A World Record Accelerating Gradient in a Niobium Superconducting Accelerator Cavity*

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Abstract

A two-cell, 3 GHz, niobium superconducting accelerator cavity has sustained a continuous wave (CW) accelerating gradient of 34.6 MV/m, with corresponding peak surface electric electric field of 100 MV/m, record performances in each category for a superconducting accelerator cavity. Field emission (FE) loading of the cavity initially limited the cavity to E_{acc} = 21 MV/m (E_{peak} = 60 MV/m). The record field was achieved by reducing the FE loading through High Peak Power (HPP) RF processing of the cavity. Analysis of previous results of the HPP experimental program indicated that maximum fields under both pulsed and CW conditions were limited by thermal breakddown, which is related to the surface magnetic field in the cavity. The two-cell cavity shape was chosen to bypass the thermal breakdown limitations by reducing the ratio of peak surface magnetic field to peak surface electric field, from a value of H_{peak}/E_{peak} = 23 Oe/(MV/m) in the previous cavity, to 14 Oe/(MV/m) in the two-cell cavity. A simple thermal model accurately simulates the pulsed breakdown.

I. INTRODUCTION

A. SRF Cavities

Niobium Superconducting Radio-frequency (SRF) cavities are a promising technology for construction of the next generation of electron-positron colliders. In order for SRF to become a viable method for construction of these machines, however, attainable accelerating gradients must be increased from the 5-10 MV/m attained in present SRF accelerators to 25-30 MV/m.[1] The gradients reached in this work show that it is possible to achieve the desired performance for TeV colliders, using HPP to overcome field emission (FE), the major limitation to high gradients.

The HPP experiment was designed to explore the benefits of high power pulsed radio-frequency (RF) processing as a means of reducing FE loading in 3 GHz niobium accelerator cavities. RF processing is a method of cavity conditioning, where the cavity is exposed to high RF fields in the absence of a particle beam. The HPP apparatus can deliver up to 200 kW peak power for millisecond pulse lengths during processing. An in depth description of all results of the HPP experiments can be found in the Ph.D. dissertation associated with this work.[2]

B. Thermal Limitations of Previous HPP Work

The HPP experiments have shown that high power processing is a successful method of reducing FE loading in SRF cavities.[3] The initial studies were performed with single-cell and nine-cell cavities, using a geometry termed the S3C geometry. Results of the tests on nine-cell cavities are being presented in another paper to be presented at this conference.[4] Success in FE reduction via processing has been directly linked to the magnitude of the electric field attained during processing (E_{HPP}). Furthermore, the attainable E_{HPP} has been shown to be limited by thermal breakdown, the phenomena where the RF surface is locally heated above the critical temperature, initiating the growth of a normal conducting region. Thermal breakdown limited single-cell cavities to E_{peak} = 55 MV/m (H_{peak} = 1265 Oe) CW and E_{peak} = 72 MV/m (H_{peak} = 1650 Oe) during HPP. Nine-cell cavities reached E_{peak} = 42 MV/m (H_{peak} = 840 Oe) CW and E_{peak} = 62 MV/m (H_{peak} = 1250 Oe) during HPP.

Thermal breakdown is driven by the surface currents which are required to support the magnetic fields at the RF surface. We therefore chose to investigate a cavity with a lower ratio of H_{peak}/E_{peak}. This ratio is determined by the cavity geometry, and can be obtained by numerical solution of Maxwell's Equations. Several programs exist for this purpose, e.g. SUPERFISH[5]. The S3C cavities used for the single-cell and nine-cell experiments have H_{peak}/E_{peak} ratios of 23 Oe/(MV/m) and 20 Oe/(MV/m), respectively.

II. TWO-CELL W3C2-1

A. Cavity Fabrication and Preparation

After some investigation of potential cavity shapes, we chose a two-cell cavity using the geometry of the SRF group at the University of Wuppertal. A larger rounding of the equator region reduces the magnetic to electric field ratio of this cavity, designated W3C2-1, to H_{peak}/E_{peak} = 14.2 Oe/(MV/m). Interatom GmbH graciously agreed to press the half cells for this cavity (gratis). Final trimming, yttrification (for purification, and thus higher thermal conductivity), and electron beam welding were performed at Cornell.

The initial attempts at testing this cavity were limited by anomolously low thermal breakdown, initially due to insufficient surface chemistry then later due to the "Q virus." The final preparation prior to the successful test was a 2 hour bake at 900° C to eliminate the hydrogen contamination which has been identified as the cause of the Q virus.

B. Cold RF Measurement

Based on the reduced H_{peak}/E_{peak} ratio and the observed magnetic field break-down levels (H_{bd} = 1250-1300 Oe) from the S3C cavities, we predicted that the cavity would reach 90-95 MV/m prior to thermal breakdown limitation. The cavity performance exceeded this prediction. The results of the best experiment with cavity W3C2-1 are shown in Figure 1. This cavity experiment extended over two cool downs, with a room temperature cycle, but no vacuum break between.

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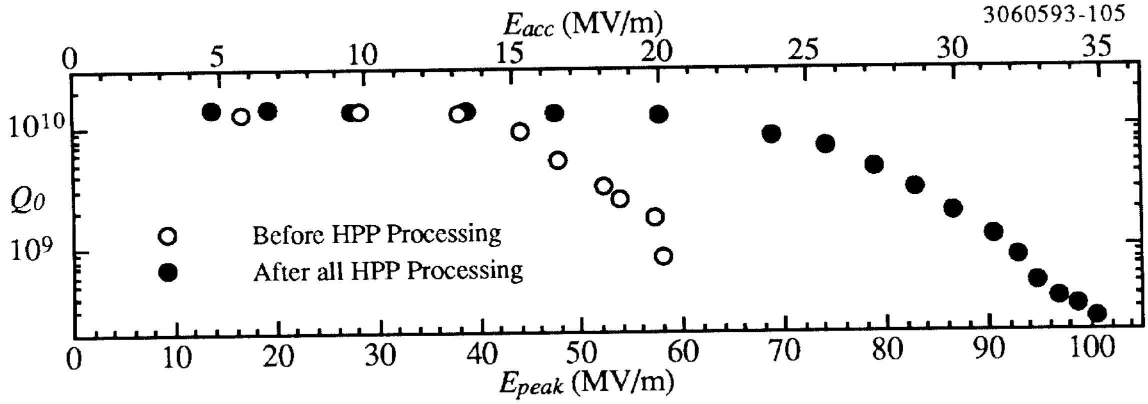

Figure 1. Q_0 vs. E_{peak} (E_{acc}) plots for the best experiment with cavity W3C2-1.

On initial rise of power, the cavity performance was similar to that of pre-HPP single cell cavities. FE related Q_0 drop was measurable at E_{peak} = 25 MV/m, though low power processing with P_{inc} = 10 W increased the threshold to E_{peak} = 35 MV/m. The second plot in Figure 1 is the best CW measurement from the second day of testing the cavity. This CW measurement followed processing with incident power up to 130 kW, and fields as high as E_{HPP} = 103 MV/m, a room temperature cycling, and processing with power up to 100 kW, and fields as high as E_{HPP} = 113 MV/m. During HPP, analysis indicates that Q_0 values dropped to 10^6. As can be seen, the improvement is remarkable. The maximum attained CW field was E_{peak} = 100.6 MV/m, limited by thermal breakdown (H_{peak} = 1430 Oe). This peak electric field is 20 MV/m higher than any accelerating cavity has ever been operated CW. The corresponding accelerating gradient at E_{peak} = 100.6 MV/m was E_{acc} = 34.8 MV/m. The Q_0 of the cavity remained above 5 x 10^9 for peak fields as high as 75 MV/m (E_{acc} = 26 MV/m). The experiment was repeated, reaching E_{peak} = 85 MV/m (with nearly identical field emission behavior), where it was limited by a superfluid helium leak.

C. Comparison with Previous HPP Results

We can now compare the results of all tests of two-cell cavity W3C2-1 with the results of tests of the S3C shape cavities. Figure 2 plots maximum attainable CW electric field as a function of the maximum processing field preceding the CW measurement. The results of the two cell cavity are in good agreement with an extrapolation of the single-cell and nine-cell results. Furthermore, this clearly supports the correlation between processing field and success in processing.

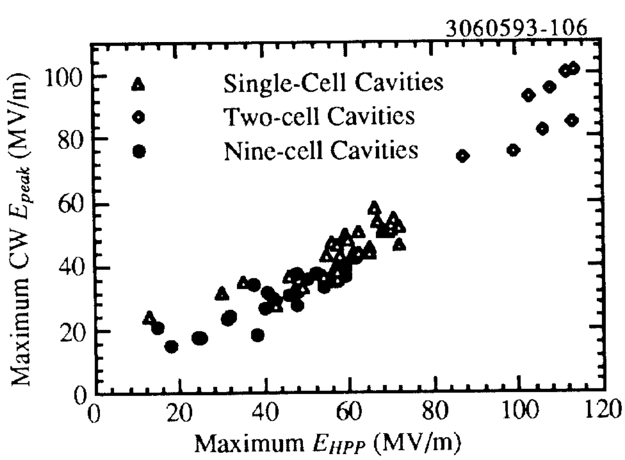

Figure 2. Maximum attainable CW peak electric field as a function of peak field attained during HPP processing. Note that the two-cell cavity behavior is in good agreement with an extrapolation of nine-cell and single-cell behavior.

Figure 3 is a similar plot, showing the X-ray detection threshold electric field as a function of maximum E_{HPP}. X-rays are produced when emitted electrons impact elsewhere in the cavity, and X-ray detection is a reproducible method of characterizing the onset of field emission in a cavity.

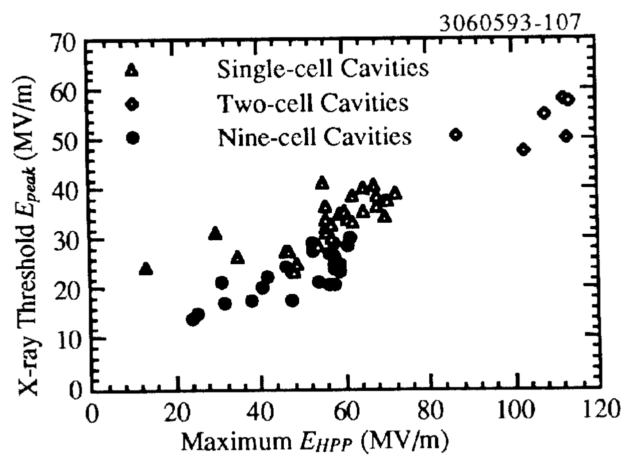

Figure 3. X-ray threshold peak electric field as a function of peak field attained during HPP processing.

III. MODELING OF THERMAL LIMITATIONS

A. The Model

With the predominance of thermal breakdown as a limitation to attainable fields during processing (and therefore success in processing), it is instructive to model the thermal processes in the cavity. Previous work on modeling (e.g. program **HEAT**[6]) has been done on the simplified system of a niobium disk, with magnetic fields (power input through dissipation) at one circular face, and a helium bath (cooling) at the opposite face. Steady state solutions of this problem provided reasonable predictions for thermal breakdown field levels in typical cavities. More recently, this model was expanded, in program **Transient_HEAT**,[7] to include transient effects. With **Transient_HEAT**, we were able to gain an initial understanding of the time evolution of a normal conducting region on a superconducting surface. With this understanding, the following model was developed.

We allow for four different loss mechanisms: superconducting wall losses, FE losses, input coupler losses, and normal conducting wall losses. FE losses are estimated by extrapolating the low field behavior to HPP conditions.

We assume the cavity has a single breakdown initiation region, which activates at a fixed magnetic field (H_{BD}). When H_{BD} is surpassed, a circular normal conducting region begins to grow on the RF surface of the cavity, with expansion velocity v_{nc}, which was obtained by determining the growth rate of the normal conducting region as a function of magnetic field with **Transient_HEAT**. The results of **Transient_HEAT** indicate that v_{nc} varies quadratically with increasing magnetic field, with a typical growth rate being 500 m/s for $RRR = 400$, $H_{BD} = 1200$ G, $H_{surface} = 1400$ G.

During application of high pulsed power, it is possible to exceed the CW thermal breakdown field while the NC region grows in size. The amount of overshoot is a function of many parameters, including incident power, CW breakdown field, loaded Q, FE loading.

A more complete description of this model can be found in the previously mentioned dissertation.[2]

B. Model Predictions and Analysis

The result of simulation is an explaination of the relationship between CW thermal breakdown field and the attainable peak field during HPP. Given the experimental conditions of RF processing, this model predicts the "overshoot" of CW breakdown field. Figure 4 is a comparison of measured and predicted E_{HPP}, as only the input coupling (designated by Q_{ext}) changes; pulse length and input power remain constant. The CW thermal breakdown field and the predicted peak field without taking breakdown into account are also shown for reference.

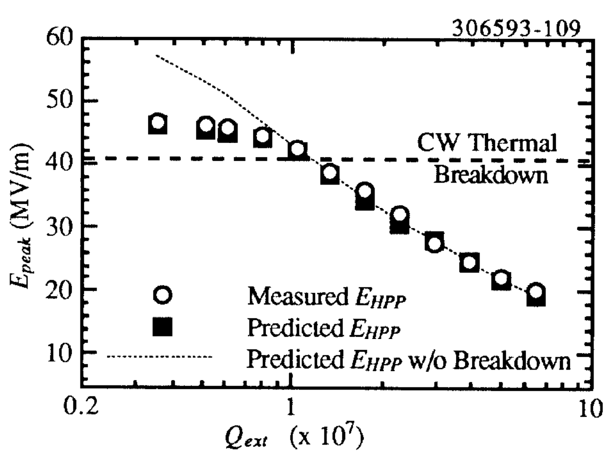

Figure 4. Comparison of Measured and Predicted E_{HPP} during HPP on a nine-cell cavity.

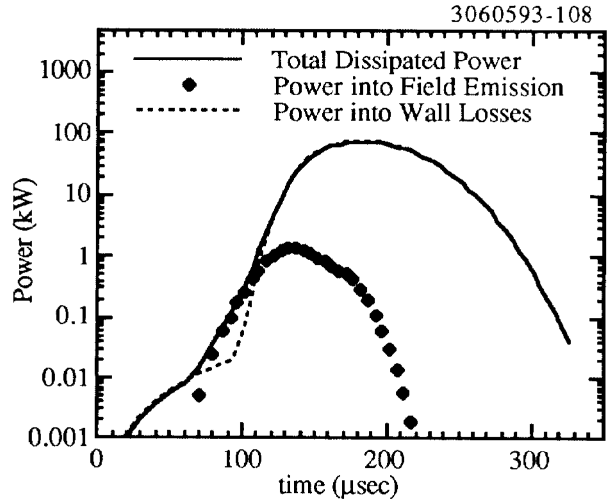

Figure 5. Power dissipation as a function of time during pulsed operation of a nine-cell cavity in quench conditions. Note that FE losses account for only 1% of total dissipation.

With this model, we are also able to analyze where the power being dissipating during HPP processing. HPP was performed with 50 kW (maximum) on single-cell cavities, 130 kW on the two-cell cavity, and 200 kW on nine-cell cavities. Based on this analysis, however, we find that if thermal breakdown is occurring during the HPP, a very small part of the dissipated power is going into field emission. Figure 5 shows an example of the time evolution of the power dissipation in a nine-cell cavity with 200 kW peak power incident upon it. While the power dissipation reached as high as 100 kW, we find that only slightly more than 1 kW was coupled into FE. Similarly, we find that in all single-cell, two-cell, and nine-cell tests, if thermal breakdown is occurring, then FE losses account for no more than 5% of the total losses. In order to optimize future HPP processing, thermal breakdown must be avoided if possible. Possible methods include higher purity material, lower RF frequencies, or lower H_{peak}/E_{peak} ratios. The last method was successfully implemented in cavity W3C2-1, allowing the record performance reported here.

IV. ACKNOWLEDGMENTS

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