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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 (~ 0.01 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.

THREE MAIN TYPES OF BREAKDOWN

A. During initial processing.

B. After initial processing, but below gradient level for surface damage

C. Gradient-limiting breakdown (produces surface damage and measurable changes in iris geometry).

SEQUENCE OF EVENTS LEADING TO BREAKDOWN

1. Formation of a plasma spot at a field emission site. To explain the physics of plasma spot formation, a *liquid droplet model* is proposed.

2. A single plasma spot does not extract enough energy from the rf field to 'collapse' the field. If a single spot dies before 'multiplying', it leaves behind a single crater. *Or* the spot may develop into a cluster of closely spaced spots by a mechanism we'll call *crater clustering*.

3. Assume a sufficient number of plasma spots are alive at one time in a crater cluster field to trigger a breakdown event. The breakdown rate is predicted by a *field emission model.*

4. To produce a gradient-limiting breakdown event, the model proposes that rapid *surface melting* must take place over a significant area (the order of 0.01 mm^2 or larger) of the surface. A model for the temperature rise is formulated that takes into account the physical properties of the surface material.

5. To go from *surface melting to breakdown*, a model in which conical surface projections with rounded tops grow slowly over many rf pulses.

LIQUID DROPLET MODEL FOR PLASMA SPOT FORMATION

Once initial field emission sites have been processed off, only emitters that depend on the topography of the base metal remain.

Assume that an emitter tip begins to melt as a result of resistive heating produced by the field emission current. The radius of curvature of the molten tip is set by the balance between the force per unit area, $F_A = 1/4\ \varepsilon_0 E_S^2$ pulling on the surface and the surface tension α of the liquid metal. The radius of curvature is given by the expression

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

As the surface field increases, the radius of curvature decrease until an unstable point is reached. The tip begins to neck down and a droplet (or a train of droplets) is pulled off. Once this droplet has separated from the emitter tip, it is subjected to intense electron bombardment from the field emission beam coming from the tip of the remaining emitter. The rate of vaporization, and the resulting vapor density, is proportional to the field emission current. 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.*

CRATER CLUSTERING

After initial high beta field emission features have been burned off, only craters remain. After 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 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 gives a total rim circumference proportional to 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. The probability of a breakdown event per pulse is then proportional to T^3, where T is the pulse length.

FIELD EMISSION MODEL FOR BREAKDOWN RATE

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

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

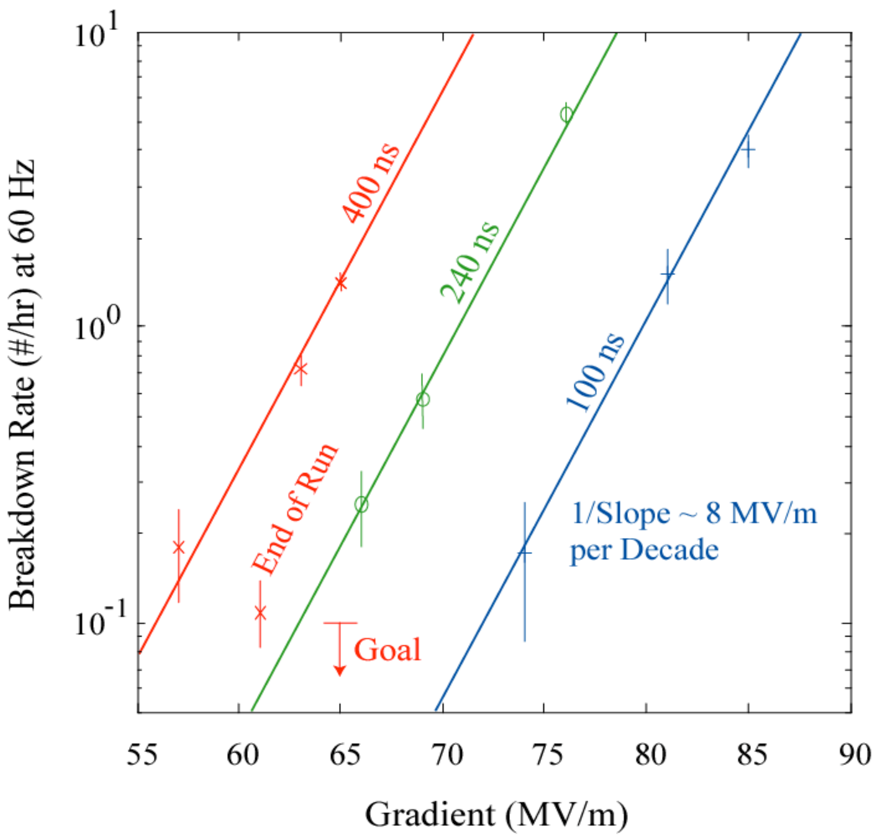
Here $\beta_{BD} = \beta/2$, where β is the usual field enhancement factor and $C = 7\text{x}10^4$ for copper. The factor of two in the betas is verified by measurements at SLAC on NLC accelerator structures.

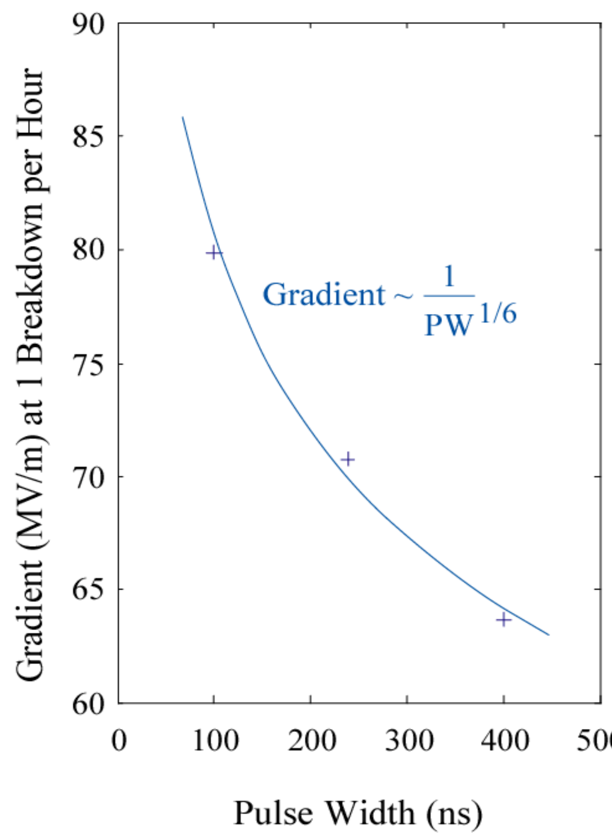
Now define normalized variables $g = \beta_{BD}E_S/C$ and $\tau = T(A/p)^{1/3}$. Then $g = [3\ln(\tau)]^{-1}$.

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 NLC structure, values of $\beta_{BD} = 22$ and $g = 0.051$ at 70 MV/m were obtained (data courtesy of C. Adolphsen) giving $n = 0.153$. This is quite close to the measured value of 1/6 (see Figure).

Breakdown Rates for H90VG3 -vs- Pulse Width





C. Adolphsen

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. 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 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.

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 following table.

Figure of Merit FM for Surface Melting

$$FM = x_D^2/(x_P K T_m)\times 10^4$$

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**

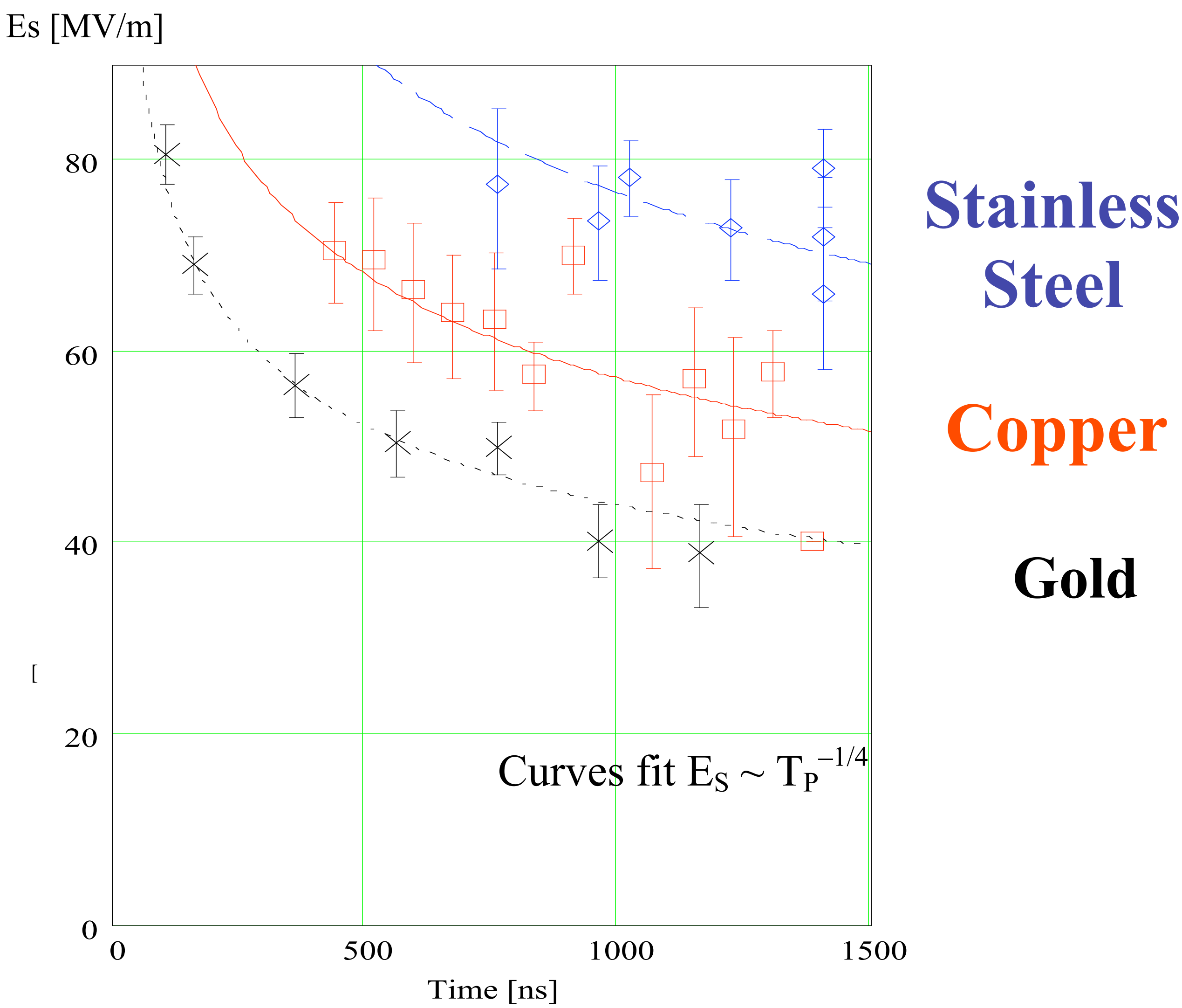
The relative breakdown levels for copper, gold, and stainless steel surfaces have been measured by Tantawi and Dolgashev. The measured ratios of breakdown field levels, and the ratios predicted from the table are

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

The agreement between theortical and experimental values is seen to be quite good (see Figure).

Waveguide test

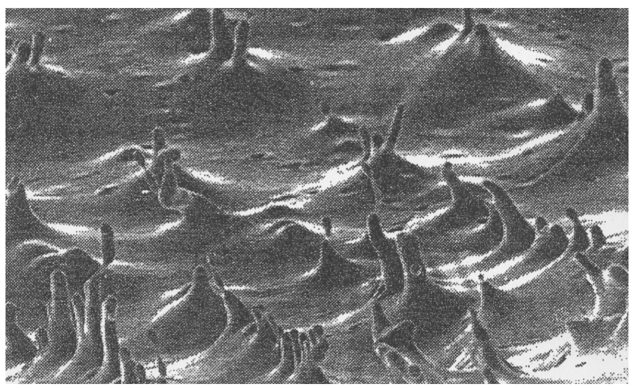
Stainless steel processed to higher Es then copper



S.G. Tantawi
V.A. Dolgashev

FROM SURFACE MELTING TO BREAKDOWN

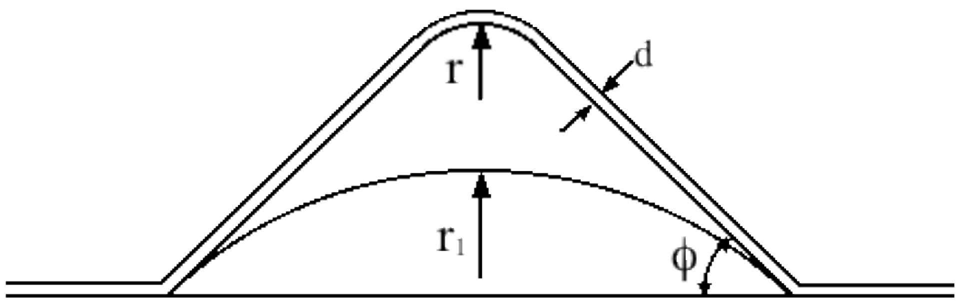
The figure below shows the geometric features formed by exposing a thin layer of molten metal to a dc electric field. We propose that similar features also form when an rf field acts on the liquid surface layer produced by back-bombardment heating in a cluster of plasma spots. These features follow a 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 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) for hydrostatic equilibrium, 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 the previous figure, 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 the figure below.



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. 2. 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 $\beta_1 = 1.90$.

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

$$\beta = 1.9[1 - BE_0^4T]^{-1/6}$$

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 ~ 30 ns subtracted from the pulse length). Note that E_0^4T is a constant at the singularity, in agreement with the experimental measurements of Tantawi and Dolgashev.

ACKNOWLEDGEMENT

I would like to thank Chris Nantista for producing Figure 2, and Valentin Ivanov for calculating the field enhancement factor for the geometry shown in this figure.