GRADIENT LIMITATION IN ACCELERATING STRUCTURES IMPOSED BY SURFACE MELTING*

Perry B. Wilson, SLAC, Stanford, CA 94309, USA

Abstract

A rough picture is beginning to emerge of the physics behind the maximum gradient that can be sustained in an accelerating structure without producing surface damage at a level sufficient to cause a measurable change in the rf properties of the structure. Field emission sites are known to trigger the formation of so-called plasma spots in regions of high dc or rf surface electric fields. A single plasma spot has a finite lifetime (~20–50ns) and leaves behind a single crater. In the rf case, some fraction of the electrons emitted from the spot pick up energy from the rf field and back-bombard the area around the spot. Depending on the gradient, pulse length and available rf energy, multiple spots can form in close proximity. The combined back-bombardment power density from such a spot cluster can be sufficient to raise the surface temperature to the melting point in tens of nanoseconds over an area on the order of 100 microns in diameter. This molten area can now support a plasma capable of emitting several kiloamperes of electrons with an average energy of 50–100kV. This is sufficient beam power to collapse the field in a travelling structure in 30 ns or so. The plasma also exerts a tremendous pressure on the molten surface, sufficient to cause a macroscopic amount of material to migrate toward a region of lower surface field. Over time, this process can modify the profile of the iris tip and produce an unacceptable change in the phase shift per cell.

FIELD EMISSION AS A TRIGGER FOR BREAKDOWN

Plasma Spots

The breakdown process begins with the formation of a plasma spot. In measurements on breakdown in a dc field, it is observed that a plasma spot forms only at a previously existing field emission site [1]. Some details concerning the formation and properties of plasma spots are given in [2]. A few of their properties are summarized here. Single dc plasma spots are usually roughly hemispherical in shape, although sometimes elongating toward a mushroom shape. A Langmuir sheath forms at the plasma–metal interface, forming a dc Child's Law diode that subjects the surface to an intense bombardment of ions from the plasma (energy ≈ 20 eV, current density ≈10^{12} A/m^2). This power density is sufficient to raise the temperature of the metal surface below the spot to the melting point in a nanosecond or so. The molten region expands to a diameter of 5–20 microns during the lifetime of the spot (30–50ns), leaving behind a crater 'foot print'. The craters produced by spots in both dc and rf fields are remarkably similar, indicating that the physics of the formation and evolution of plasma spots is quite similar in both cases. In a dc field a single plasma spot emits an electron current of 5–50A and an ion current 10–20% of this. In the following, we assume a typical dc single spot current of of 20A.

Field Emission Model for Triggering Plasma Spots

The model assumes that the probability per unit time for triggering the formation of a plasma spot is a function of the field emission current, $I_{FE} \sim \exp(-C/\beta_{FE}E_S)$. Here E_S is the surface electric field, β_{FE} is the electric field enhancement factor at the field emission site and C = 6.4 × 10^4 MV/m for copper. In recent measurements on dark current from traveling-wave (TW) accelerating structures at NLCTA, values for β_{FE} in the range 30 – 40 have been obtained [3]. The field emission model next assumes that, with some probability, the formation of a plasma spot leads to a full breakdown event (defined by the collapse of the transmitted power in a TW structure). It is observed that the breakdown rate also follows an exponential dependence on $1/E_S$, but that the values for beta (β_{BR}) tend to be about 1/2 β_{FE} [4]. This indicates that the probability for triggering a plasma spot varies as I_{FE}^2. This variation with current makes sense if adsorbed gas molecules are knocked off the surface by the intense electron back-bombardment near a field emission site, and the resulting gas is then ionized by the field emission current.

The probability of a breakdown per pulse at a fixed gradient will also be a function of pulse length. In our model, we assume this probability is proportional to T^m, where T is the pulse length. Here we will take m as a parameter to be fit by comparison with experiment (in [5] a physical model for m is developed). The net breakdown rate is given by $R = AT^m\exp(-C/\beta_{BR}rG)$, where r is the ratio of the surface electric field to the accelerating gradient. Now introduce normalized time and gradient variables defined by $\tau = T(A/R)^{1/m}$ and $g = Gr\beta/C$, giving

$$g = [m \ln(\tau)]^{-1} \quad (1)$$

This can be compared with a variation of gradient vs. pulse length parameterized by $g = B/T^n$. By equating the values and derivatives of this expression and Eq. (1), we obtain

$$n = mg \quad (2)$$

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In recent measurements at NLCTA on H90VG3 (r = 2.3), values of β_{BR} = 20 and m in the range 3 to 4 were obtained for gradients in the range 64 to 80 MV/m [4]. Calculating the exponent n at the center of this range using Eq. (2), we obtain n = 0.18. This can be compared with a measured value n $\approx$ 1/6 = 0.17.

ELECTRON MOTION IN AN RF GAP

Particle motion in a gap between two parallel planes is an excellent model for the motion of electrons and ions emitted from a plasma spot in a low group velocity rectangular waveguide. The model is also better than might be expected for the motion of particles emitted near an iris tip in a disk-loaded accelerating structure. This is especially true for electrons that are emitted and then turn back to impact on the emitting surface. The low energy component of these back-bombarding electrons will travel out into the rf field by less than a millimeter. The local surface looks reasonably flat on this scale.

The equations of motion (non-relativistic) for an electron emitted with zero velocity from a plane at y = 0 at a phase angle θ_e with respect to the crest of an rf field with peak value E_0 are

$$y/\lambda = [E_0\lambda/(2\pi)^2 V_e]\ y_n; \quad v/c = [E_0\lambda/2\pi V_e]\ v_n \qquad (3)$$

where y is the distance from the emitting surface, v is the electron velocity, λ is the rf wavelength and $V_e = mc^2/e$ = 511 kV. The parameters y_n and v_n are a normalized distance and velocity given by: $y_n = [\cos\theta_e - \cos\omega t - (\omega t - \theta_e)\sin\theta_e]$; $v_n = [\sin\omega t - \sin\theta_e]$. The normalized trajectories for electrons emitted during the positive half of the rf cycle ($\theta_e = -\pi/2$ to $+\pi/2$) are plotted in Fig.1. Electrons emitted in the phase range $\theta_e = -\pi/2$ to 0 cross the rf gap and eventually hit the opposing surface, no matter how far away. A plane at y_n = 3, for example, corresponds to the distance from one iris tip to the tip of a neighboring iris in an 11.4 GHz, $2\pi/3$-mode accelerating structure operating at a gradient on the order of 70 MV/m. However, the model is very crude in this case because of relativistic effects and the fact that the real field is far from uniform. Of more importance for our purpose here are the electrons emitted in the phase range $\theta_e = 0$ to $+\pi/2$. All of these electrons return back to impact on the emitting surface if the normalized gap width is greater than y_n = 2. Electrons emitted at θ_e = 0 venture out to y_n = 2, then return to skim the surface with zero velocity at $\omega t = 2\pi$. For a very narrow gap, however, most of the electrons in this phase range will impact the opposing surface. As an example, the line at y_n = 0.11 in Fig.1 corresponds to parameters for the "Windowtron" X-band cavity breakdown experiment [6] at SLAC, at a surface field of 500 MV/m (the gap width is 1.9 mm). Even for this narrow gap, a substantial fraction (about 15%) of the emitted electrons still return to the emitting surface to produce local heating near the plasma spot emitter. The velocity (and energy) of these back-bombarding electrons can be calculated from the slope of the trajectories at y_n = 0.

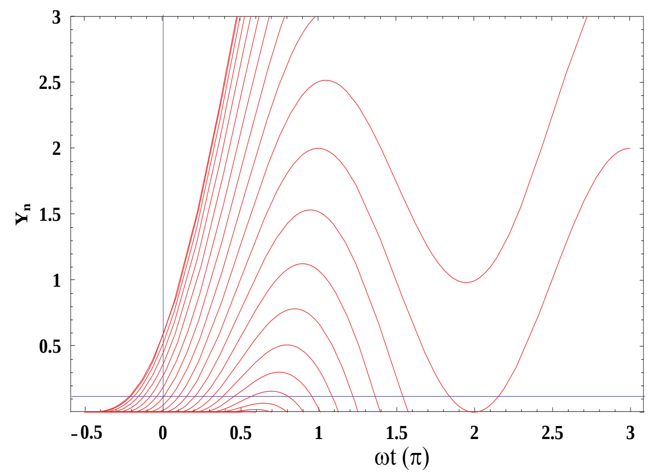

Figure 1: Normalized distance from the emission surface as a function of time for an electron emitted at at various phase angles in a parallel-plane rf gap.

SURFACE HEATING NEAR A PLASMA SPOT

Material Properties Related to Surface Melting

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 [7],

$$X_P\ (\mu m) = .0276\ (A/\rho Z^{0.89})[V(kV)]^{1.67} \qquad (4)$$

where A is the atomic mass, Z is the atomic number and ρ is the density in g/cm^3. The energy deposited per unit length is a function that rises from zero at the metal surface, reaches a maximum at about one-half X_P, and then trails off toward zero above X_P. To 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 for our purposes here it will be useful to compute the temperature rise in two limits. In the heat diffusion limit, power is absorbed in a relatively thin region close to the surface. The diffusion depth as a function of time 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

$$\Delta T = (2P_A/\pi^{1/2}K)(Dt)^{1/2} \qquad (5)$$

where P_A is the incident power per unit area. In the second limit, we calculate the heating due to electrons that penetrate well beyond the heat diffusion depth, $X_P >> X_D$. The temperature rise is

$$\Delta T = P_A t/(\rho C_S X_P). \qquad (6)$$

Some useful quantities for calculating material melting are given in Table 1. The last two columns compare the relative melting times in the bulk heating limit for 50 kV electrons, and in the diffusion limit at 30 ns. The actual melting times are given by $t_m = (1/P_A)T_P$ and by $t_m = (\pi/4\ P_A^2)T_D$.

Table 1:Useful Quantities for Calculating Surface Melting

Metal	X_D at 30 ns (μm)	X_P at 50 kV (μm)	Relative Melt. Time T_P at 50 kV	Relative Melt. Time T_D at 30 ns
Cu	1.9	6.7	2.5	16 x 10^6
Au	1.9	4.0	1.0	8.3
Mo	1.3	6.5	4.4	24
SS*	.04	7.3	4.1	1.2
W	1.4	2.1	1.8	38
Ta	0.8	4.5	3.1	11
Nb	0.8	7.5	4.2	7.2

*304 stainless steel

Surface Temperature Rise

The next step in the model is to calculate the temperature rise due to electron back-bombardment in the region of the plasma spot during a typical spot lifetime of 30 ns. We compare the temperature rise for a copper surface in the two limits discussed above: diffusive heating from low energy electrons that penetrate less than the diffusion depth, and bulk heating from higher energy electrons that penetrate deeper than the diffusion depth. Details of the calculation are given in an expanded version of this paper [5]. We assume a surface field of 150 MV/m at 11.4 GHz. For a typical plasma spot that emits 10 A of electrons during the positive half of the rf cycle, about 6 kW is absorbed in the 2 micron diffusion depth at 30 ns. We also need to know the spot area. Based on an estimate of the transverse velocity component of electrons emitted from the plasma we calculate an impact area of about 3×10^{-4} cm^2, giving a power per unit area of about 2×10^7 W/cm^2. Puting this value for P_A in Eq. (5) along with values of D and K for copper, we calculate a temperature rise of about 1000°C at 30 ns. The deeply penetrating back-bombarding electrons have an average energy of about 50kV and penetrate to an average depth of about 7 μm. The total power extracted from the rf field for these electrons is estimated to be about 400 kW. However they travel, on the average, several iris tip diameters away from the emission point and will return to the surface over a much larger area. A crude estimate gives $P_A \approx 4 \times 10^7$ W/cm^2. Equation (6) then gives a temperature rise of about 500°C.

We conclude that, in a surface field of 150 MV/m, a single plasma spot can raise the temperature of a copper surface close to the melting point in 30 ns over a region 100–200 μm in diameter.

DISCUSSION

In the model presented above, it was shown that electron back-bombardment can produce substantial heating in the area around a single plasma spot. However, on all surfaces that have been exposed to high surface fields, a multitude of single craters (footprints of plasma spots) are observed with no evidence of surface melting in the surrounding area. This implies that, to produce such melting, a number of plasma spots must be present at the same time within an area on the order of 1×10^4 μm^2. In [5] it is shown how this might happen through the phenomenon of crater clustering. Once this area has been raised to perhaps twice the melting point (to produce a substantial vapor pressure), we propose that the plasma spots responsible for the melting then coalesce to form a plasma ‘cloud’ extending over the liquid region. In simulations, Dolgashev [8] has shown that this macroscopic plasma layer is capable of emitting kiloamperes of electrons and tens of amperes of ions. A full breakdown event then follows the formation of this plasma.

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REFERENCES

[1] N.S. Xu and R.V. Latham, ”Electrical and spatial correlations between direct current pre-breakdown electron emission characteristics and subsequent breakdown events”, J. Phys. D: Appl. Phys. **27**, 2547 (1994).
[2] P.B. Wilson, “A Plasma Model for RF Breakdown in Accelerator Structures”, *Proceedings of Linac 2000*, (SLAC-R-561, SLAC, Stanford, CA (2000) p. 618.
[3] Steffen Doebert, private communication.
[4] Calculated from data supplied by C. Adolphsen.
[5] P.B. Wilson, SLAC/AP–142, SLAC, Stanford, CA (2003). To be issued.
[6] L. Laurent, “A Study of RF Breakdown”, Ph.D. Thesis (SLAC, Stanford, CA, 2002).
[7] Electron Microprobe Notes: Electron Interaction with matter, p.4 (http://jan.ucc.nau.edu/~wittke/Interact.html).
[8] Valery Dolgashev, private communication.