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FIELD EMISSION AND RF BREAKDOWN IN COPPER LINAC STRUCTURES*

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INTRODUCTION

This paper presents a status report on RF field emission and high-gradient breakdown studies in linac structures at SLAC. The motivation behind these studies, begun in 1984, is to determine the maximum accelerating field gradients that could be used safely in future $e^{\pm}$ colliders, to contribute to the basic understanding of the RF breakdown mechanism, and to discover if special surface treatments might make it possible to shorten the time needed for RF processing and to supersede the field limits presently reachable in room temperature copper structures. Both theoretical ideas and experimental results are discussed.

PROPOSED THEORY

Over the past forty years or so, a number of theories have been proposed to explain RF breakdown in the cavities of accelerator structures. While there are still some gaps in our understanding, we believe that many of our observations can be explained by the combination of two of these theories: Explosive Electron Emission[1] (EEE) and a modified form of Field Emission (FE) called Field Induced Hot-Electron Emission[2] (FIHEE). According to the EEE model, RF breakdown occurs when the local field-emitted current density from a given site reaches 10^{12}–10^{13} A/m^2 and causes enough heat dissipation to vaporize a small amount of surface material. This material is either metal in a surface irregularity (machining mark, microprotrusion, whisker, crater edge, crack, crystal boundary), dielectric (oxide, adsorbed organic residue, thin layer, inclusion, dust), or most probably a combination of both. When this explosion takes place, a local plasma discharge occurs together with a spark. By absorbing the ambient RF energy, this discharge causes the collapse of the fields in the cavity and produces a sudden surge in observable current due to ionization, above and beyond the field-emitted current. It is also conjectured that when the metal at the breakdown site becomes liquid and then vaporizes, the pressure from the expanding plasma causes the metal to splash and form a crater. Metal droplets and

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discontinuities on the edge of the crater then become further sites of future breakdown events which can propagate and create adjacent and/or deeper craters.

The required average field-emitted current density can be calculated from the standard Fowler-Nordheim equation converted to the RF case:[3]

$$\bar{j}_F = \frac{5.7 \times 10^{-12} \times 10^{4.52\phi^{-0.5}}}{\phi^{1.75}} (\beta E_s)^{2.5} \exp\left(-\frac{6.53 \times 10^9 \times \phi^{1.5}}{\beta E_s}\right) \tag{1}$$

where $\bar{j}_F$ is in A/m^2, ϕ is the metal work function in eV, E_s is the surface field, and β is the local surface field enhancement factor. It turns out that to obtain 10^{13} A/m^2, one needs a microscopic field βE_s of over 10 GV/m. The heat dissipation per m^3 through ohmic loss from such a current in a medium of resistivity ρ is then $\bar{j}^2\rho$. If we assume to first order that this heat does not have the time to be conducted away appreciably, it will raise the temperature of the volume by ΔT(°C) in a time $\Delta t = (4.18MC\Delta T)/(\bar{j}^2\rho)$, where M is the density and C is the heat capacity of the metal. As it turns out, the time to reach the melting point of the metal does not depend very much on which metal is considered (in agreement with the results of Ref. 4) and is roughly equal to $\Delta t = (2 \times 10^{17})/\bar{j}^2$ seconds. Thus, for $\bar{j}_F = 10^{13}$ A/m^2, $\Delta t \sim 2$ ns, which is essentially instantaneous on the scale of microsecond-long pulses.

As we will see later from our experimental results, β-values on the order of 40–80 are commonly measured, which indeed lead to effective microscopic fields in excess of 10 GV/m. However, if we examine the size and shape of the protrusions and eventual craters in our cavity walls, we can explain "geometric" β-values (call them β_1) of at most 2 to 8 (2 to 4 before damage, 4 to 8 after damage). The possibility of higher effective β's, particularly at the beginning of RF processing when the cavity surfaces are still very smooth and exhibit mostly machining marks, can be explained by the FIHEE theory. This theory assumes that there are dielectric layers or "patches" on the surface of the metal. The externally applied electric field penetrates into such intermediate layers and accelerates the electrons from the Fermi level in the metal. This acceleration is equivalent to heating up the electrons, thereby called "hot electrons," which can then escape into the vacuum through a quasi-thermionic process, following the old Richardson-Dushman law for which the emitted current density is given by:

$$j_F = KT_e^2 \exp(-e\chi/kT_e) \quad \text{A/m}^2 \tag{2}$$

where χ is the height of the surface potential barrier, K is a constant ($\sim 1.2 \times 10^{-6}$ A/m^2), k is Boltzmann's constant and the energy of the hot electrons, measured by the kinetic energy they acquire in the dielectric layer of width Δd and of relative dielectric constant ϵ, is $(3/2)kT_e = (eE/\epsilon)\Delta d$. The average RF current density analogue to Eq. (1) is then:

$$\bar{j}_F = 2.36 \times 10^{-7} \chi^{-0.5} \left(\frac{e}{k}\right)^2 \left(\frac{\Delta d\, E}{\epsilon}\right)^{2.5} \exp\left(-\frac{3\chi\epsilon}{2\Delta d E}\right) \quad \text{A/m}^2 \quad . \tag{3}$$

By comparison of the exponents, a β_2 corresponding to the dielectric contribution can be defined as $\beta_2 = 4.353 \times 10^9 \phi^{1.5} (\Delta d/\chi\epsilon)$. Assuming $\phi = 4.65$ eV, $\chi = 4$ eV and Δd measured in nanometers, we see that $\beta_2 = 10.9(\Delta d/\epsilon)$, and the effective β that is measured is then equal to the product $\beta_1\beta_2$.

The conclusion to be drawn from this composite theory is that if any accelerator structure is to sustain the maximum possible accelerating fields with the minimum amount of field emission, it must be conditioned or RF processed to keep the product $\beta_1\beta_2$ as low as possible. This result can be achieved by minimizing the number and sharpness of metallic protrusions or craters (which reduces β_1), and by minimizing the number and thickness (Δd) of dielectric "patches." Both chemical action and RF sputtering may be capable of producing this latter result. We will now describe our experiments and the efforts that have been made so far in this direction.

EXPERIMENTAL STRUCTURES AND RESULTS

All experiments reported here were performed on standing-wave (SW) structures.[5] Another paper at this conference[6] presents the first results for an 11.4 GHz traveling-wave (TW) structure. The structures used in the S-band measurements were equipped with a variety of temperature sensors to measure disk temperature, internal probes to measure field emission (FE), glass and copper windows, external magnets, a spectrometer and Faraday cup to measure the intensity and energy of extracted currents, an x-ray pin-hole camera, radiation monitors, a TV camera with video recorder to look at breakdown sparks, pumps and a residual gas analyzer (RGA). The most recent S-band structure,[7] shown in Fig. 1, was built to test whether the slots, ultimately designed to couple out the HEM_{11} deflecting-mode and lower its Q, reduce the electric breakdown threshold below those reached with the earlier structures. Note that the slots in successive disks are oriented at 45° with respect to each other. All measured peak RF input powers corresponding to the maximum obtainable breakdown surface fields, as computed by the programs SUPERFISH and MAFIA, are shown in Table 1. We see that the three S-band structures reached approximately the same limit of peak surface field. However, because of different values of a/λ, the resulting $E_s/\bar{E}_{acc}$ ratios are different, and the corresponding traveling-wave accelerating fields vary accordingly.

The peak surface fields in MV/m scale roughly as $E_s \sim 195[f(\text{GHz})]^{1/2}$, as a function of frequency. This approximate relation, which is used to fit only three points that are clearly subject to experimental errors, is functionally similar to the traditional Kilpatrick criterion transcribed here in a somewhat

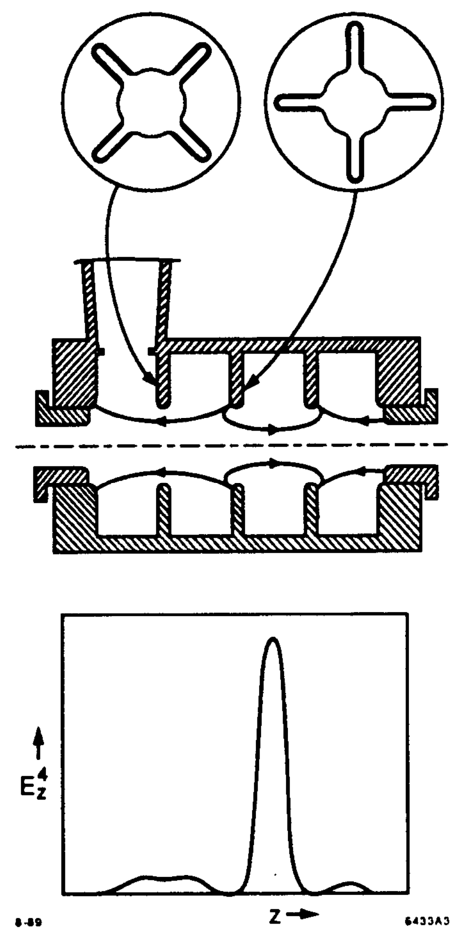

Fig. 1. Cross-sections of slotted-disk structure, with axial field profile.

unfamiliar form as $E_s \exp(-4.25/E_s) = 24.7\,[f(\mathrm{GHz})]^{1/2}$. We note that our experimental points exceed Kilpatrick's predictions by a factor of about 8. We will come back to this point later.

Table I. Experimentally obtained breakdown-limited gradients.

	S-band Disk-loaded (2π/3-mode)	S-band With nose cone (π-mode)	S-band Slotted-disk (2π/3)	C-band Half-cavity	X-band Half-cavity
Frequency, f (MHz)	2856	2858	2857	4998	9303
Total length (cm)	24.5	10.5	21	1.507	0.806
Filling time* (μs)	0.77	1.0	0.87	0.172	0.082
Pulse length (μs)	1.5-2.5	1.5-2.5	1.5-2.5	3.5	3.8
Peak power input (MW)	47	10.8	16.2	0.8	1.2
E_s (MV/m)	313	340	315	445	572
$E_s/\bar{E}_{acc}$ for TW structure	1.94†	1.94	2.83‡	1.94	1.94
$\bar{E}_{acc}$ (MV/m)** for TW	161	175	111	229	295
Measured factor β	~60	~60	~60	~38	not avail.
βE_s (GV/m)	18.8	20.4	18.9	16.9	not avail.

*Assuming critical coupling. †Obtained from SUPERFISH.

‡The relative number obtained from MAFIA (2.22) was corrected to give 2.83 by normalizing it to SUPERFISH.

**Assuming structure operating in traveling-wave (TW), $2\pi/3$-mode, with $E_s/\bar{E}_{acc}$ shown above.

Except for the slotted-disk structure, the procedure for all the measurements has been fairly similar. After the structures are fabricated, cleaned and generally baked to 200–250°C, gradual RF processing is invariably needed to reach the maximum breakdown fields. Starting at macroscopic peak surface fields of about 100 MV/m, measurable field emission appears. The resulting RF processing is accompanied by steady outgassing at pressures between 10^{-8} and 10^{-7} Torr and interrupted occasionally by an RF breakdown "event" within a pulse (or a succession of pulses if the power is pushed up too fast). These breakdown "events" are manifested by a sudden power reflection from the structure, the appearance of a spark in the high field region on the rim of a disk or nose cone, an instantaneous current surge by a factor of 20–40 above the steady-state FE current in the cavity, a severe x-ray burst alongside the structure, and a sudden discontinuous release of CH_4, CO and CO_2 gas as measured at the RGA. The pattern of breakdown, subsequent recovery and gradually increasing field continues all the way up to the maximum attainable field and has taken typically between three and fourteen hours. There seems to be no observable difference between the breakdown events in the range from 100 to 340 MV/m, except that the steady-state FE current increases as the field increases. Once the maximum attainable breakdown level is reached, a steady-state regime of operation is generally obtained at all fields below it and it is possible to get a reliable Fowler-Nordheim plot[5] from which an effective value of β can be derived. The effective values of ~60 for the S-band structures and of ~38 for the C-band cavity, which are shown in Table I, allow one to calculate the "equivalent microscopic field" at breakdown which is shown at the bottom of the table. This is really only a pseudo-field from which one can calculate the current density at breakdown from Eq. (1).

When the tests with the first two S-band structures were discontinued and they were internally examined, considerable damage was found in the high field regions (see Fig. 2). While this cumulative damage did not affect stability of operation except at the maximum level, avoiding such damage during the processing would certainly have kept the β_1 component of β at a lower level, and reduced the FE current. For this reason, in the slotted structure we began RF processing at low level with argon to see if the higher fields could be reached with less or no damage. The results and the chronology of successive Fowler-Nordheim plots are summarized in Fig. 3. They indicate that RF "scrubbing" with argon at a pressure of $\sim 10^{-5}$ Torr can shorten the process somewhat but does not make it possible to reach the maximum breakdown field. "Brute force" RF processing under vacuum still is more effective, and this is how the ultimate peak surface field of 315 MV/m was reached with this structure. Other less damaging techniques are now being explored. Such an effort, if successful, would clearly be very beneficial because a reduction by a factor of two in ultimate microscopic field would not only provide an extra margin of safety but would also reduce field emission at

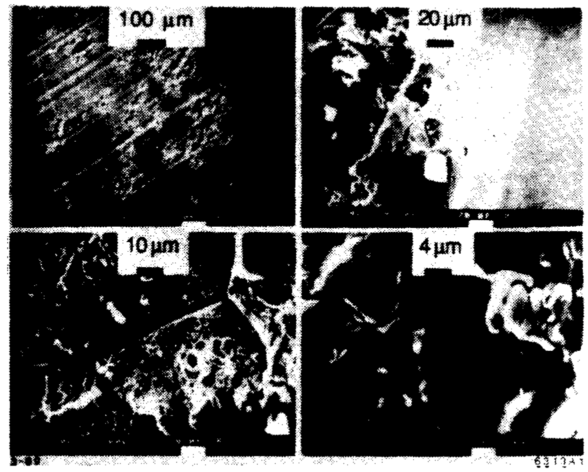

Fig. 2. Scanning electron microscope pictures of S-band, π-mode two-cavity nose cone showing RF breakdown damage (note different scales in microns).

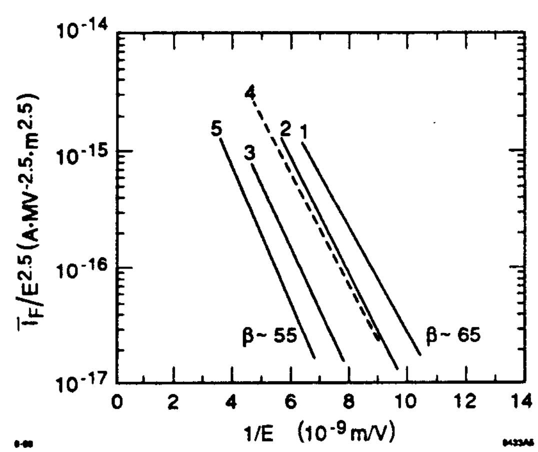

Fig. 3. Fowler-Nordheim plots obtained during successive stages of RF processing with argon at 10^{-5} Torr. 1. Status before starting argon processing; 2. After one hour at low power; 3. After another hour at slightly higher power (argon atoms at about 2 kV); 4. After sudden damage; 5. After another $1\frac{1}{2}$ hours of argon and vacuum processing.

the operating level, an important feature to reduce detrimental dark currents which can cause transverse wakefields and absorb RF energy. Note that the dark current per unit length scales as f^{-2} because of available emitting area, but as f^1 because of the number of disks per unit length, thus yielding a net scaling of f^{-1} which favors the higher frequencies.

DISCUSSION

Our proposed theory, while it offers a model and a possible recipe for improved performance, leaves two questions unexplained: breakdown dependence on frequency and pulse length. If the breakdown limit is set by field emission "eruptions" of 10^{13} A/m^2, then breakdown would happen whenever βE_s reaches ~20 GV/m. "Brute force" RF processing probably brings β down by a factor of ~3 and E_s up accordingly. The frequency dependence ($f^{1/2}$) of E_s shown in Table I agrees functionally with the Kilpatrick criterion but this agreement may be purely coincidental. But can β vary with f? Arguments[5] based on stored energy or available emitting area are not very convincing. The only suggested possibility[8] is that the "hot electron" population has a finite build-up time which causes β_2 to decrease with frequency. Conversely, it is possible that the available data in Table I is insufficient and that further tests will show that there is no frequency dependence at all. Regarding pulse length, neither our model nor our observations seem to say anything about the breakdown dependence on pulse length. The S-band measurements shown in Table I and ranging between 1.5 and 2.5 μs pulse length showed only a small (<5%) decrease in breakdown field for the longer (2.5 μs) pulses. What happens at much shorter pulses, say 50 ns, which are contemplated for the next generation of linear colliders? If the breakdown due to EEE can occur in one nanosecond or less, why should some workers in the field give breakdown field dependences scaling as perhaps t^{-1} or $t^{-1/3}$? We do not know. More work is needed to elucidate this interesting question.

REFERENCES

1. G. A. Mesyats, "Explosive Processes on the Cathode in a Vacuum Discharge," IEEE Trans. Elec. Insul., Vol. EI-18 No. 3, June 1983.
2. R. V. Latham, "Prebreakdown Electron Emission Processes," Proceedings XIIth Int. Symp. on Discharges and Electrical Insulation in Vacuum (1986).
3. J. W. Wang, "RF Properties of Periodic Accelerating Structures for Linear Colliders," SLAC-Report-339, July 1989, Ph.D. Dissertation.
4. E. Tanabe, "Breakdown in High-Gradient Accelerator Cavities," Proceedings of the 1984 Linear Accelerator Conference, Seeheim/Darmstadt, West Germany, p. 403.
5. For example, see G. A. Loew and J. W. Wang, "RF Breakdown Studies in Room Temperature Electron Linac Structures," SLAC-PUB-4647, May 1988.
6. G. A. Westenskow, *et al.*, "Recent Progress in Relativistic Klystron Research," presented at this Conference.
7. H. Deruyter, *et al.*, "Damped Accelerator Structures for Future Linear $e^{\pm}$ Colliders," Proceedings of the IEEE 1989 Particle Accelerator Conference, Chicago, IL, 1989.
8. J. Halbritter, "Dynamical Enhanced Electron Emission and Discharges at Contaminated Surfaces," Appl. Phys. A **39**, (1986).