Conditioning of High Gradient H^- Accelerating Cavities

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Abstract

Three prototype cavities for the side-coupled accelerating structure of Fermilab's Linac Upgrade have been powered. The cavities operate at a nominal maximum surface electric field of 37-42 MV/m and have been run at close to 60 MV/m at 805 MHz. This paper will present the experience accumulated on x-ray production and RF breakdown frequency. We will try to compare our data with others' experiences with high surface electric fields.

Introduction

The Fermilab Linac Upgrade involves the replacement of the second half of the Alvarez drift-tube linac with a side-coupled structure similar to that used at Los Alamos. Because the Los Alamos structure was developed twenty years ago, a large R&D effort has been undertaken to take advantage of advances in technology and to develop local expertise. Included in this effort have been studies to understand the frequency of RF breakdown (sparking) and bremsstrahlung x-ray production to be sure that they fall within acceptable limits. RF breakdown inhibits the propagation of the beam through the linac, degrading the efficiency of the system and increasing activation levels. The amount of x-ray production determines the lifetime of organic materials in the vicinity and affects the shielding and therefore the civil construction requirements of the project.

The Fermilab structure will be operated at 805 MHz, have a maximum surface field of 37 MV/m, and a pulse length of 120 μsec. These parameters provide the opportunity to explore a relatively unexplored area of high surface electric fields and long pulse lengths and therefore may assist in the understanding of RF breakdown phenomena.

Physical Description

The side-coupled structure is based on the design of LAMPF shown in figure 1. Because of the high curvature on the nose piece, the surface electric field is approximately 5 times the accelerating field. The shunt impedance is 30% higher than LAMPF's and the the accelerating gradient is 5 times that of LAMPF[1].

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The copper pieces are first annealed and then machined using a water soluable cutting lubricant. The coupling slots are machined in and a section is stacked and tuned. Then the whole structure (up to 16 cells) is brazed together in 3 steps in a hydrogen furnace at temperatures reaching 1910° F.

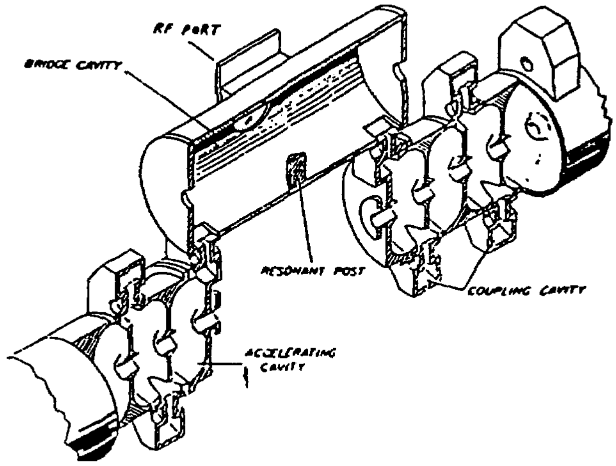

Fig. 1. View of LAMPF style side coupled accelerating structure. Prototypes 1, 2, and R-4 had 6, 6, and 16 cells respectively connected to a power cell. Prototype 1-A had 6 and 2 cells connected by a bridge coupler.

In order to guide the design of the production cavities, three prototype cavities were built and tested. Each had a different nose cone geometry. Prototype 1 (1-A) was a six cell structure (six plus two with a bridge coupler) that was given a sharper nose cone profile to enhance sparking for these studies. Prototype 2 was a six cell structure with a gentler nose profile. An even gentler nose cone profile was developed which was used in the sixteen cell Prototype R-4. (Prototype R-4 is actually one section of four that will make up a full prototype module which will be powered by a single klystron.) The average axial fields for Prototypes 1, 2, and R-4 were 7.67, 7.67, and 8.04 MV/m respectively. The ratio of the peak voltages on the nose cone to the average axial fields (E_{peak}/E_0) were 5.189, 5.001, and 4.547.

For these tests, the cavities were powered by a Litton L-5120 Klystron. It produced 1.5 MW (peak) in 120 μsec pulses at 15 Hz. For Prototype R-4 it was run at 2.9 MW with a pulse length of 50 μsec.

Sparks were recorded by a gated comparator that looked at the diode rectified signal from a directional coupler on the waveguide. The counter only counted pulses in which there was a spark even though there could be more than one spark within a single pulse (see fig. 2). The pulse length was nominally 120 μsec although the modules were sometimes run at 40 and 65 μsec. The gate for the comparator reduced the sensitive time to 75% of the pulse length.

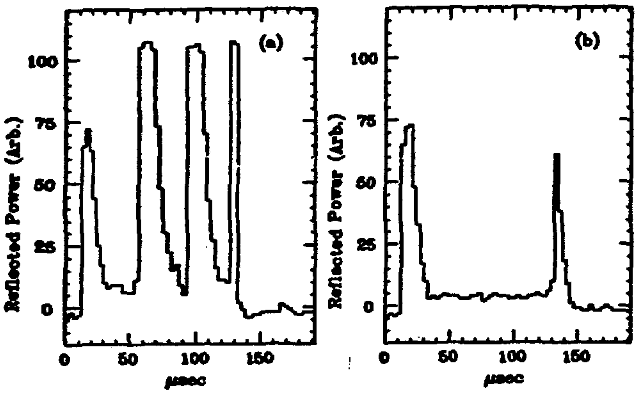

Fig. 2. Reflected power for a spark (a) and a normal pulse (b). The comparator was active for the time interval between t= 40 and 120 microseconds. If the reverse power was above a threshold, the comparator signaled that a spark had occurred. (a) illustrates that the sparks can be short lived phenomena, as short as ~ 10 μsec, and that more than one can occur within a pulse. The peaks in (b) occur due to the impedance mismatch during filling the cavity and the emptying of the cavity at the end of the pulse.

Figure 2 shows the results of a second spark monitoring system. The signal from the directional coupler was digitized and available for storage by a Sun workstation. If the comparator signaled that a spark had occurred the signal was stored. This permitted scanning of the reputed sparks to eliminate "false" sparks such as occurred when the comparator gate was not set correctly or the amplitude feedback loop on the signal generator had ranged out. A number of devices were used to measure the x-ray production of the cavities. All cavities were monitored by a Fermilab-built "Scarecrow". Prototypes 1 and 1-A also had a Victoreen-555 while Prototypes 2 and R-4 had a Nuclear Chicago 2592. The measurements from these were found to agree to within 10%.

Experimental Results

The data for Prototype 2 demonstrate best how the conditioning of these cavities occurs and are shown in figure 3. For this report, the chronological history of a cavity is measured by the number of RF pulses that have been applied. The counting was reset for Prototype 1, when the bridge coupler and the other two cells were added, which we then refer to as Prototype 1-A. Over the course of this investigation, Prototypes 1, 1-A, 2, and R-4 accumulated 8.53, 11.33, 18.87, and 17.81 million pulses respectively. In figure 3, the diamonds present the history of the sparking conditioning, the crosses show the x-ray production conditioning, and the ticks along the lower portion of the figure show when the cavity was energized to a higher level for the first time.

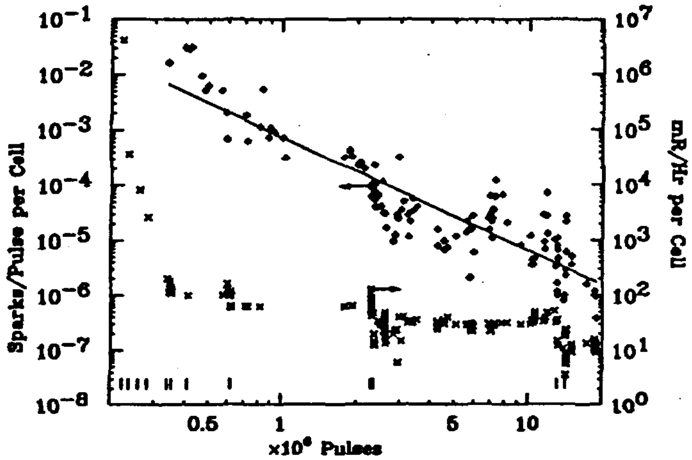

Fig. 3. Sparking rate (◇) and x-ray production (×) as a function of conditioning time as measured by the number of pulses in Prototype 2. Each have been corrected for pulse length and normalized to 37.1 MV/m. The ticks along the bottom indicate when a new electric field was achieved for the first time. The line is fit to the sparking rate for the interval between 500,000 and 19 million pulses and has a slope of -2.

Sparking

It was noticed that the sparking rate varied as the surface voltage to the ~19.5 power for fields between 33 and 60 MV/m. Since the cells are operated at various levels (X) for various lengths of time we assume the power law to be true and project all the rates (R) to the operating gradient of 37.1 MV/m.

$$R_{\text{proj.}}(37.1\tfrac{\text{MV}}{\text{m}}) = R(X\tfrac{\text{MV}}{\text{m}}) \times (\frac{X}{37.1})^{19.5} \qquad (1)$$

We have also observed that the sparking rate is directly proportional to the pulse length, so the rates are normalized to a full 120 μsec pulse length. The diamonds in figure 3 show how the sparking rate decreased as the cavity was conditioned. The line has a slope of -2 indicating that once 500,000 pulses have been accumulated, the sparking rate falls off as $1/(\#_{\text{pulses}})^2$. There is no indication of an asymptotic leveling off to a constant rate.

X rays

The x-ray production is governed by field emission as described by the Fowler-Nordheim equation. Over the range of operation explored here, the F-N equation can be represented by a power law of order 11 - 14. The x-ray production is scaled in a manner similar to the sparking as in equation 1. The x-ray production was also corrected for pulse width. It would be preferable to use absolute values of the F-N equation but we have no way of measuring either the field-emitted current nor the area of the emitters. Notice that while the reduction in sparking is continuous, the change in x-ray production is not. The drops in x-ray production seem to be correlated with attaining higher electric fields within the cavity.

Discussion

Historically much work on RF breakdown (sparking) has been related to the "Kilpatrick Limit"[2] although today truly catastrophic breakdown seems to occur at a level about seven times this limit[3]. For Prototype R-4 careful attention was made to measure the sparking rate as soon as the gradient was high enough for the comparator to function. This occurred as soon as multipacting was passed. Sparks were recorded beginning at 0.2 times the Kilpatrick limit. We have gone as high as 1.7 times the Kilpatrick limit and others have gone up to the catastrophic breakdown threshold. Sparking occurs all through this region as a random statistical process. It appears that within this range, one needs only to condition long enough until the breakdown rate subsides to acceptable levels. Our results so far indicate that this is easy to achieve and that there is no indication of an asymptotic leveling off.

As mentioned above, field emission is described by the Fowler-Nordheim equation, however, most measurements of the field emitted current require a multiplicative enhancement factor, β, for the electric field. This factor is assumed to be due to geometric or dielectric characteristics of the metal surface which increase the electric field in localized areas. Wang and Loew have investigated the possibility of RF "scrubbing"[4] to try to process to high gradient without causing physical damage to the surface in order to reduce β. If one is not going to run near the catastrophic breakdown limit, it seems that "brute force" processing is perfectly adequate. Presumably this burns off emitting sites and the reduction in the emitting area offsets any increase in β due to damage from sparking, at least at our operating levels.

The x-ray spectrum is produced by bremsstrahlung from the impact of field-emitted electrons onto the copper surface and should be directly proportional to the field-emitted current. The fact that the x-ray dose can be reduced by high-gradient processing suggests that the field-emitted current can be reduced, possibly by deactivating field emission sites.

As discussed above we see different behavior of the sparking rate and the x-ray production rate as a function of the conditioning time. The sparking improves continuously while the x-ray production improves in a stepwise manner whenever higher gradients are achieved. This suggests to us that different mechanisms govern the two processes. The x-ray production mechanism seems firmly tied to bremsstrahlung and field emission. Most RF breakdown mechanisms are also based on field emission. Latham also talks about microparticle based processes[5] but it would seem that these processes would also lead to high field emitted currents. These currents would suggest that the x-ray production and the sparking behave similarly.

Conclusion

The Fermilab Linac Upgrade project requires that the losses due to sparking to be less than 1%. For each of the prototypes tested, this level has been attained after 5 - 10 million pulses of conditioni ıg. At the linac's 15 Hz repetition rate this will occur in 4 to 8 days. We have not seen any evidence yet of the conditioning ceasing to improve. After the cavities have been let up to air, the previous sparking rate is recovered within a few minutes to hours. The x-ray production does not seem to be affected by the nose cone geometry and therefor the peak fields as one might have expected. However, it does seem possible to condition the cavities for lowest x-ray production by running the cavity to the highest fields available. These results are acceptable for the Fermilab Linac Upgrade.

In terms of understanding the dynamics of the two processes, the results are not as clear as each do not follow the same conditioning pattern as theories describing their origin would suggest.

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