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RF BREAKDOWN AND FIELD EMISSION

G. A. Loew and J. W. Wang

*Stanford Linear Accelerator Center**
Stanford University, Stanford, California 94309

One of the crucial parameters in the design of TeV $e^{\pm}$ linear colliders is the maximum electric field gradient that can be attained and used safely in the accelerating structure. In the absence of definitive knowledge on the availability and cost of RF power sources, the optimum machine length for a given energy cannot be determined at this time. However, the designs considered in this report could require gradients as high as 200 MV/m at RF frequencies of 11.424 GHz or 17.136 GHz, corresponding to peak powers of up to 1 GW/m. On the basis of research done at SLAC and at Varian, it now appears that such gradients are reachable, at least in short standing-wave (SW) structures.[1] Considerably more work, however, is needed to determine if the required gradients are achievable in long and complicated structures, and to verify that the accompanying field emitted currents which can absorb power, cause parasitic wakefields and spurious x-rays along the accelerator, are tolerable.

All experiments reported in Ref. 1, except for one X-band test started in collaboration with LLNL but not yet completed, were performed on SW structures. The equivalent traveling-wave accelerating fields were then calculated using the SUPERFISH computer program. 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. C-band and X-band tests, done in collaboration with Varian, used nose-cone-shaped half-cavity structures powered by ~1 MW magnetrons. The overall results are shown in Table 1. For the pulse lengths used in the measurements (~1.5-4 μs), the breakdown-limited copper surface electric fields scale roughly as

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

(about seven times the levels predicted by the Kilpatrick limit). If this empirical relationship is valid at higher frequencies, then breakdown-limited surface fields of 660 and 807 MV/m could be reached at 11.424 GHz and 17.136 GHz respectively (corresponding to 264 and 323 MV/m accelerating fields, assuming $E_s/\bar{E}_{acc} = 2.5$). This extrapolation assumes no improvements due to the much shorter pulse lengths required at these higher frequencies (~20 to 100 ns), and conversely no worsening due to the probable need for more complex damped structures (see next section) with slots in the disks.

The structures used in the above 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 pinhole camera, radiation monitors, a TV camera with video recorder to look at breakdown sparks, pumps and a residual gas analyzer (RGA). Intensive studies were carried out of both pre-breakdown and breakdown phenomena, during and after RF processing. Upon completion of RF processing, Fowler-Nordheim plots of FE currents versus $1/E_s$ yielded β-field enhancement factors of ~60 at 2.856 GHz and 38 at 4.998 GHz. (For more details, see below.) RF-focused beams with peak currents as high as 25 mA and energies up to 13 MeV were extracted from the seven-cavity structure, and energy spectra in agreement with theoretical calculations were analyzed.

The pre-breakdown currents produced intense x-ray fields around the seven-cavity structure, in excess of 0.75 Mrad/h. When breakdown took place at a given RF power input, the resulting reflected RF pulse was invariably accompanied by a momentary current jump by a factor of 20 to 40 (as measured by internal transverse probes), the appearance of a spark, generally on the edge

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Table 1. Experimentally obtained breakdown-limited gradients.

	S-band Disk-loaded (2π/3-mode)	S-band With nose cone (π-mode)	C-band Half-cavity	X-band Half-cavity	X-band Disk-loaded (2π/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†

* 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 $E_s/\overline{E}_{acc} = 2.28$.

of the disk, and a marked increase in CH_4, CO and CO_2 gas at the RGA. As the gas burst was pumped away and RF processing was continued, the FE current gradually subsided to its pre-breakdown level and could eventually be decreased to a lower level for a given RF power input. Further RF breakdown events could then be triggered by increasing the RF power until the quasi-asymptotic levels shown in Table 1 were reached.

All SW structures listed in Table 1 were RF-processed for periods of 3 to 20 hours. Afterwards, they all showed considerable damage in the form of numerous pits and craters, mostly around the high-field points on the disk edges and/or nose cones. It is interesting to note, however, that this damage did not prevent the structures from continuing to operate at the highest electric field levels.

Our conjecture of what happens during RF processing can be understood by considering the expression for the Fowler-Nordheim average FE current density in an RF cavity:

$$\bar{j}_{FE} = \frac{K}{\phi^{1.75}} (\beta E_s)^{2.5} \exp\left(-\frac{6.53 \times 10^9 \times \phi^{1.5}}{\beta E_s}\right)$$

where ϕ is the metal work function in eV and β, the surface field enhancement factor, is a composite equal to $\beta_1\beta_2$: here β_1 is due to surface microprotrusions and β_2 is due to dielectric surface impurities. When RF processing starts, β_1 is relatively low (~2) except perhaps for a few whiskers which burn up early in the process, and β_2 is relatively high (~60-120) because of the thickness of the dielectric layer. As RF processing proceeds, the dielectric surface impurities are gradually desorbed and β_2 decreases; however, as a breakdown "event" takes place through explosive electron emission[1)] (EEE), a crater is formed and β_1 grows. When RF processing reaches the asymptotic state (in our case, $\beta_1\beta_2$ ~60 at S-band), β_2 may be reduced to ~10 but β_1 is raised to ~6 because of the craters. The idea that comes to mind is that it may be possible to prevent β_1 from growing by processing the structure more gently, possibly with argon. There is evidence already that this procedure can at least reduce the "clean-up" time. If, in addition, it could reduce the number of craters, then the ultimate β_1 could perhaps be reduced by a factor of two. By operating at gradients at least 10 to 20% below breakdown, the so-called "dark current" due to captured FE current could be reduced considerably. Furthermore, to get the "dark current" per unit length, the above expression for the current density must be multiplied by the area available for FE per disk (which varies as f^{-2}) and the number of disks (which varies as f), yielding a net scaling as f^{-1}, thus favoring the higher frequencies. It is hoped that the experiments at X-band with a traveling-wave section will soon be performed, thus confirming some of these conjectures and predictions.

References

1) Loew, G. A., and Wang, J. W., "RF Breakdown Studies in Room Temperature Electron Linac Structures," SLAC-PUB-4647, May 1988 .