium becomes harder at low temperatures, requiring higher field gradients to produce fracture.

PLASMA MODELING

OOPIC Pro is a serial 2D code already in use for breakdown modeling [12]. OOPIC Pro has two features that make it appealing for studying breakdown: (a) an option for r-z geometry, and (b) a well-documented, user-friendly graphical interface. In order to determine the plasma parameters it seems necessary to understand the energy balance of the event to some degree.

Radiation produced from equilibrium plasmas is bounded below by bremsstrahlung, and by blackbody limits at the highest level. (It is not clear these plasmas will be in thermal equilibrium.) Radiation losses from multiply ionized metal plasmas come primarily from excitation and recombination radiation of multipli-ionized copper atoms, and involve re-absorption and a variety of parameter dependent effects.

For plasmas not in local thermodynamic equilibrium (LTE), the coronal equilibrium model is appropriate to describe plasmas dense enough to have an equilibrium ionization state but not so dense that three-body processes are important. This density window is given by

$$10^{12}\,\tau^{-1} < n_e < 10^{16}\,\theta^{7/2},$$

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where τ is the time scale in seconds over which the plasma radiates, n_e is the plasma density in cm^{-3}, and θ is the electron temperature in eV. Mosher [13] calculated the ionization state of copper for various temperatures. For 100 eV, the mean charge state is roughly 15, thus multiple ionization is significant. To model this multiple ionization, we will need cross sections for ionization of Cu^{+n} to Cu^{+n+1}. These cross sections have been evaluated and are in the literature.

In the coronal equilibrium model with low ionization levels, the continuum radiation (bremsstrahlung and recombination) depends on the ion and electron densities, (n_i, n_e) and as the temperature, T, multiplied by a temperature-dependent factor:

$$P_{cont} = A_{cont} n_e n_i T^{1/2}.$$

The factor A_{cont} is a known constant. The line radiation also depends on the density density, since $n_e \sim n_i$, and as the inverse square root of temperature, T, multiplied by a temperature-dependent factor, A_{line},

$$P_{line} = A_{line} n_e n_i T^{-1/2}.$$

These expression must, however, be evaluated over a geometry which is strongly space and time dependent.

Initial OOPIC Simulation Results

Initial results look at a simple configuration with a Fowler-Nordheim emitter driving beam into a background gas. Since the basic mechanism of breakdown includes the interactions among ions and electrons in a plasma, i.e., multiple scattering, ionization, excitation, radiation etc. and without losing generalization, we just fill the region with 30 Torr neutral Ne gas, which can produce neon ions via ionization. The electrons are emitted from a Fowler-Nordheim emitter in the boundary, the potential difference (voltage) is 100 kV DC between the upper and lower boundary. In order to create breakdown, the gas density, the voltage, and the field emission current must be chosen very carefully. In the simulation, the electrons are emitted over an extended period. The electrons and ions spread widely and form a cloud with the dimension

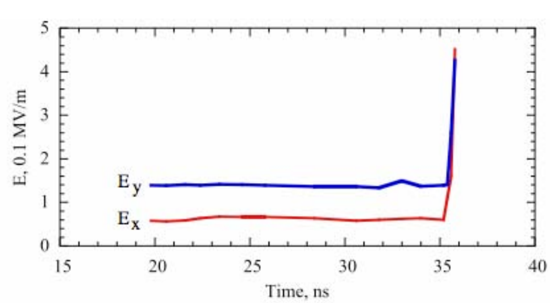

Figure 2: Time history of local E field.

much larger than the original emitter. Fig. 2 shows the time history of the total number of ions. With a discontinuity we assume to be due to the gas breakdown.

This work is just beginning and we anticipate a better understanding this parameter space.

USEFUL EXPERIMENTS

While the field is very old, there is a great deal of duplication and redundancy in the available data. The following experimental and theoretical efforts would be very helpful in understanding current problems.

- There is an immediate need for experimental and theoretical studies of the geometry of the E and B fields and the surface. We assume that magnetic fields could confine or disperse arc plasmas depending on the geometry and plasma parameters.
- The gradient limits / ionization loading of gasses and dielectrics are vital to the operation of high pressure cavities, however they are very poorly explored and understood. Some advantages have been demonstrated, however the physics of these environments is poorly understood.
- Studies of spectra of enhancement factors, both in undamaged condition and after operation in rf systems. are central to the operation of both warm and cold systems. Some preliminary measurements have been made in a variety of environments, but systematic studies are required
- Studies of materials with high E fields using Atom Probe Tomography can help understand surface effects.

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