RF BREAKDOWN IN ACCELERATOR STRUCTURES: FROM PLASMA SPOTS TO SURFACE MELTING*

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Abstract

Plasma spots are known to form at field emission sites in regions of high dc or rf electric field. Several mechanisms for the formation of plasma spots in an rf field have been proposed, and one such mechanism which fits experimental data is presented in this paper. However, a plasma spot by itself does not produce breakdown. A single plasma spot, with a lifetime on the order of 30 ns, extracts only a negligible amount of energy from the rf field. The evidence for its existence is a small crater, on the order of 10 μm in diameter, left behind on the surface. In this paper we present a model in which plasma spots act as a trigger to produce surface melting on a macroscopic scale (~ 0.1 mm^2). Once surface melting occurs, a plasma that is capable of emitting several kiloamperes of electrons can form over the molten region. A key observation that must be explained by any theory of breakdown is that the probability of breakdown is independent of time within the rf pulse—breakdown is just as likely to occur at the beginning of the pulse as toward the end. In the model presented here, the conditions for breakdown develop over many pulses until a critical threshold for breakdown is reached.

INTRODUCTION

The theory presented here assumes that, for a gradient-limiting breakdown event to develop in an accelerator structure, a fairly large area near an iris tip (0.01mm^2 or more) must be brought to the melting point in a fairly short time at the beginning of each of many rf pulses. Such an event will produce serious surface damage, and a few hundred of them will produce a measurable change in the iris geometry. The sequence of events leading to such a breakdown starts with the formation of a plasma spot at a field emission site (for a description of the physics of plasma spots see [1]). A proposed mechanism for the formation of plasma spots is given in the next section. Following that, we construct a field emission based model for the breakdown rate after a structure has undergone initial processing, but at gradient levels below the surface damage threshold. Next, we examine the conditions necessary to produce rapid, large-scale surface melting, including the dependence on the physical properties of the surface metal. The predictions of the theory are then compared with experiment. Finally, we give a theory for the development of geometric surface forms over many rf pulses that lead to a gradient-limiting breakdown event.

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LIQUID DROPLET MODEL FOR THE FORMATION OF PLASMA SPOTS

Once initial field emission sites have been processed off, only emitters depending on the topography of the base material remain. A plasma spot formation mechanism must kick in which depends only on the geometry of these emitters. We propose a model that is closely related to the "mechanical breakup" model of Norem *et al.* [2]. In this model the force due to the intense surface field at the emitter tip exceeds the tensile strength of copper, causing a fragment of the tip to break loose. Once this micro-particle has separated from the emitter tip, it is subjected to bombardment and vaporization by the field emission beam from the remaining tip. The rate of vaporization, and the resulting vapor density, is proportional to the field emission current for a given surface field. The rate of ionization in the metallic vapor cloud is proportional to both the vapor density and the current. *Thus the ionization rate should vary roughly as the square of the field emission current.*

A variation in this scenario assumes that tip of the emitter begins to melt due to resistive heating rather than to mechanically break off. The radius of curvature of the molten tip is set by a balance between the force per unit area, F_A, due to the E^2 force pulling on the surface and the surface tension α of the liquid metal (1.3 Nt/m for copper). It is given by [3]

$$r_0 = 2\alpha/F_A = 8\alpha/\varepsilon_0 E_S^2. \quad (1)$$

As the E-field increases the radius of curvature of the molten tip decreases until an unstable point is reached. The tip begins to neck down (possibly due to a pinch effect from the increasing magnetic field associated with the FE current??) and a droplet or a train of droplets are pinched off and pulled away. Many experimental measurements on field emitters have shown that the maximum surface field at the tip of the emitter cannot exceed about 7–10 GV/m before the emitter is destroyed. Also, it is observed that emitters in superconducting cavities cannot be processed (implying creation of a plasma) unless the emitter area is greater than about 10^{-15} m^2 [4]. Using α = 1.9 Nt/m for niobium and E_S = 7 GV/m, Eq. (1) gives an effective emitter area (≈ $2r^2$) of $2.4\text{x}10^{-15}$ m^2.

A FIELD EMISSION MODEL FOR TRIGGERING BREAKDOWN EVENTS

In the initial stages of processing, we expect that the field emission features with the highest beta values will be burned off first, leaving single isolated craters. When a crater is formed, it leaves behind its own beta distribution due to the topography of the crater rim and the presence of ejected material. At this point, new plasma spots will tend to form on or near the rims of existing craters, beginning the process of crater clustering. This second spot will wipe out 1/3 of the rim of the first crater, so that the total rim circumference is 1-2/3, or 2^X where x = 0.74. A third spot is most likely to occur where two crater rims intersect. The geometry of the situation (see Fig. A-7 in [5]) gives x = 0.70. For a large number of overlapping craters, x approaches 2/3. A reasonable assumption is that the probability for the formation of an additional plasma spot in a crater cluster is proportional to the total rim circumference $dN/dt \sim N^{2/3}$. An integration shows that the total rim circumference varies as t^2. Next, assume that the probability per unit time of having a critical number of plasma spots alive at the same time in the crater field, so as to produce surface melting and a breakdown event, is proportional to the total rim circumference, t^2, at a given value of the collective field emission current from the crater cluster. We assume that, as a function of FE current, the breakdown probability is proportional to the ionization rate, or to the square of the FE current. The net breakdown probability per pulse is

$$p = AT^3\exp(-C/\beta_{BD}E_S \qquad (2)$$

Here $\beta_{BD} = \beta/2$, where β is the usual field enhancement factor and $C = 7x10^4$ for copper. The factor of two in the betas is verified by measurements at SLAC on NLC accelerator structures. From dark current measurements on several structures the betas ranged from 30 to 47, while the β_{BD}'s ranged from 18 to 25 [6]. Now define normalized variables $g = \beta_{BD}E_S/C$ and $\tau = T(A/p)^{1/3}$. Then $g = [3\ \ln(\tau)]^{-1}$. Suppose the variation in gradient over a range in pulse length is modeled by the power law expression $g \sim T^{-n}$. By equating the values and slopes of the two preceding expressions at the center of the range, the exponent n is related to g by n = 3g. From measurements on a typical structure, values of $\beta_{BD} = 22$ and g = 0.051 at 70 MV/m were obtained [6] giving n = 0.153. This is quite close to the measured value of 1/6.

SURFACE MELTING PRODUCED BY MULTIPLE PLASMA SPOTS IN A CRATER CLUSTER

A typical plasma spot emits about 10 A of electron current in an rf field. In a wide rf gap, half of this current is emitted into the rf field and the other half returns to back to hit the emitting surface (see [7] for a discussion of electron motion in an rf gap). A back-bombarding electron has a typical energy of 50 keV and power per spot of about 250 keV dissipated in the surface layer of the metal. A complicating factor in calculating the temperature rise produced at a metal surface by the impacting electrons is the fact that these electrons can penetrate a substantial distance into the metal for typical impact energies. The penetration depth is given by [8] X_P (μm) = $.0276\ (A/\rho Z^{0.89})[V(kV)]^{1.67}$, where A is the atomic mass, Z is the atomic number and ρ is the density in g/cm^3. As a first approximation, we can assume that the energy is deposited uniformly to depth X_P and is zero beyond this. As energy is being deposited in the region up to X_P, heat is also flowing out of this region following the equation for heat diffusion. The equation can be solved analytically for the temperature as a function of X and t, but the limit in which power is absorbed in a relatively thin region close to the surface provides a reasonable approximation for estimating the surface temperature rise. The diffusion depth as a function of time for this case is $X_D(\mu m) = 1\times10^4\ (Dt)^{1/2}$ where $D = K/\rho C_S$ is the diffusivity in cm^2/sec, K is the thermal conductivity in W/cm-°C and C_S is the specific heat in J/gm-°C. The surface temperature rise is given by $\Delta T = (2P_A/\pi^{1/2}K)(Dt)^{1/2}$, where P_A(W/cm^2) is the incident power per unit area. We will find later that, for a gradient-limiting breakdown to occur, surface melting must take place in a time that is relatively short compared to the pulse length. In general, the diffusion depth, x_D, for such short times will be considerably smaller than the penetration depth, x_P, of a typical back-bombarding electron. Crudely, the surface power per unit area driving diffusive heating is the total incident power density, P_A, multiplied by the ratio x_D/x_P. The temperature rise due to diffusive heating is then given by $\Delta T \sim P_A(x_D/x_P)(x_D/K)$. A figure of merit can now be formed as $\Delta T/T_m \sim x_D^2/(x_P K T_m)$, where T_m is the melting point. Values for this figure of merit for various metals of interest are given in the table below. Tables giving values for the melting point, density, specific heat, thermal conductivity, resistivity, diffusivity, diffusion depth at 30 ns and penetration depth for a 50 keV electron are given in [8].

Figure of Merit for Surface Melting
$FM = x_D^2/(x_P K T_m)\times10^4$

Metal	Cu	Au	Mo	SS*	W	Nb	Be	Cr
FM	1.24	2.96	0.73	0.75	0.84	0.72	0.32	0.55

*304 Stainless Steel

The relative breakdown levels for copper, gold, and stainless steel surfaces have been measured by Tantawi and Dolgashev [9]. The measured ratios of breakdown field levels, and the ratios predicted from the table are

	Measured	Theory
Au/Cu	0.71	0.65
SS/Cu	1.36	1.28

The agreement between theoretical and experimental values is seen to be quite good.

FROM SURFACE MELTING TO BREAKDOWN

Figure 1 shows the geometric features formed by exposing a thin layer of molten metal to a dc electric field. We propose that similar features also form when an rf field acts on the liquid surface layer produced by back-bombardment heating in a cluster of plasma spots. These features follow a somewhat regular pattern. Many of them have a roughly conical base with a vertical column or jet emerging from the apex. The sides of the cones make a

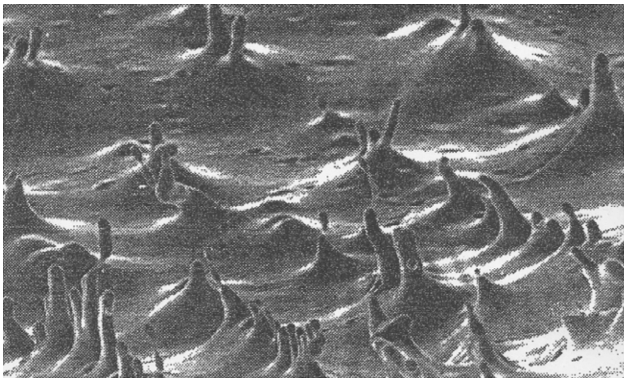

Figure 1: Surface features after action of an electric field on a thin layer of molten metal on a planar electrode [10].

roughly 45° angle with respect to the base. In the following, we develop a model based on this shape.

The model first assumes that the back-bombarding electrons produce sufficient heating to melt a thin layer of the surface in 30 ns or so at the beginning of each rf pulse, cooling and solidifying between pulses. Since the molten material cannot move very far in one rf pulse, geometric features with a scale of tens of microns must develop over hundreds or even thousands of pulses. Next assume that there are random height perturbations on the liquid surface, and that these can be modeled as portions of a spherical surface with radius r_0, as given by Eq. (1), where the surface field E_S is approximately equal to the unperturbed electric field, E_0, at the surface. The field will actually be slightly enhanced at the surface of the perturbation causing it to grow higher, which enhances the field still more etc. Following the shape of the surface projections suggested by Fig. 2, we model the growing perturbation as a conical pyramid with sides making angle ϕ with respect to the base. We assume that the cone is capped by a segment of a sphere with radius r, as show in Fig. 2. We assume that the analytic part of the growth process, where the cap radius is set by the condition for hydrostatic equilibrium (Eq. (1), starts with a spherical segment of radius r_1 as shown in Fig. 3. As the height of the cone increases the radius of the cap decreases and the surface field E_S and enhancement factor $\beta = E_S/E_0$ also increases. Simulations show that beta can be modeled as $\beta \sim r^{-n}$, where n is a function of ϕ. For the molten cap to be in hydrostatic equilibrium, the radius must vary as $r/r_1 = E_1^2/E_S^2$, giving $\beta = \beta_1\,(r/r_1)^{-1/2}$, where β_1 is the value of beta at $r = r_1$. Simulations show that for n to be exactly 1/2 the base angle ϕ must be 40.0 degrees with $\beta_1 = 1.90$.

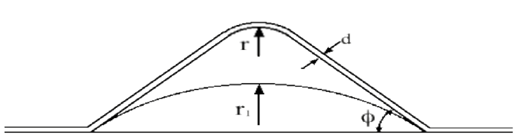

Figure 2: Geometry modeling growth of features in Fig. 1.

We next develop a model for the growth of the cone height with time. The liquid metal in the molten cap is under negative pressure from the E^2 force per unit area, F_A, pulling on the surface. This force also acts at the junction between the cap and the side of the cone, serving to pull the viscous molten metal up the side. The average flow velocity of the material follows the expression $v = \varepsilon_0 E_S^2 d/8\eta$, where η is the viscosity. This can be converted to a growth rate in height and hence in β. With a little algebra, we obtain

$$\beta = 1.9[1 - BE_0^4T]^{-1/6}, \qquad (3)$$

where $B \approx 6d^2\varepsilon_0^2/\alpha\eta r_1$ and T is the integrated time (repetition rate times the pulse length, with some initial melting time ~ 30ns subtracted from the pulse length). Note that E_0^4T is a constant at the singularity, in agreement with experiment [9].

The scale of these geometric forms is set by Eq. (1). Small initial perturbations on the liquid surface would have small heights and large radii of curvature. The enhanced field at the crest of the perturbation sets up a pressure gradient along the surface that pulls liquid material toward the crest, building up the height. This pressure gradient, proportional to the gradient of E_S^2, is also responsible for pulling molten metal up the side of the cone shown in Fig. 3. It is essentially a ponderomotive force acting in the direction of increasing E_S.

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