RF BREAKDOWN STUDIES IN COPPER ELECTRON LINAC STRUCTURES

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1. Introduction

This paper presents a summary of RF breakdown-limited electric fields observed in experimental linac structures at SLAC and a discussion of how these experiments can be interpreted against the background of existing, yet incomplete, theories. The motivation of these studies, begun in 1984, is to determine the maximum accelerating field gradients that might be used safely in future $e^{\pm}$ colliders, to contribute to the basic understanding of the RF breakdown mechanism, and to discover if a special surface treatment might make it possible to supersede the field limits presently reachable in room temperature copper structures.

2. Experiments and Maximum Field Gradients

All experiments reported here,[1] with the exception of one X-band test started in collaboration with LLNL but not yet completed, were performed on standing-wave (SW) structures. The S-band experiments were done on a seven-cavity disk-loaded ($2\pi/3$-mode) structure and on a two-cavity nose-cone-shaped (π-mode) structure, powered by a klystron operated up to 47 MW. The C-band and X-band tests, done in collaboration with Varian, used nose-cone-shaped half-cavity structures powered by ~1 MW magnetrons. All measured peak RF input powers corresponding to the maximum obtainable breakdown fields are summarized in Table I. The computer program SUPERFISH was used to derive the relationship between these measured RF power levels and the peak surface fields given in Table I and plotted in Fig. 1. The predicted traveling-wave (TW) accelerating fields, also shown in Table I, were then calculated, assuming a typical SLAC disk-loaded structure with a ratio of peak-surface to average accelerating field of 1.94. For the pulse lengths used in the measurements (~1.5-4 μs), the obtained breakdown-limited copper surface electric field in MV/m scales with frequency roughly as

$$E_s \sim 195[f(\mathrm{GHz})]^{1/2} \qquad (1)$$

This approximate relation, which is used to fit only three points obviously subject to experimental errors, is functionally similar to the traditional Kilpatrick criterion transcribed here in a somewhat unfamiliar form:

$$E_s \exp(-4.25/E_s) = 24.7\,[f(\mathrm{GHz})]^{1/2} \qquad (2)$$

We note that our experimental points exceed Kilpatrick's predictions by a factor of about 8. We will come back to discuss this discrepancy later in the paper.

The structures used in the S-band measurements were equipped with RF couplers, 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). A typical setup used for the two-cavity π-mode structure is shown in Fig. 2.

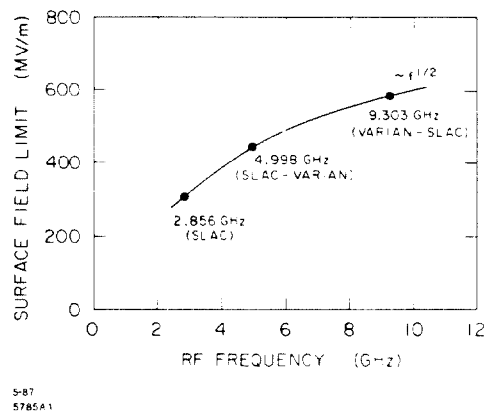

Fig. 1. Peak breakdown surface fields measured as a function of frequency.

3. Field Emission and RF Breakdown: Theories and Observations

Over the past forty years or so, many theories have been proposed to explain RF breakdown in the cavities of accelerator structures. Combining several of these theories, we believe that the most likely model is that RF breakdown occurs when the local field-emitted current from a given site causes enough heat dissipation to vaporize a small amount of surface material. This material can be either metal

Table I. Experimentally obtained breakdown-limited gradients.

	S-band Disk-loaded ($2\pi/3$-mode)	S-band With nose cone (π-mode)	C-band Half-cavity	X-band Half-cavity	X-band Disk-loaded ($2\pi/3$-mode)
Frequency, f (MHz)	2856	2858	4998	9303	11424
Total length (cm)	24.5	10.5	1.507	0.806	26.25
Filling time* (μs)	0.77	1.0	0.172	0.082	0.028
Pulse length (μs)	1.5-2.5	1.5-2.5	3.5	3.8	0.025†
Peak power input (MW)	47	10.8	0.8	1.2	200†
Peak surface field, E_s (MV/m)	313	340	445	572	303†
Corresponding traveling-wave accelerating field‡	161	175	229	295	133†
Field enhancement factor β (Fowler-Nordheim)	~60	~60	~38	NA	NA
Peak microscopic field βE_s (GV/m)	18.8	20.4	16.9	NA	NA

*For critical coupling in the case of standing-wave structures.
†Preliminary results, limited by available RF power and not by breakdown.
‡Assuming SLAC structure, working in the traveling-wave mode, in which $E_s/\overline{E}_{acc} = 1.94$, except for X-band disk-loaded TW structure which was built with $E_s/\overline{E}_{acc} = 2.28$.

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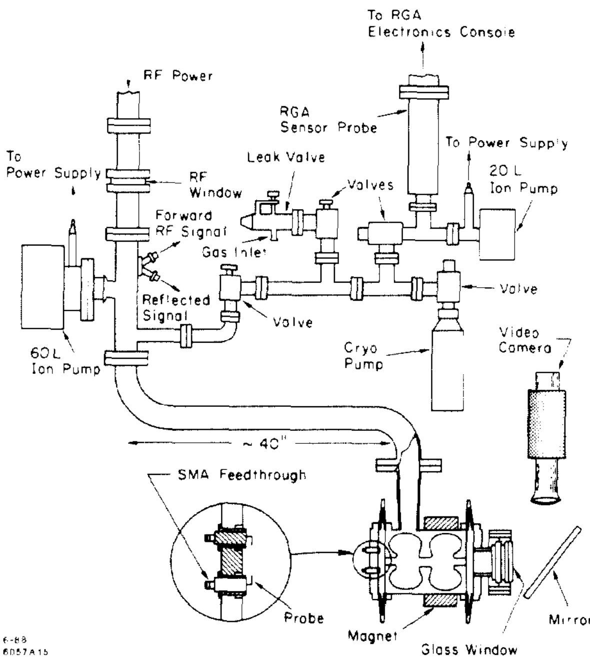

Fig. 2. Experimental set-up used for S-band (two-cavity, π-mode) structure, showing details of vacuum system.

in a surface irregularity (machining mark, microprotrusion, whisker, crater edge, crack, crystal boundary) or dielectric (oxides, adsorbed organic residues, thin layers, inclusions or dust), or a combination of both. When this happens, a local plasma discharge occurs together with a spark. This discharge causes the collapse of the RF 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 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 latter model is called Explosive Electron Emission (EEE).[2] It requires an average field-emitted current density, $\bar{j}$, on the order of or greater than 10^{13} A/m^2. Such a current density can be calculated from the standard Fowler-Nordheim equation converted to the RF case:

$$\bar{j} = \frac{5.7\times10^{-12}\times10^{4.52\phi^{-0.5}}}{\phi^{1.75}}(\beta E_s)^{2.5}\exp\left(-\frac{6.53\times10^{9}\times\phi^{1.5}}{\beta E_s}\right) \quad (3)$$

where $\bar{j}$ is in A/m^2, ϕ is the metal work function in eV 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 about 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. 3) and is roughly equal to $\Delta t = (2\times10^{17})/\bar{j}^2$ seconds. Thus, for $\bar{j} = 10^{13}$ A/m^2, $\Delta t \sim 2$ ns, which is essentially instantaneous on the scale of microsecond-long pulses.

Let us now review how our observations agree with this model:

- After our structures are fabricated, cleaned and sometimes baked to 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 (FE) 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 (see Fig. 3).

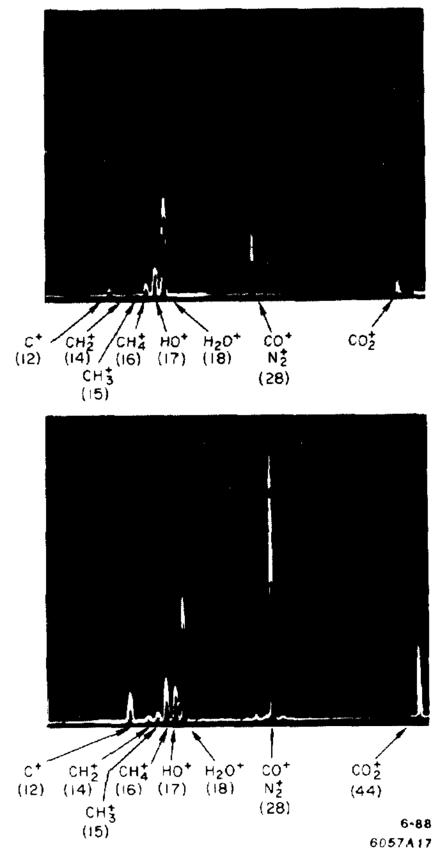

Fig. 3. Residual gas analyzer displays during RF processing of S-band, two-cavity structure, a) before breakdown, and b) immediately after breakdown.

- If the RF power is kept constant after such a breakdown event, normal RF operation resumes, the FE current comes back exactly to its previous level (not lower!), the vacuum improves, carbon-related lines return to steady state and RF processing can continue. This sequential pattern of breakdown, subsequent recovery and gradually increasing field repeats itself all the way up to the maximum field. With freshly constructed structures or structures processed earlier but exposed to air for several hours, this process has taken 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 field is reached (beyond which the cavity breaks down almost continuously), it is possible to decrease the power input and then instantaneously increase it back to its maximum value without any breakdown. If, after this, the structure is left under good vacuum (10^{-7} to 10^{-8} Torr) for several days, the process takes only a few minutes.

- Finally, when a series of tests is discontinued and the structures are internally examined, they invariably show considerable damage in the form of numerous pits, craters and molten metallic convolutions in the high field regions (see Fig. 4). Note that this cumulative damage may limit operation at even higher fields but has not so far prevented steady running at whatever asymptotic maximum field was reached up to then.

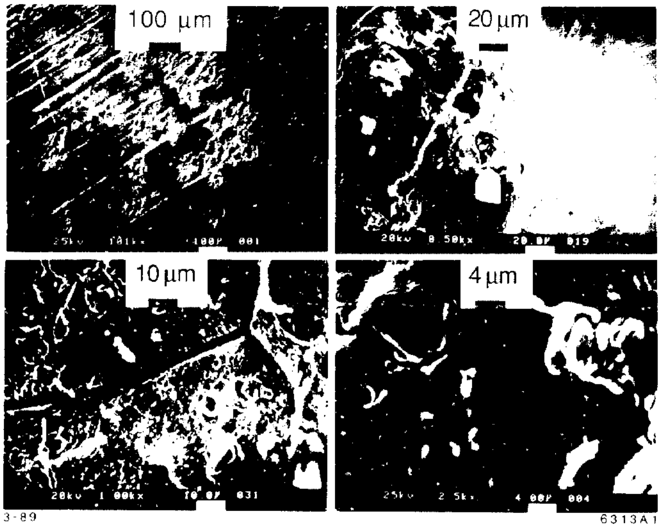

Fig. 4. Scanning electron microscope pictures of S-band, π-mode two-cavity nose cone showing RF breakdown damage (note different scales in microns).

4. Discussion and Outstanding Problems

Even though our observations and the above model are in reasonable agreement, there are still a number of outstanding questions and problems which we will now discuss.

We pointed out earlier that to explain FE current densities of 10^{13} A/m^2 or greater, we need microscopic fields in excess of 10 GV/m. As it turns out, with the field-enhancement factors β measured from Fowler-Nordheim plots after the completion of RF processing (see bottom of Table I), these microscopic fields exceeded this level by a factor of almost 2 and EEE is easy to explain. However, if we examine the size of the protrusions and craters on our damaged disks, we can explain geometric β-values (call them β_1) in the range of 5 to 8, but certainly not 40–60. Before the damage is done, the β_1 value is probably in the range of 2–4. Even though we cannot get stable Fowler-Nordheim plots when we start RF processing, it is probably true (but not sure) that the effective β is greater at the beginning since the macroscopic field is lower, say ~100 MV/m. This possibility is explained by the so-called FIHEE (Field Induced Hot-Electron Emission) model proposed by Latham[4] which assumes a dielectric layer on the surface of the metal. The external field penetrates into the layer and accelerates the electrons from the Fermi level to the surface of the layer where they are effectively "heated." They then behave like in a thermionic cathode according to the Richardson-Dushman equation. By analogy, Latham derived an effective "dielectric β" which we shall call β_2:

$$\beta_2 = 4.353 \times 10^9 \phi^{1.5} \frac{\Delta d}{\chi \epsilon} \tag{4}$$

where χ is the height of the surface potential barrier (typically 4 eV), Δd is the thickness of the layer (in nm), ϕ is the work-function (4.65 eV for Cu) and ϵ is the dielectric constant (typically ~3). For Cu then, the effective β becomes:

$$\beta_{eff} = \beta_1 \beta_2 = \beta_1 \, 10.9 \frac{\Delta d}{\epsilon} \tag{5}$$

Thus, for example, assuming $\epsilon = 3$ and an initial $\beta_1 = 3$, to get an initial $\beta_{eff} = 200$ would require a dielectric layer of ~19 nm. If, because of damage, β_1 grows to 6 and the final β_{eff} is 60, then after RF processing, the layer would be reduced to 2.8 nm. We do not know if this model is correct but it is at least plausible. If it is correct, then the creation of pits and craters might be avoided by starting the RF processing at a low-field level with argon which is very effective in reducing dielectric layers. Thus β_1 might be kept at its initial level, gaining us an ultimate factor of 2. We had originally planned to perform such an experiment with a demountable cavity, but lack of time has not allowed us to complete it yet. A reduction by a factor of two in ultimate microscopic field would not only give us an extra margin of safety, particularly for future structures[5] with higher peak-to-average fields, but it would also reduce field emission at 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, thus yielding a net scaling of f^{-1} which favors the higher frequencies.

Another question that remains unanswered is the frequency dependence of Eq. (1). On the one hand, it more or less agrees with the Kilpatrick criterion of Eq. (2) even though the scale is off by a factor of 8. On the other hand, the principal mechanism behind EEE does not seem to require the hydrogen ions which are involved in the derivation of this criterion. Thus, the resemblance between the two formulas may be purely fortuitous, unless the ultimate breakdown "trigger" before EEE takes place is somehow related to the ion energy which scales as $(eE)^2/m_0 f^2$. Note, however, that in our experiments the probability of breakdown events was quite pressure-independent in the 10^{-8} to 10^{-6} Torr range. A second possibility is that the probability of breakdown is related to the energy stored per unit length, which scales as E^2/f^2. However, this argument also appears to be flawed because the energy required to melt a surface irregularity on the order of $(1\text{–}10\ \mu\text{m})^3$ is an extremely small fraction of the few joules stored in each cavity. A third possibility is a model proposed by Halbritter[6] which suggests that the hot-electron population has a finite build-up time, saturates and then is depressed and briefly stopped: as a result, the field emission pulsates and the full enhancement factor cannot materialize at higher frequencies, thus leading to decreasing β versus f. This theory is still speculative.

Finally, 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 are not sure. More work is needed to elucidate these interesting questions.

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References

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