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PROGRESS REPORT ON HIGH-GRADIENT RF STUDIES IN COPPER ACCELERATOR STRUCTURES *

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Abstract

This paper is a progress report on studies carried out at the Stanford Linear Accelerator Center to understand the behavior of copper accelerator structures under extremely high RF fields. Such structures are being designed for future electron-positron linear colliders. Recent studies include field emission and breakdown experiments with an S-band slotted-disk structure, a single demountable S-band cavity and a short X-band structure which has not yet been tested. The demountable cavity was built specifically to examine the effects of copper quality, surface conditioning, gaseous exposures, and surface damage. Results to date and recent theoretical conjectures are discussed.

Introduction

In May 1988, the authors gave a comprehensive report of their work at the previous conference of this series.[1] This report contained results of experimental measurements of RF field emission and breakdown in S-, C-, and X-band cavities and a lengthy discussion of the effects of RF processing, regular Field Emission[2] (FE), Field-Induced Hot-Electron Emission[3] (FIHEE), Explosive Electron Emission[4] (EEE), and breakdown damage. Three basic ideas emerged from these earlier studies:

(1) RF processing leads to surface cleaning through field emission bombardment and a gradual reduction of this emitted "dark current" as a result of the removal of surface imperfections and impurities.

(2) Reduction of dark current is essential for reliable operation of the accelerator. As shown by our Japanese colleagues,[5] in a long accelerator structure, the dark current can grow by a progressive electron acceleration and multiplication process along the machine. Eventually, dark current can absorb considerable amounts of RF energy, cause transverse wakefields, radiation damage, and instrumental problems.

(3) RF breakdown occurs when the local field-emitted current density from a given site reaches 10^{12} to 10^{13} A/m^2 and causes enough heat dissipation to melt and 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, absorbed 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 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.

As we shall see, it would be desirable to avoid some of the above damage during the RF processing of the cavities to high fields.

Earlier and Recent Experimental Results

We first summarize our earlier and present experimental results. All tests reported in Table 1 were performed on standing-wave (SW) structures. The structures used in the S-band measurements were equipped with a variety of 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

Table 1. Experimental breakdown-limited gradients obtained with SW structures.

	S–Band				C–Band	X–Band	
	Disk-Loaded ($2\pi/3$-mode)	**With Nose Cone** (π-mode)	**Slotted-Disk** ($2\pi/3$)	**Demountable Cavity** (0-mode)	**Half-Cavity** (0-mode)	**Half-Cavity** (0-mode)	**Disk-Loaded** ($2\pi/3$-mode)
Frequency, f (MHz)	2856	2858	2857	2656	4998	9303	11424
Iris diameter, $2a$ (cm)	1.99	1.6	3.6	1.6	0.748	0.4	0.75
Total length (cm)	24.5	10.5	21	1.9	1.507	0.806	6.2
Filling time* (μs)	0.77	1.0	0.87	0.54	0.172	0.082	0.08
Pulse length (μs)	1.5–2.5	1.5–2.5	1.5–2.5	1.5–2.5	3.5	3.8	0.5–1.5
Peak power input (MW)	47	10.8	21.5	3.5	0.8	1.2	not yet avail.
E_s (MV/m)	313	340	315	314	445	572	not yet avail.
Measured factor β	~60	~60	~60	~60	~38	not avail.	not yet avail.
βE_s (GV/m)	18.8	20.4	18.9	18.8	16.9	not avail.	not yet avail.
$E_s/\bar{E}_{acc}$ for tested SW	3.88 ▹	4.15 ▹	5.1 +	not applic.	7.81 ▹	5.37 ▹	4.55 ▹

* Assuming critical coupling.
▹ Obtained from SUPERFISH.
+ The value obtained from MAFIA was 4.86. However, SUPERFISH being more accurate, we multiplied this value by a factor of 1.047, the ratio of the values calculated for an unslotted-disk structure (4.73 with SUPERFISH and 4.516 withMAFIA).

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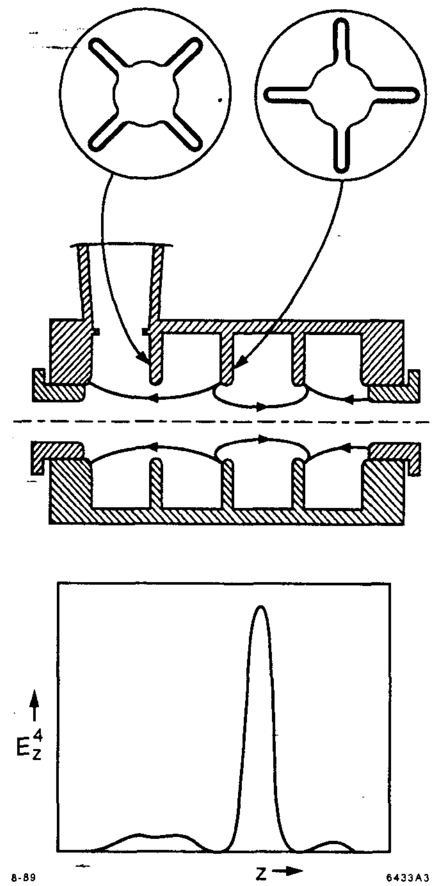

Fig. 1. Cross section of slotted-disk structure, with axial field profile.

look at breakdown sparks; pumps; and a residual gas analyzer (RGA). The most recent structures include an S-band $2\pi/3$-mode slotted-disk structure, a demountable S-band, 0-mode cavity from which an end-plug or nose can rapidly be removed for internal examination, and a seven-cavity X-band cavity which is not yet completed. The first new structure, shown in Fig. 1, was built to test whether the slots ultimately designed to couple out the HEM_{11} deflecting-mode and to 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. The demountable cavity is shown in Fig. 2, and the seven-cavity X-band structure is shown in Fig. 3. 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 all the S-band structures reached approximately the same limit of peak surface field. However, because of different values of a/λ and nose-cones, the resulting $E_s/\bar{E}_{acc}$ ratios are different. The peak surface fields in MV/m scale roughly as $E_s \sim 195\ [f\,(\text{GHz})]^{1/2}$. This approximate relation, which at this time 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 unfamiliar form as $E_s \exp(-4.25/E_s) = 24.7\ [f\,(\text{GHz})]^{1/2}$. We note that our experimental points exceed Kilpatrick's predictions by a factor of about eight. We will come back to this point later.

The procedures for all the earlier measurements were fairly similar. After the structures were fabricated, cleaned and generally baked to 200°C to 250°C, gradual RF processing was invariably needed to reach the maximum breakdown fields. Starting at macroscopic peak surface fields of about 100 MV/m, measurable field emission appeared. The resulting RF processing

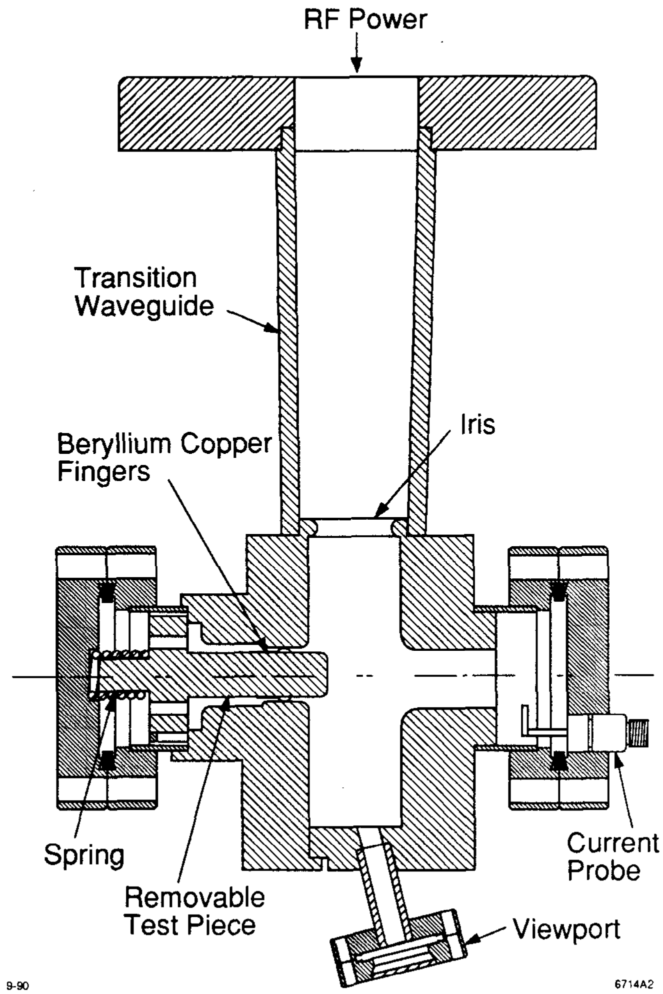

Fig. 2. Cross section of demountable cavity.

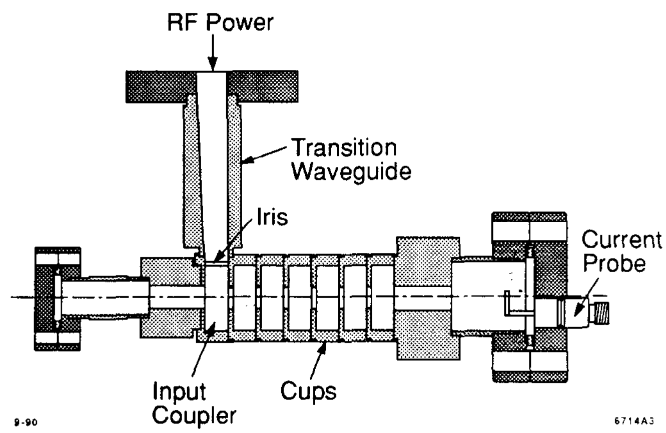

Fig. 3. Cross section of seven-cavity X-band structure.

was accompanied by steady out-gassing 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 was pushed up too fast). These breakdown "events" were 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 to 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 continued all the way up to the maximum attainable field, and took typically between three and fourteen hours. There seemed 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 increased as the field increased. Once the maximum attainable breakdown level was reached, a steady-state regime of operation was generally obtained at all fields below it and it was possible to get reliable Fowler-Nordheim plots using the expression below, which is applicable to measuring average field-emitted current $\bar{I}_f$ under RF conditions:

$$\frac{d\left(\log_{10}\, \bar{I}_F/E_s^{2.5}\right)}{d\left(1/E_s\right)} = \frac{-2.84\times 10^{9}\,\phi^{1.5}}{\beta}\,,$$

where E_s is the peak surface field in V/m, and ϕ is the work function of the metal in eV. From the Fowler-Nordheim plots, effective values of the field enhancement factor β and the "equivalent microscopic field" $\beta\, E_s$ shown at the bottom of the table were derived. When typically after tens of hours of testing the structures were internally examined, considerable damage was invariably found. While this cumulative damage did not affect stability of operation except at the maximum level, avoiding such damage during RF processing could probably reduce the ultimate field-emitted current at the operating level of the structure by keeping the surfaces as smooth and as clean as possible. For this reason, in the slotted-disk 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 indicated that RF "scrubbing" with argon at a pressure of 10^{-5} Torr could shorten the process somewhat but did not make it possible to reach the maximum breakdown field. "Brute force" RF processing under vacuum was still more effective, and this is how the ultimate peak surface field of 315 MV/m was reached with this structure.

Following this test, we built and began experiments with the demountable cavity. Its design was made so that the maximum surface field would occur on the nose piece which can be removed and observed immediately after a significant test. The first experiment was conducted with a poorly cleaned and polished nose piece, which was rapidly and severely damaged. We then removed the nose piece, very carefully cleaned and polished it (see Fig. 4) , and reinserted it into the cavity. RF processing to the top field level ($E_s \sim 314$ MV/m) was much more rapid and seemed to progress without light flashes. However, very close to the maximum field, obvious breakdown occurred (as witnessed by the TV monitor and RF reflections) and within a few minutes, considerable damage and melting took place. Figure 5 shows a number of SEM pictures taken at various sites. Note the variety of different types of damage. A third test is now in progress. Then, different materials and processing gasses will be tried.

Regarding the X-band disk-loaded structure, it is a copy of the $2\pi/3$ disk-loaded S-band structure. As this paper is being published, the structure is not yet ready. The results to be obtained will be crucial in determining whether the $f^{1/2}$ dependence of breakdown field really holds. Predicted surface fields of 660 MV/m would necessitate an X-band input power of about 24 Mw which should soon become available. However, it is possible that these future tests will show that the earlier C- and X-band measurements were in error and that there is no frequency dependence at all at these extremely high gradients. Also, at this point, neither our model nor our observations seem to say anything about the breakdown dependence on pulse length. The S-band measurements shown in Table 1 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 to 100 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 still do not know.

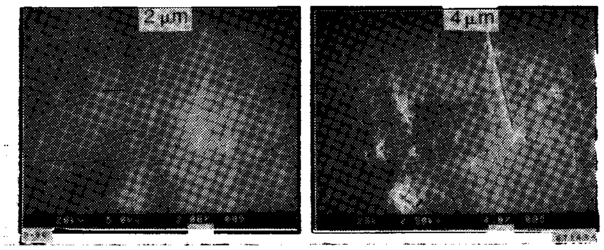

Fig. 4. Scanning electron microscope pictures of a part of the demountable S-band cavity nose before high-power test.

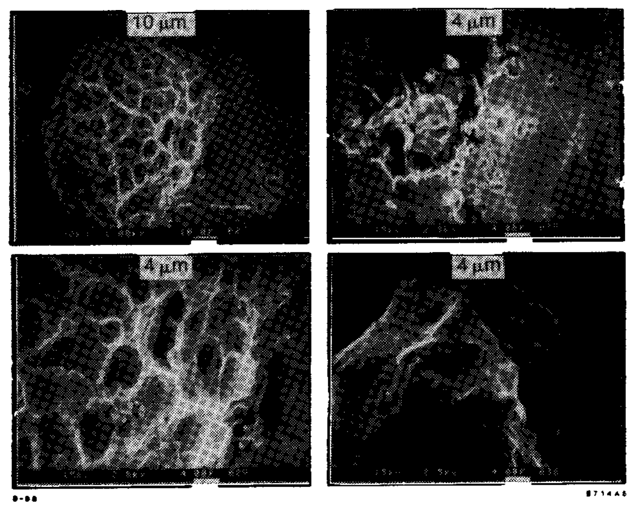

Fig. 5. Scanning electron microscope pictures of a part of the demountable S-band cavity nose showing breakdown damage after high-power test.

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