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HIGH GRADIENTS IN LINEAR COLLIDER SUPERCONDUCTING ACCELERATOR CAVITIES BY HIGH PULSED POWER TO SUPPRESS FIELD EMISSION*

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Previous studies on 9-cell, 3 GHz superconducting accelerator cavities have shown the effectiveness of High Pulsed Power RF (HPP) conditioning against field emission.[1] Extrapolating from the experience with conditioning these cavities using 150 kwatt pulsed RF power, we installed 1 Mwatt of RF power (150 μsec pulses) for conditioning 5-cell cavities at 1.3 GHz chosen for TESLA (for **T**e**V** **E**nergy **S**uperconducting **L**inear **A**ccelerator). A high power cold test stand was built to transmit 1 Mwatt pulsed power to the cavities operating at 2 K. Several 5-cell, 1.3 GHz cavities were built. After some learning experience in operating couplers at high power levels, we succeeded in putting more than 1 MW into 5-cell superconducting cavities to reach pulsed surface electric fields between 80–90 MV/m. The pulsed conditioning was very effective in suppressing field emission. After conditioning in a few hours, three 5-cell units were operated in continuous wave (CW) at *accelerating* fields 27–28 MV/m. These are the first results to demonstrate gradients in excess of the design goal (25 MV/m) for TESLA.

KEY WORDS: Superconducting cavities, linear colliders, high pulsed power processing

1 INTRODUCTION

A linear collider with center-of-mass energy 500 GeV is receiving widespread attention as the next step in electron–positron collider energy. The pioneer linear collider is the SLC at SLAC (100 GeV in the center of mass). For useful physics in the TeV energy range, the luminosity needs to be increased by four orders of magnitude over the SLC (SLAC Linear Collider), which is a serious challenge.

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The long wavelength, superconducting RF approach to TeV energy and to the desired super-high luminosities is a very attractive option as compared to the short wavelength, normal conducting route for the following reasons. Since the intrinsic Q_0 of a superconducting cavity is very high, it is not necessary to fill the cavity very fast to avoid wasting energy, which means that modest peak RF powers (200 kW/m) can be used. By comparison, normal-conducting cavities need 10–100 MW/m.[2] Because the amount of energy that has to be delivered to the superconducting structure is orders of magnitude lower, the high Q_0 also permits a much lower RF frequency, 1.3 GHz instead of the 3–12 GHz for normal conducting versions under consideration. The low RF frequency has the pleasant consequences that the short and long wakefields are substantially lower, fighting the main enemies of high luminosity. Yet another important advantage stemming from the high Q_0 is that the RF pulse length can be made long enough to accelerate a large number of well separated bunches. The desired high luminosity can thereby be achieved by higher collision frequency, rather than by squeezing the final spot size to the nanometer level. The relaxed spot size in turn eases the burdens on the source and final focus systems. (An overview of the advantages of the TESLA approach can be found in Reference 3.)

Because of the many advantages of the TESLA approach, a large collaboration is working on the goal of building a TESLA Test Facility at DESY in Hamburg, Germany.[4]

The challenges for the SRF approach to linear colliders are to achieve gradients of 25 MV/m or higher, and to reduce the cost of the structures, cryostats and peripheral devices, like couplers. We present here a breakthrough in the gradient goal. Using advanced preparation and processing techniques, three half-meter long units at the TESLA RF frequency of 1.3 GHz have achieved gradients between 25–28 MV/m accelerating.

2 FIELD LIMITATIONS IN SUPERCONDUCTING CAVITIES

The goals for TESLA call for a substantial improvement over the present day performance of niobium cavities. In the present state of the art, the achievable gradient in acceptance tests of cavities is near 10 MV/m, compared to the design value of 5 MV/m for exisiting and intended applications such as TRISTAN, HERA or CEBAF or LEP-II. The present state of the art in superconducting cavities as well as the technological aspects of RF superconductivity discussed here are reviewed in Reference 5.

There are two major field limiting mechanisms operative: thermal breakdown and field emission. A proven approach to avoid thermal breakdown is to use high thermal conductivity Nb. (An alternate approach is to use thin films of niobium on a high thermal conductivity copper substrate.) For a given imperfection on the RF surface the breakdown field value scales roughly as the $\sqrt{}$(thermal conductivity). The thermal conductivity of niobium is increased by purification which involves removal of the most harmful interstitially dissolved impurities: oxygen, nitrogen, carbon and hydrogen. A convenient way to characterize the purity and thermal conductivity is the residual resistivity ratio (RRR). The RRR of sheet Nb delivered by industry for superconducting cavities has been going up steadily over the last 10 years from 30 to 300. The RRR of industrially produced Nb can be further improved by a factor of two (or more) by solid state gettering removal of the major impurity, oxygen.

It is now generally agreed that microparticle contaminants, most often micron and submicron size foreign particles of a conductive nature, are the culprits responsible for field emission. Increased vigilance in cleanliness during chemical etching, rinsing and assembly procedures has kept field emission under control up to the level $E_{acc} = 10$ MV/m. There are several new efforts underway to further improve cleanliness, such as UHV heat treatment,[6] high pressure water rinsing[7] etc. There is evidence to show that with these clean treatments, emitter density is reduced.[6]

While these efforts have the unarguable potential to improve cavity performance, there are important concerns about any super-cleanliness approach. As is often observed, a single field emission site in an accelerating unit can limit the maximum field level, if this emitter will not "process" away. There is always some probability, high for large area cavities, that one or more such emitters will find their way on to the cavity surface. This shortcoming is especially clear in the light of the experience of all laboratories that there is a 20–25% decrease in the performance between the acceptance (or vertical cryostat) tests and the in-tunnel test results. It is also clear that due to the random nature of contamination, cavities with a large surface area show field emission limitation at lower fields.

Therefore a technique that processes (eliminates) emitters in-situ is highly desirable. Besides increasing the performance of a cavity prepared by existing cleaning techniques, such a technique would be effective against accidental contamination of the cavity in an accelerator or during assembly of couplers and other components into a pre-cleaned cavity. Such a technique would also help to reduce the large spread typical in the performance of cavities. For example in a set of 338 CEBAF 5-cell cavities[8] the highest achieved fields ranged from $E_{acc} = 5$–20 MV/m, with the mean value of 10 MV/m, and a standard deviation of 7 MV/m.

A technique with just these desirable features has recently been demonstrated.[1] By applying High Pulsed RF Power (HPP) to 3 GHz superconducting cavities, emitters have been processed and operating field levels raised. With power levels between 5 and 150 kW, and pulse lengths between 5 μsec and 1 msec, the CW operating field levels for several 1-cell, 2-cell and 9-cell cavities were raised consistently over a series of 25 separate tests. For example, in the 8 separate tests on 9-cell cavities, CW accelerating field levels improved from 8–16 MV/m before HPP to 15–20 MV/m after HPP. The HPP technique was also demonstrated to recover high gradient performance after deliberately introducing field emitting contaminants through cold and warm vacuum accidents.

The present level of understanding that has emerged from these studies is that, as the field is raised, the strongest emitters put out so much field emission current that a micro-discharge (RF spark) takes place, and the ensuing explosive event destroys (processes) the field limiting emitter. When the field level is raised further, the next strong emitters process, and so on. The essential idea of using high power pulses is to raise the surface field as high as possible. The processing is effective even if the fields reach high values for times as short as μsecs, because spark formation times are $< \mu$sec.[9]

The goal of the present study is to evaluate the effectiveness of the HPP technique to multi-cell cavities at the TESLA RF frequency of 1.3 GHz and to compare the results with the previous 3 GHz study.[1]

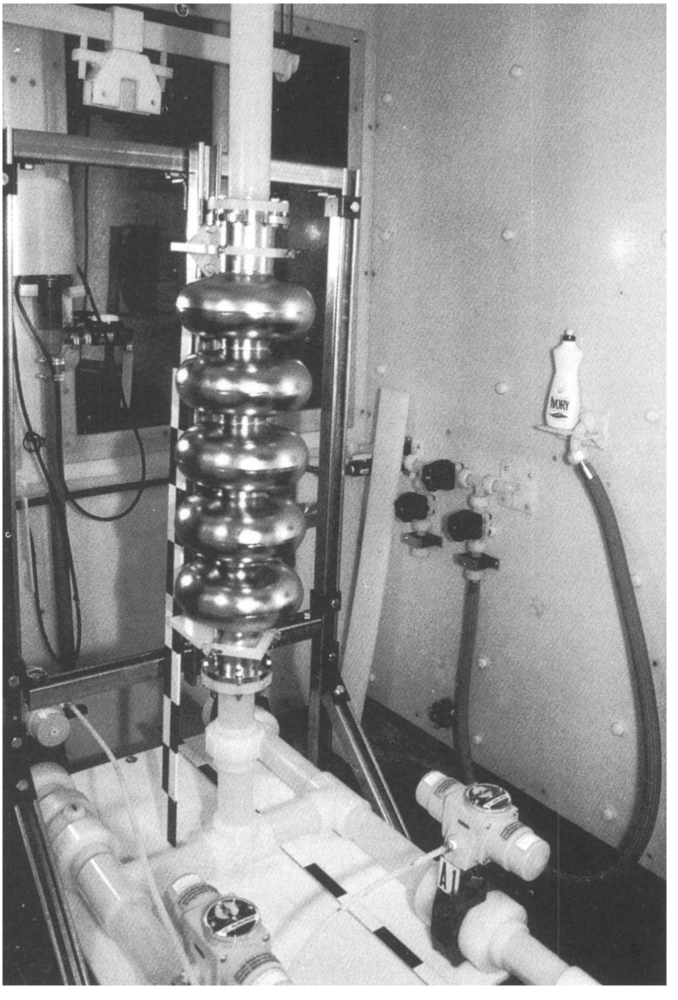

FIGURE 1: 5-cell niobium accelerating section set up for chemical etching.

3 NIOBIUM ACCELERATING STRUCTURES

Two 5-cell, 1.3 GHz cavities were purchased from industry (Cavities #1 and #2) and two 5-cell cavities were built at Cornell (Cavities #3 and #4). The important properties of the accelerating mode are listed in Table 1. During construction, one of the Cornell-built cavities (#4) had a weld hole which had to be repaired, but the repair was not very successful as judged from the premature thermal breakdown field. Results from this cavity will be omitted. Figure 1 shows one of the 5-cell cavities as it is set up for chemical treatment.

TABLE 1: Accelerating Mode Properties of the 5-cell, 1.3 GHz Cavities.

Property	Industry Built	Cornell Built
R/Q(Ohm/m)	1012	1088
E_{pk}/E_{acc}	2.5	2.0
H_{pk}/E_{acc}	41	43

The starting sheet material for all cavities had a RRR = 250–300. After preliminary RF tests, during which thermal breakdown limited the performance at $E_{acc} < 14$ MV/m, cavities #1 and #3 were further purified by solid state gettering as shown in Figure 2. Both the inside and outside surfaces were exposed to Ti vapors at 1400 C. After RRR improvement, both the inside and outside surfaces were chemically etched to remove the Ti rich layers. Previous tests with samples treated in the same way have shown that the RRR improves to 500–600. The titanium diffuses into the bulk to the order of 100 μm, requiring removal of a comparable thickness of material by chemical etching, which was carried out.

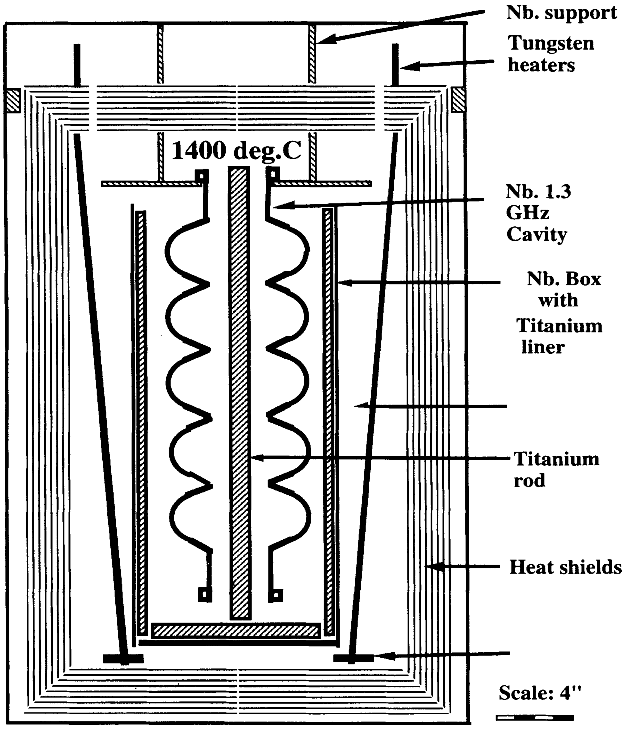

FIGURE 2: Schematic of solid state gettering purification of niobium cavity.

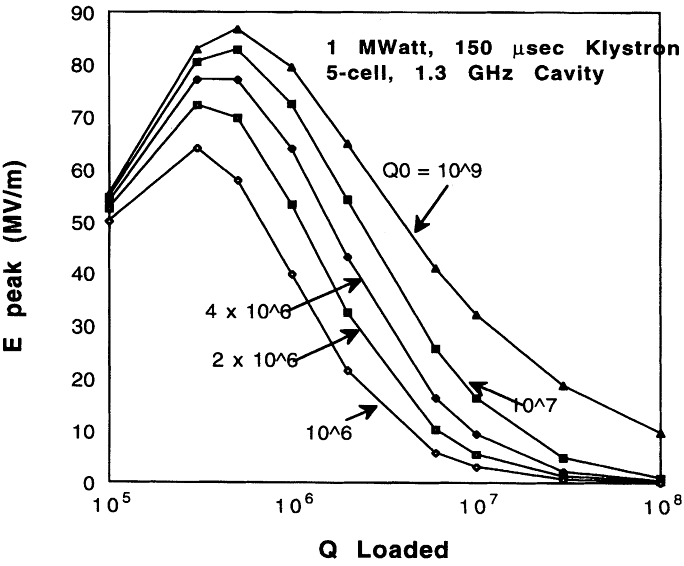

FIGURE 3: Calculated maximum surface electric field accessible with 1 MW, 150 msec pulsed RF power.

4 HIGH POWER SOURCE AND TEST STAND

The high power klystron and modulator system available were capable of providing a maximum of 1 MW of power (P_{inc}) at a pulse length (t) of 150 μsec. Figure 3 shows the theoretical maximum surface field level, $E_{pk}(t)$ that a 5-cell cavity can reach as a function of input coupling (Q_{ext}) and for different Q_0 values. For simplicity of calculation, we make the pessimistic assumption that the Q_0 takes on the reduced values throughout the pulse. E_{pk} is calculated from E_{acc} using the cavity properties listed in Table 1.

$$\frac{R}{Q} = \frac{E_{acc}^2}{\frac{\omega U}{L}} \tag{1}$$

where U = stored energy, L = length of cavity

$$E_{acc}(t = \infty) = \sqrt{\frac{4\beta P_{inc}(R/Q)Q_0}{(1+\beta)^2 L}} \tag{2}$$

$$\beta = \frac{Q_0}{Q_{ext}} \tag{3}$$

$$\frac{1}{Q_{Loaded}} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \tag{4}$$

$$E_{pk}(t) = E_{pk}(1 - e^{-(t/2\tau)} \tag{5}$$

$$\tau = \frac{Q_{\text{Loaded}}}{\omega} \tag{6}$$

$$\omega = 2\pi f \tag{7}$$

The design of the high power test set-up is shown in Figure 4. The high power enters the top plate (not shown) at a warm window through a reduced height waveguide. Near the bottom of the cryostat is a waveguide to coax door-knob transition with an integrated cylindrical ceramic window to isolate the high vacuum, cavity region. The ceramic was coated with TiN on both sides. The VSWR of the entire assembly was less than 1.6 between 1280 and 1320 MHz. The penetration of the antenna into the cavity is adjustable over 10 cm by flexing a copper plated hydroformed bellows in the outer conductor. The coupler Q_{ext} can thus be adjusted over the necessary range between 10^5 and 10^{10}. The slotted region of the outer conductor above the door-knob is connected to the vacuum pumping line.

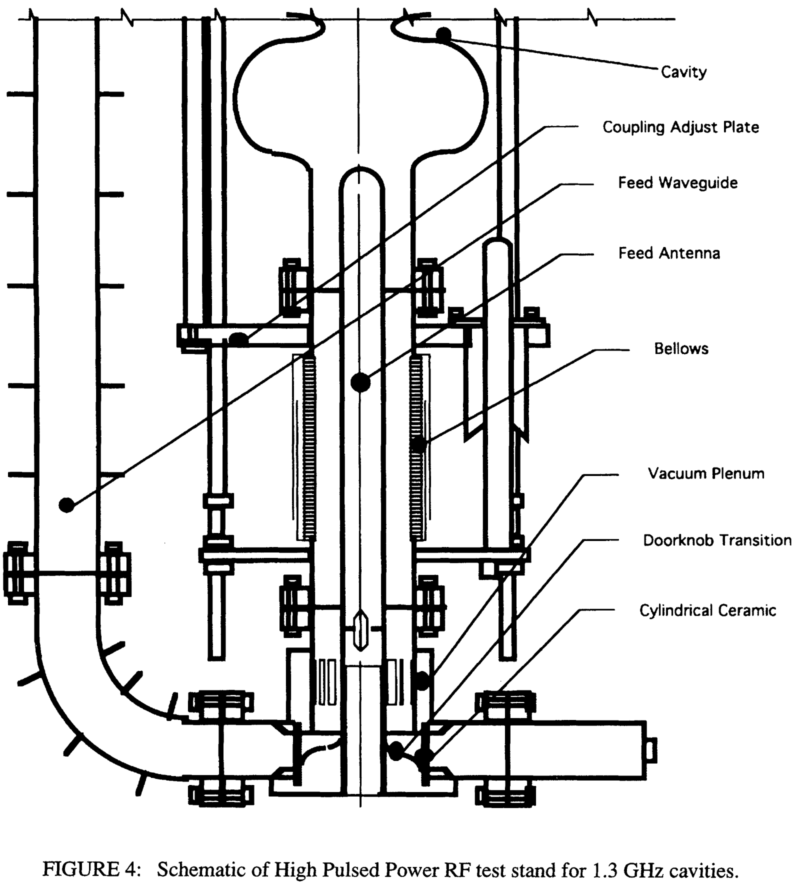

FIGURE 4: Schematic of High Pulsed Power RF test stand for 1.3 GHz cavities.

We had to overcome several difficulties with the high power test stand before we could transmit 1 MW of incident power to the cavity. For the best high power performance of the cold window, we found it essential that the length of the antenna be such that there is a standing wave voltage minimum at the side of the ceramic closest to the waveguide elbow (see Figure 4). When the antenna length was approximately a quarter wavelength different, we observed breakdown events at 300–400 kW incident power during which the incident power was completely absorbed, but not in the cavity. We found that on the coax side of the waveguide-to-coax transition, the door-knob was coated with silver (from the braze material used for construction) presumably from sputtering in the degraded vacuum during breakdown.

For the warm window we first used a 1.5 mm thick teflon sheet with Indium wire vacuum joints. But there were breakdown events between 300 and 700 kW. These events were also accompanied by vacuum bursts in the waveguide region. Tracks of metal deposit (presumably from the hold down flanges) were found on the teflon sheet near the high electric field center of the waveguide cross section. Placing the teflon window at the standing wave voltage minimum allowed higher power operation. Only after replacing the warm teflon window with a warm ceramic (alumina) window were we able to increase the power to 1 MW without breakdown.

After diagnosing and remedying these problems we could raise the power to 1.2 MW without any significant delays associated with the conditioning of the coupler. Before understanding and implementing the improvements mentioned, we needed conditioning for many hours to approach 300 kW.

5 FIVE-CELL TEST RESULTS

As mentioned, two of the cavities (#1 and #3) had their RRR improved by solid state gettering. Before RRR improvement these cavities were limited by thermal breakdown during CW operation at $E_{\mathrm{acc}} = 14$ MV/m (#1) and $E_{\mathrm{acc}} = 12.5$ MV/m (#3). Cavity #2 did not show a low field breakdown and its RRR has therefore not yet been enhanced. The spread in the CW thermal breakdown field values before RRR improvement is consistent with the large set of statistics from CEBAF with 5-cell cavities built from nominally the same RRR Nb. In 146 structures that were limited by thermal breakdown, the spread in the breakdown field value was from $E_{\mathrm{acc}} = 7$–20 MV/m, with the mean value of 13.1 MV/m.[8] As we shall discuss below, after RRR improvement the maximum CW field in our cavities improved to $E_{\mathrm{acc}} = 28$ MV/m (#1, limited by field emission) and $E_{\mathrm{acc}} = 27$ MV/m (#3, limited by thermal breakdown). Therefore, on a statistical basis, the RRR improvement increased the field by a factor of 2 or more, confirming the documented dependence of average quench field on $\sqrt{\mathrm{RRR}}$.[5]

Figures 5–9 show the performance of each of the three five cell cavities before and after HPP to process field emission. These test results were obtained after the coupler performance was improved as discussed in the last section so that processing of field emission could be carried out to 1 MW. We could not process much above 1 MW of pulsed power because the test stand would break down more often.

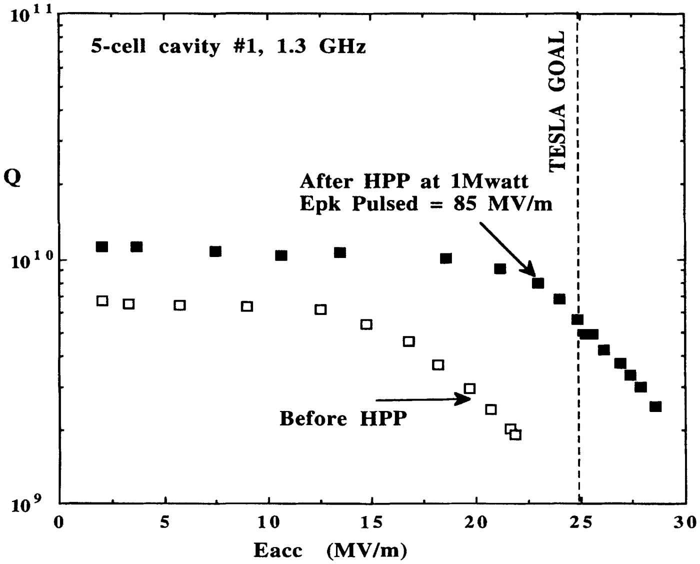

FIGURE 5: RF test results on 5-cell, 1.3 GHz cavity 1 before (open squares) and after (filled squares) HPP.

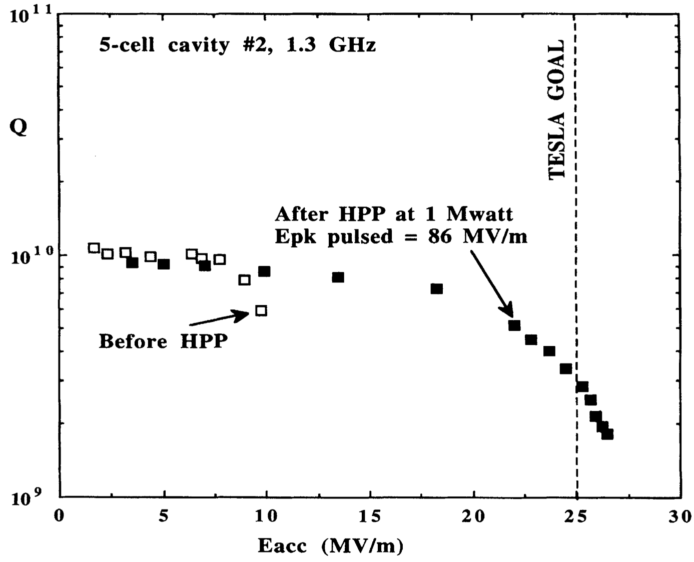

FIGURE 6: RF test results on 5-cell, 1.3 GHz cavity 2 before (open squares) and after (filled squares) HPP.

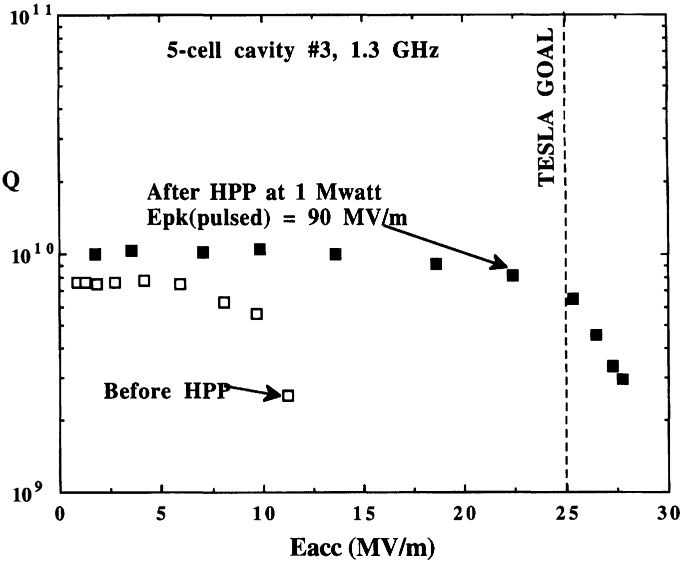

FIGURE 7: RF test results on 5-cell, 1.3 GHz cavity 3 before (open squares) and after (filled squares) HPP.

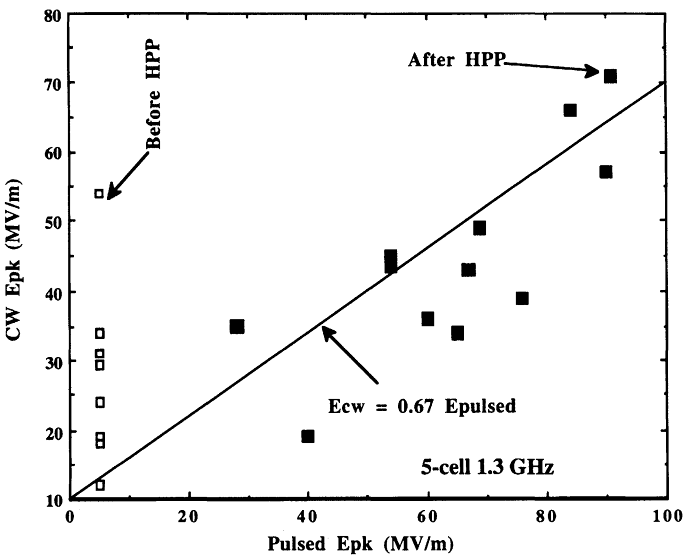

FIGURE 8: A summary of the benefits of HPP on 1.3 GHz cavities. The open squares are the CW results before HPP and are plotted offset from the vertical axis. The filled squares are results after HPP. The higher the field achieved in the pulsed conditioning stage, the higher the CW operating field.

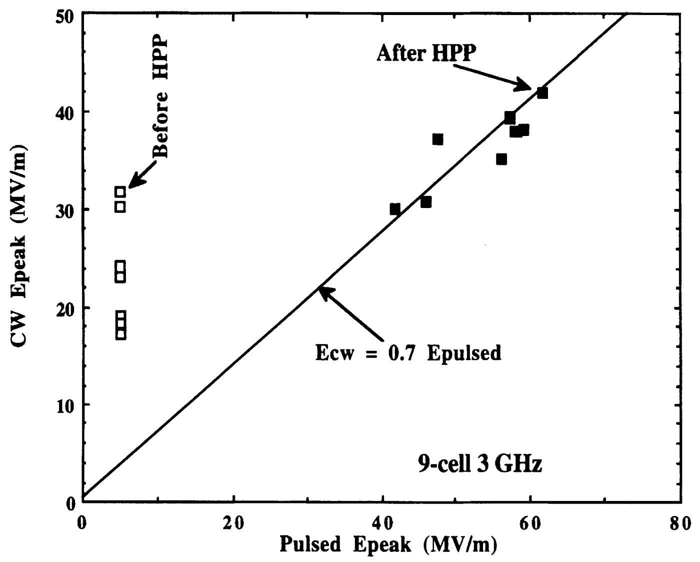

FIGURE 9: A summary of the benefits of HPP on 9-cell. 3 GHz cavities.[2] See Figure 9 for explanation of symbols.

Figures 5–9 show how, before the application of HPP, the CW gradient for all three cavities was limited by field emission. In two cases the Q_0 had dropped substantially at $E_{acc} = 10$ MV/m, and in one case at $E_{acc} = 22$ MV/m. The spread in field emission limited performance is typical for the etching, rinsing and preparation techniques now in vogue. For example the average field emission limited gradient in 338 cavities at CEBAF was 10.5 MV/m, with the spread ranging from $E_{acc} = 5$–20 MV/m.[8]

In all three cavities, after HPP with 1 MW of power, the field emission was substantially suppressed, so the maximum CW accelerating gradients reached were 27, 28 and 28 MV/m, all above the TESLA goal of 25 MV/m. During the pulsed processing stage, the surface electric fields reached were between 85–90 MV/m. After HPP at 1 MW, the CW performances of cavities #1 and #2 were ultimately limited by field emission. Because of field emission loading, cavity #1 was limited by available CW RF power, and cavity #2 was limited by the radiation level safety trip point. The CW performance of cavity #3 was finally limited by thermal breakdown.

6 DISCUSSION

Our results confirm that after the RRR improvement the probability of thermal breakdown limitation at the 12–14 MV/m level was drastically reduced, and much higher fields are possible provided field emission does not take over. Even if cavities are limited by field emission to CW $E_{acc} = 10$ MV/m, they can be improved to $E_{acc} = 28$ MV/m with HPP.

Therefore the HPP technique provides a way to reduce the spread in performance typical of field emission limited cavities.

Our results for the effectiveness of HPP are very consistent with 3 GHz HPP experiments. We find as before that the most important parameter for successful processing of field emission is the value of the surface field reached during the pulsed conditioning stage. To demonstrate this we plot the results from 5-cell 1.3 GHz cavities as the maximum CW surface field reached versus the pulsed conditioning field imposed on the RF surface.

A similar plot for the 9-cell 3 GHz cavities[1] is included for comparison. For both 1.3 GHz as well as for 3 GHz cavities we observe that

$$E_{\mathrm{pk}}(\mathrm{CW}) = (0.6 - 0.7) \times E_{\mathrm{pk}}(\mathrm{pulsed}). \tag{8}$$

7 CONCLUSIONS

This study proves that the solid state gettering purification of niobium substantially reduces the probability of encountering thermal breakdown and the HPP processing technique works effectively against field emission, the two chief limitations in performance of superconducting cavities. Using both techniques, we have surpassed the TESLA goal of accelerating field of 25 MV/m in 5-cell 1.3 GHz structures.

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