On Reaching 25 MV/m Accelerating Using High Pulsed Power RF Processing 1.3 GHz, 5-cell TESLA Cavities

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Introduction

Previous studies on 9-cell, 3 GHz cavities have shown the effectiveness of High Pulsed Power RF (HPP) conditioning against field emission, the present show stopper for high gradients. These results are reviewed in [1]. Extrapolating from the experience with 150 kwatts of power at 3 GHz, we estimate the need for at least 1 Mwatt of pulsed power for sucessful conditioning of 1.3 GHz 5-cell cavities. Accordingly we installed a 1.3 GHz klystron and modulator capable of delivering 1.5 Mwatt pulses, 150 μsec long, at a rep rate of 1 - 2 Hz. A high power cold test stand was built at Fermilab. Several 5-cell cavities were built, along with a 1-cell and a 2-cell. After some learning experience about high power couplers, we succeeded in putting more than 1 MWatt into 5-cell SC cavities and successfully processed field emission. Two five cell cavities have reached Eacc = 25 MV/m and Eacc = 27 MV/m, both record performances. A third 5-cell cavity reached Eacc = 20 MV/m. Similar good results were obtained with the 1-cell and 2-cell cavities.

Needed Power

For TESLA the RF frequency chosen is 1.3 GHz, and the structure is a 9-cell with length 1.038 meters, R/Q = 1088 ohms/m and Epk/Eacc = 2.0[2]. We decided to test a 5-cell structure because the existing SRF facilities at Cornell (chemical treatment, shielded cold test area, furnace, clean rooms etc) are not of the appropriate size to handle a 1 meter long cavity.

To determine the peak power we need to supply, we are guided by the result from our 3 GHz experiments. If we can expect E(CW) = (0.6-0.7) x Epulsed after HPP, with some field emission still present, we need to be prepared to reach Epk = 80 - 90 MV/m in the pulsed mode. We must also be prepared for the Q0 to fall to 2×10^6, or so during HPP due to increasing field emission. How much the Q0 falls with E depends on the field emission intensity, which reduces during the run. In order to be prepared with the needed power, we make a pessimistic assumption that Q0 = 2×10^6 throughout the pulse. The pulse length over which the field can be built up during the pulse is also an important parameter in assessing the power. Figure 1 shows the expected field that can be reached with 1 Mwatt of power at pulse length of 200 and 300 μsec.

Klystron and Modulator

The Boeing Defense and Space Group kindly lent us a klystron (Thompson TH2104) and the pulse forming network modulator. With a constant charge, constant current regulated pulsed capacitor charging supplies, we were successful in providing 110 KV to the klystron to obtain 200 μsec long pulse (from start) of 1.5 MWatt peak RF power. With the help of Fermilab, we installed the klystron and modulator system at Cornell.

Niobium Cavities

Two 5-cell cavities of the TESLA shape were built at Cornell. The accelerating mode properties of the cavity are listed in Table 1.

Table 1: Accelerating mode properties of the Cornell built cavities

r/Q	1088 ohm/m
Ep/Ea	2.0
Hp/Ea	43 Oe/MV/m

One of these cavities had a large weld hole which had to be repaired. This cavity shows thermal breakdown below Eacc = 5 MV/m even after RRR improvement with Ti heat treatment. One 2-cell and one 1-cell of the TESLA shape were also built. All these cavities were polarized.

Two 5-cell cavities were ordered by Fermilab from Babcock and Wilcox. The accelerating mode properties of these cavities are listed in Table 2.

Table 2: Accelerating mode properties of the Babcock and Wilcox shaped cavities

r/q	1012 ohm/m
Ep/Ea	2.6
Hp/Ea	41

The RRR of all cavities started at 250 - 300 for the as received material. After first RF tests, some of the cavities were further purified by Ti heat treatment at 1400 C. Both the inside and outside surfaces were exposed to Ti vapors. At least a factor of 2 gain in RRR is expected from previous experience[3]. After RRR improvement, both inside and outside surfaces were chemically etched to remove the Nb-Ti layer. Previous tests have shown that the Ti can diffuse quite deeply, near 100 μm.

HPP Test Set Up

The design, adapted from the 3 GHz HPP test set up is shown in Figure 2. The high power enters the cryostat 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 window was coated with TiN. The VSWR of the entire assembly was less than 1.6 betweenm 1280 and 1320 MHz. The penetration of the antenna into the cavity is adjustable by a copper plated hydroformed bellow in the outer conductor. Qext can be changed from 10^5 to 10^{10} with 4 inches of travel. The slotted region of the outer conductor just above the doorknob is connected to the cavity vacuum pumping line.

At first we used a room temperature teflon window for the warm window, but it breaks down between 300 and 700 kwatt. Tracks of metal from the hold down flanges were found near the high electric field center of the waveguide cross section. Placing the teflon window at the standing wave voltage minimum allows the higher power. Only after replacing the teflon with a ceramic window (borrowed from Munich) were we able to go up to and above 1 Mwatt.

For the best performance of the cold window, we also found it essential that the length of the antenna be such that there is a standing wave voltage minimum near the waveguide input side. With the wrong length, we were limited below 300 - 400 kwatt by breakdown events, accompanied by vacuum degradation in the waveguide. Only after we chose the correct antenna length, were we able to deliver more than 400 kwatt to the cavity. We also found the doorknob near the waveguide input end was coated with silver (from the braze) presumbly from sputtering during the bad vacuum.

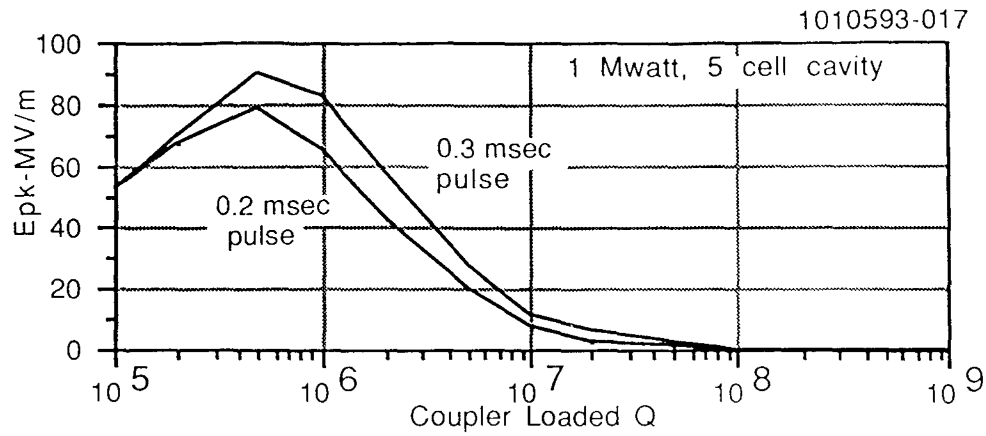


Figure 1: Calculated surface field reachable with 1 Mwatt peak RF power for a 5-cell 1.3 GHz cavity.

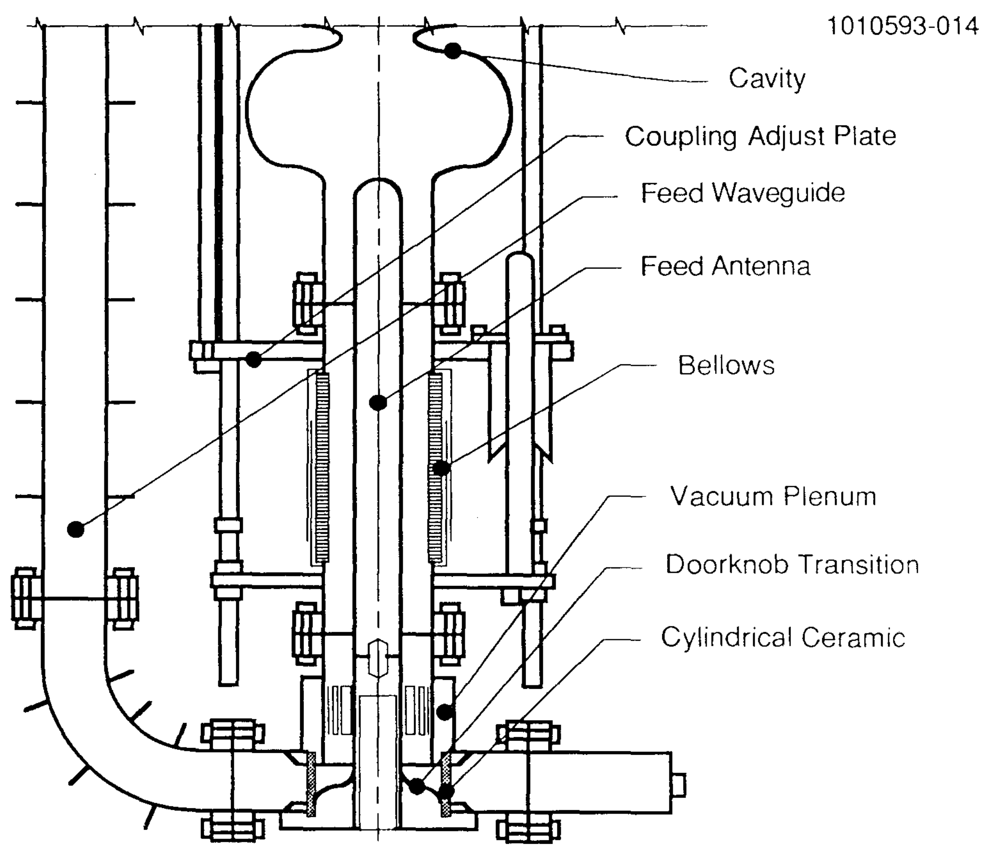


Figure 2: Schematic of the HPP test stand for 1.3 GHz cavities.

In the present state, with the ceramic warm window and proper antenna length we can raise the power to 1 Mwatt without any coupler conditioning delays. Before the improvements, we needed to condition for many hours to get up to the lower power limits mentioned.

5-cell Test Results

The RF test results reported below are not necessarily in strict chronological sequence with reference to improvements on the coupler. Before each test, the cavities were chemically etched and rinsed for several hours.

Cornell built 5-cell #1 and #2

Three CW test results are shown in Figure 3. Before HPP, each test was limited by field emission to Epk (CW-max) = 12 - 20 MV/m. This is well within the world statistics of multi-cell cavity performance after chemical etching and standard cleaning. In each test we see substantial improvement with HPP. The power levels successfully applied and the peak field reached during the pulsed stage are given.

The first two tests were done before RRR improvement. In the first test (top panel) the maximum CW field was limited to Epk = 20 MV/m by field emission because of insufficient power capability (400 kwatt) of our coupler (wrong antenna length, teflon window). The highest field for conditioning emitters was only Epk(pulsed) = 40 MV/m. So there was not much processing. In the second test (middle panel) we improved the coupler (correct antenna length) so we could process with 780 kwatt to reach Epk(pulsed) = 78 MV/m. Field emission processed, but now we were limited at Epk (CW) = 25 MV/m by thermal breakdown due to Nb RRR not being high enough.

The bottom panel shows the result after RRR improvement and chemical etching the inside 80 μm and the outside 30 μm. With 1 Mwatt we could reach Epk (pulsed) = 75 MV/m, following which we reached Epk(CW) = 40 MV/m, limited by thermal breakdown. We think we have not yet removed a sufficient amount of Ti from the RF surface, so another test will be done. The maximum Eacc is now close to 20 MV/m.

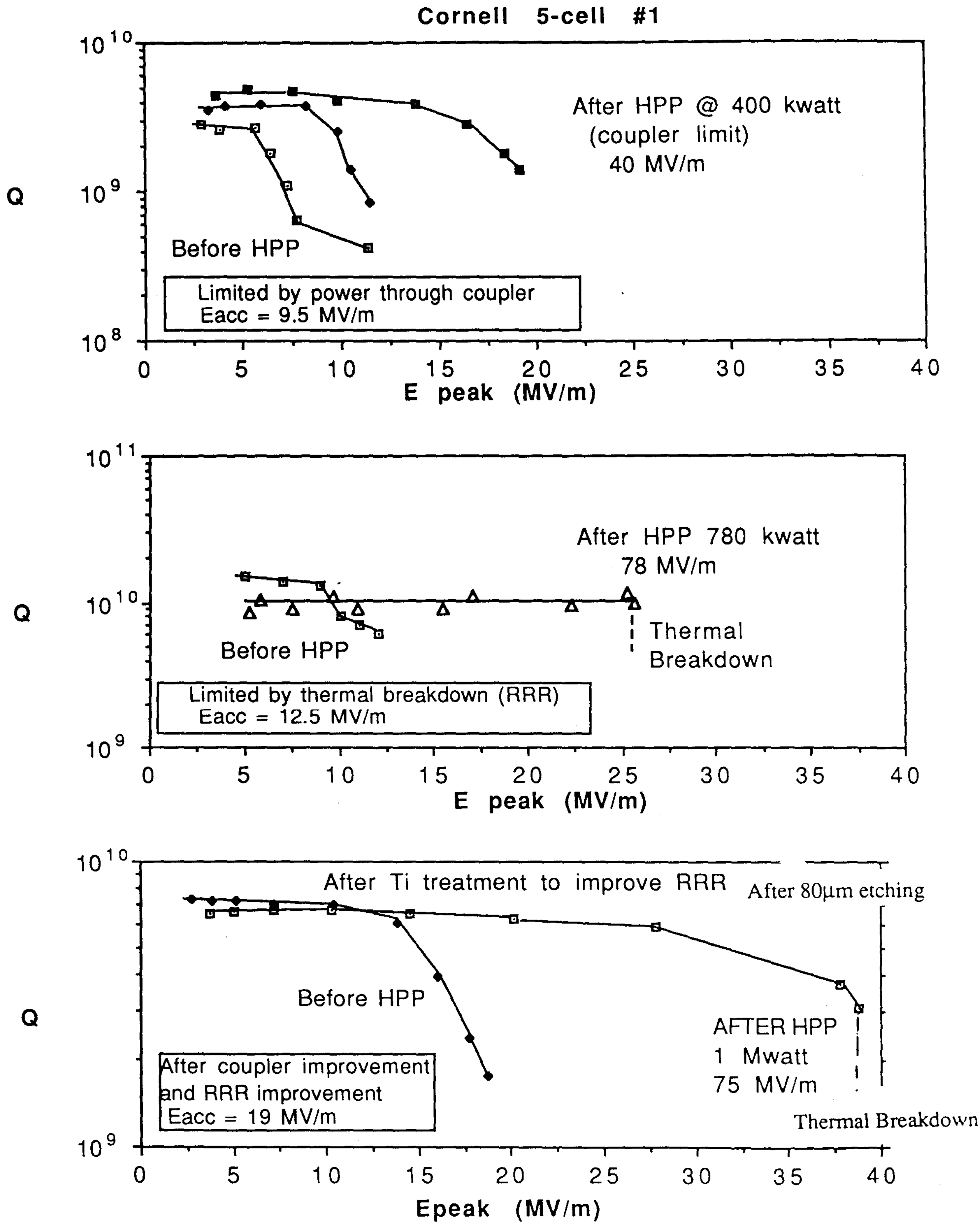


Figure 3: RF test results for the Cornell built 5-cell cavity. (top) First test, limited by coupler capability. (middle) limited by thermal breakdown (bottom) after Ti heat treatment to improve RRR, still limited by thermal breakdown, possibly due to insufficient etching after Ti heat treatment.

As mentioned earlier, cavity #2 had a large hole which was repaired. It still has a low thermal breakdown field even after RRR improvement (Eacc < 10 MV/m).

Babcock and Wilcox Cavity #1

Three CW test results are shown in Figure 4. In the first test (top panel) the maximum field was limited by thermal breakdown after some field emission processing with HPP to reach Epk(CW) = 36 MV/m. After Ti heat treatment to improve RRR, the second test was carried out after removal of only 65 μm from the RF side and 30 μm from the ouside. As we carried out HPP at progressively increasing fields, we noticed decreasing X-ray intensity, but the maximum CW field was remained limited at the same level (Epk = 36 MV/m) by an unusually sharp Q drop, followed by thermal breakdown. We do not think that this Q drop can be due to field emission, because the X-ray intensity kept decreasing. We concluded that we may not have removed enough Ti from the RF surface.

For the third test (bottom panel), we etched another 95 μm from the RF surface. Now the results were excellent. Before any HPP we obtained the highest field ever (Epk-CW = 55 MV/m), although still limited by field emission. Now with 1 Mwatt of HPP we could reach Epk (pulsed) = 90 MV/m. The reduction of field emission with HPP allowed us to further raise Epk(CW) to 71 MV/m, limited by the available CW power = 200 watts. Interestingly, we were not limited by the radiation trip points, because the field emission was well processed. We were also not limited by the thermal breakdown, presumably because of the higher RRR. Note also that we raised the thermal breakdown limit of the first test by increasing the RRR, as expected. The maximum accelerating field reached was Eacc = 27 MV/m.

Babcock and Wilcox Cavity #2

Two test results are given in Figure 5. In the first test a new doorknob/window assembly was installed. Before HPP (no curve shown), we were limited by field emission to Epk (CW) = 34 MV/m at Q = $3x10^9$. After HPP at 250 kwatts, limited by breakdown at the teflon window, we reached Epk (pulsed) = 54 MV/m. The Q vs E curve in the top panel shows we could reach Epk (CW) = 44 MV/m, limited by field emission. On replacing the teflon window, without disturbing the cavity vacuum, we could for the first time with the coupler raise the power to 900 kwatt. But the CW behavior of the cavity deteriorated (top panel); we encountered thermal breakdown at 39 MV/m. We suspect that because this was

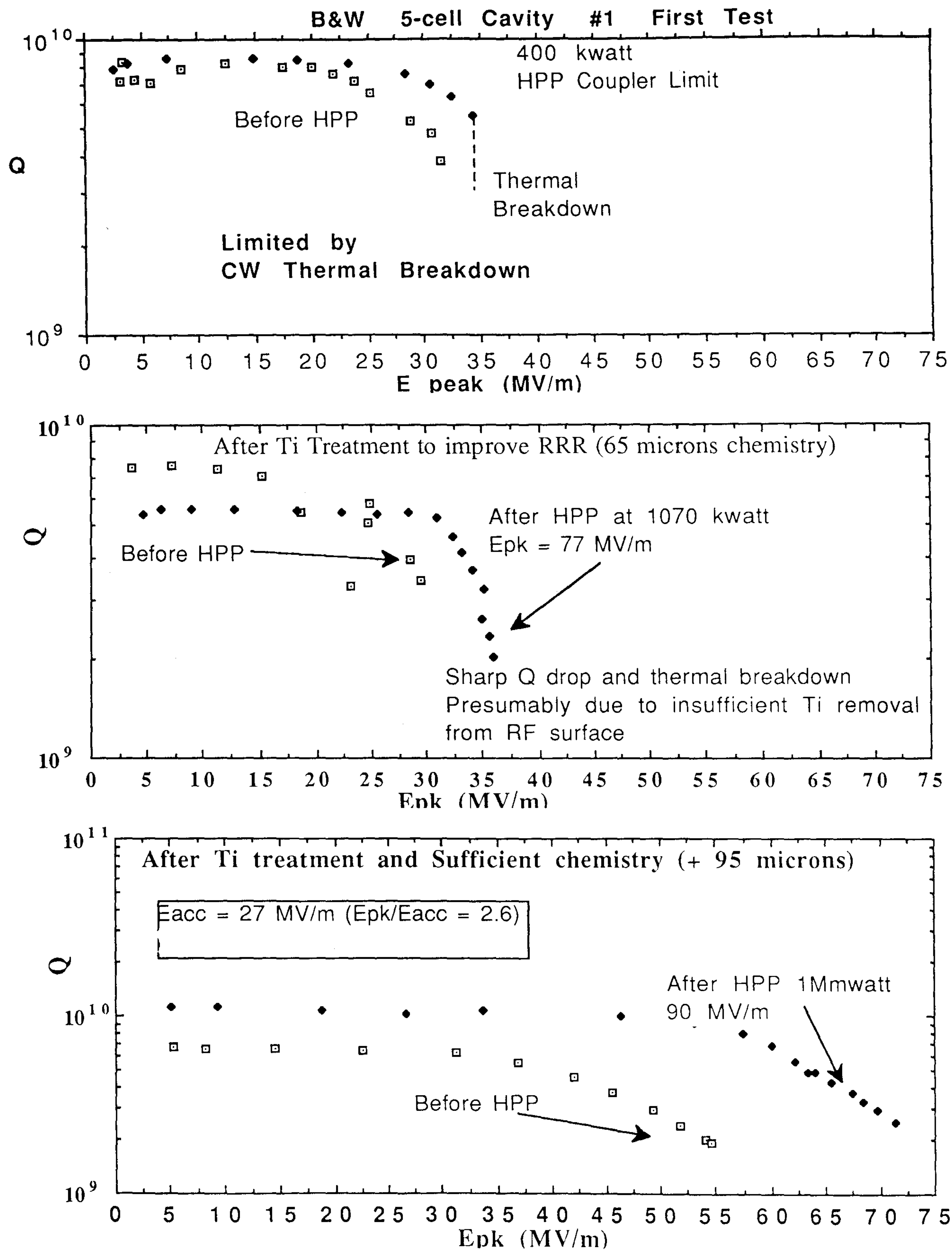
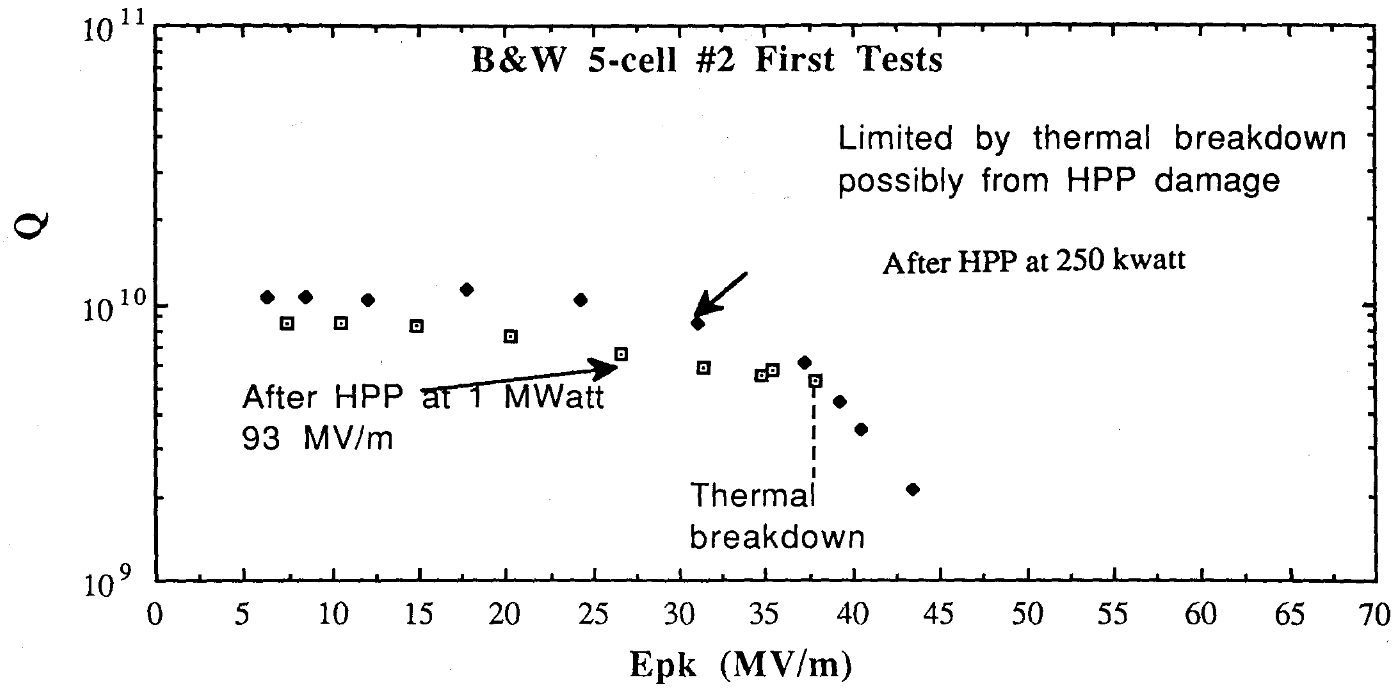


Figure 4: RF test results on Babcock and Wilcox 5-cell cavity #1 (top) limited by coupler capability (middle) after Ti heat treatment to improve RRR, limited by insufficient etching (bottom) after etching a further 95 μm.



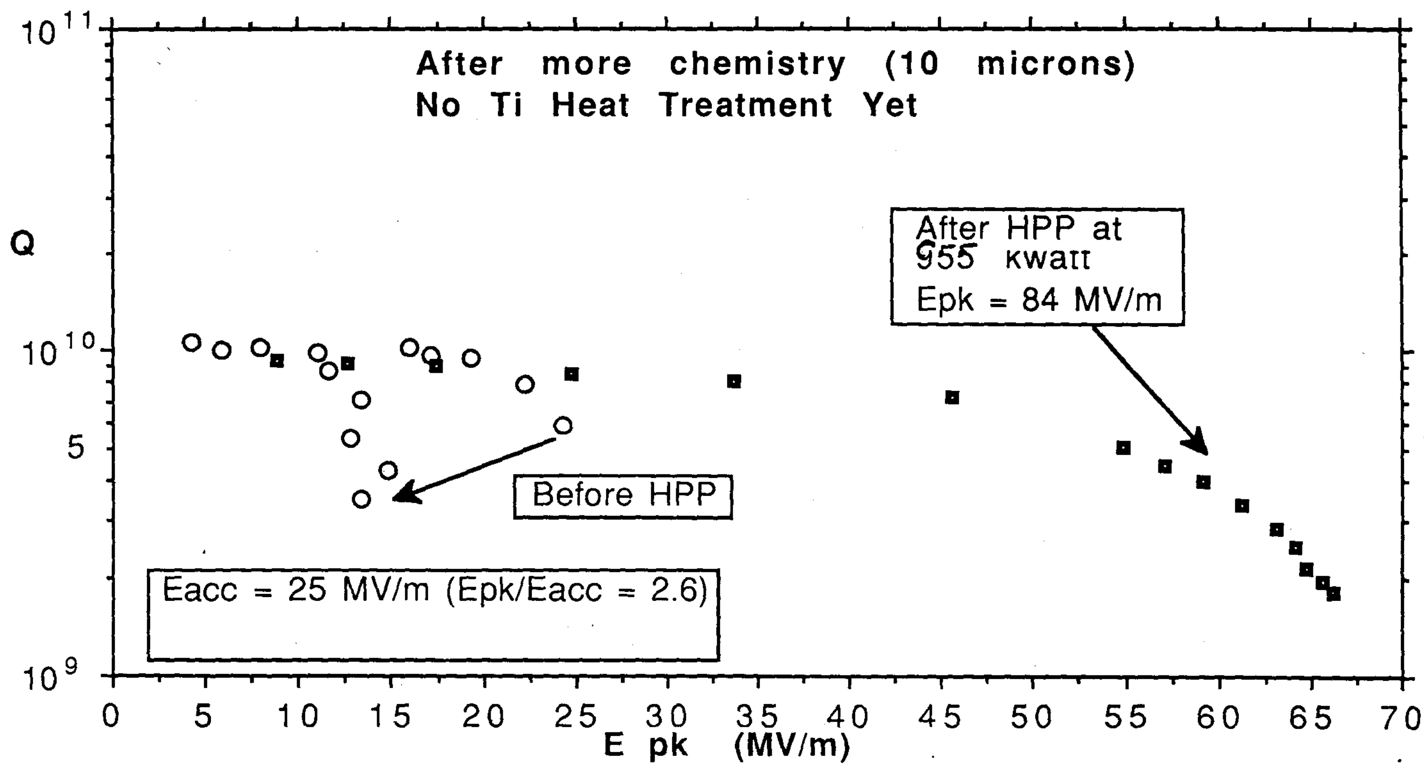


Figure 5: RF test results on Babcock and Wilcox 5-cell cavity #2 (top) first test, limited by thermal breakdown of cavity (bottom) limited by field emission only.

the first time the coupler was ever processed to such high fields, material from the coupler may have deposited on the cavity.

After re-etching the RF surface by 10 μm, we repeated the test. Strong field emission was present at Epk = 25 MV/m, when suddenly the field emission intensified and the field fell to 15 MV/m. HPP progressively lowered field emission and raised Epk(CW), until we processed with nearly 1 MWatt at Epk(pulsed) = 84 MV/m. Finally Epk(CW) reached 66 MV/m, which correspones to Eacc = 25 MV/m.

Cornell made 2-cell cavity

Towards the early phase of this project, when our coupler was still limited to below 400 kwatt, we tested a 2-cell cavity. This cavity was not yet heat treated for RRR improvement. The results are shown in Figure 6. There was some field emission from low power (100 watt) CW processing. But the big improvement came from HPP at 320 kwatt and Epk(pulsed)= 67 MV/m. This cavity reached a final accelerating field Eacc = 20 MV/m.

Summary of Results

Figure 7 shows the maximum fields reached both before and after HPP for all tests discussed above. Results before HPP are plotted as open squares to the left. The results after HPP are plotted as a function of Epk(pulsed). Our results confirm the conclusion from the 3 GHz HPP experiments, that the most important parameter for successful processing is Epk in the pulsed conditioning phase. The maximum field CW after HPP is of course also limited by other phenomena such as thermal breakdown or insufficient chemistry.

Conclusions

We have proved that HPP processing works effectively against field emission on several 5-cell cavities at 1.3 GHz. We have reached and surpassed the TESLA goal of 25 MV/m accelerating. In terms of peak surface fields we have also significantly surpassed the needs for TESLA : Epk = 50 MV/m and Hpk = 1050 Oersted. The two 5-cell cavities reached Epk = 66 and 71 MV/m with Hpk = 1056 and 1200 Oersted. The results for HPP effectiveness are very consistent with the earlier results from the 3 GHz HPP experiments, the maximum

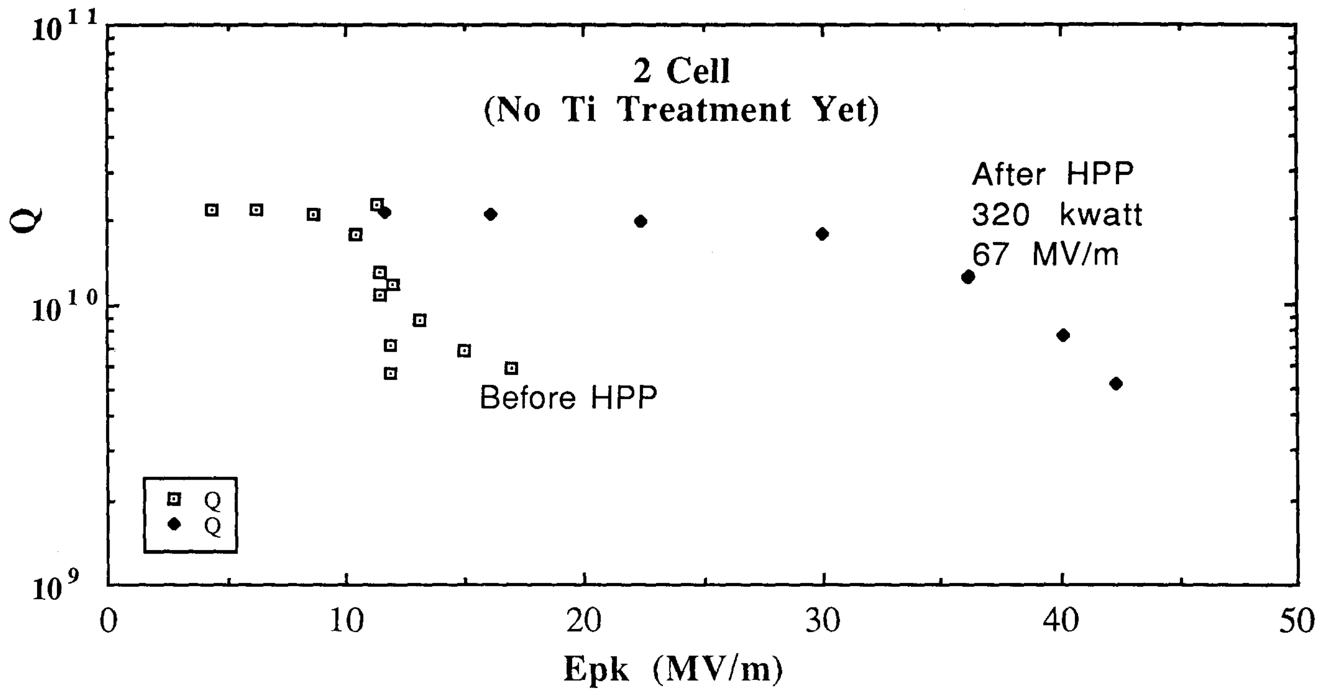


Figure 6: RF test results on Cornell built 2-cell cavity.

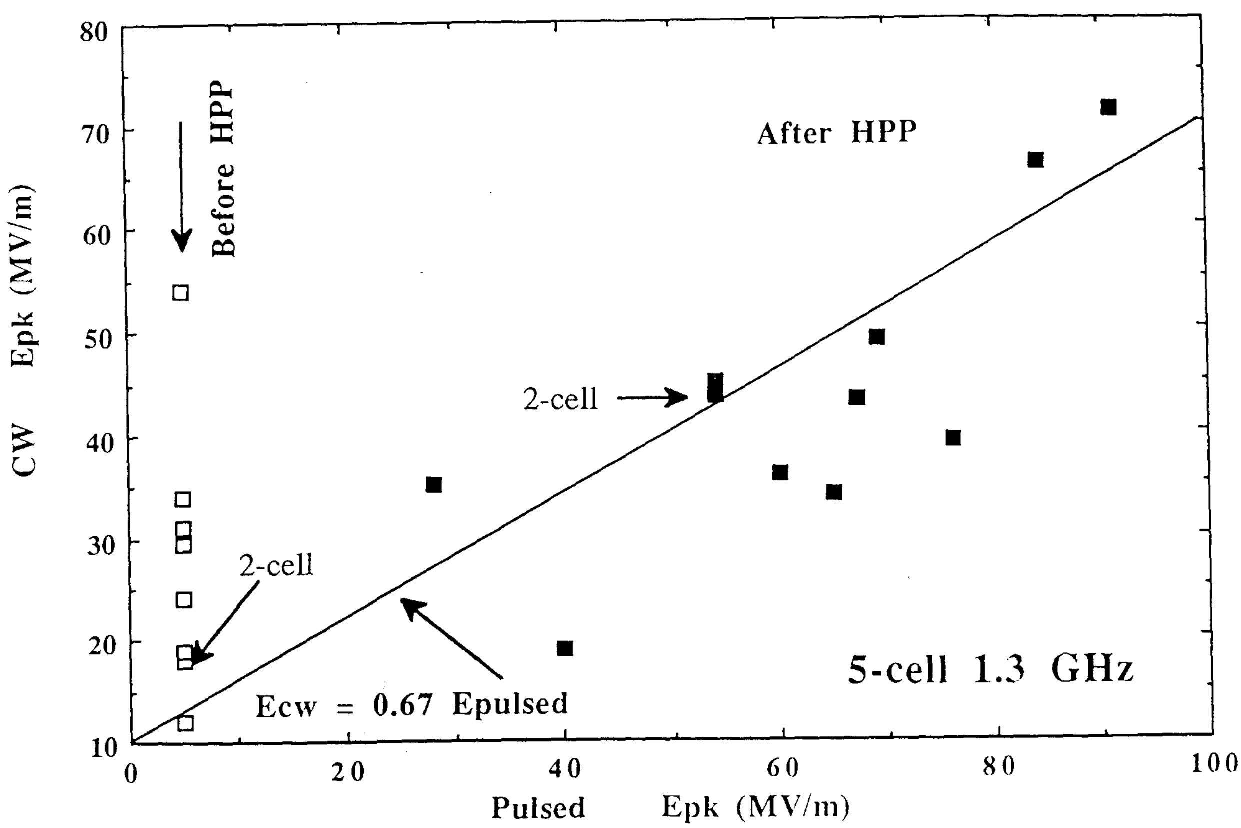


Figure 7: A summary of the benefits of HPP on 1.3 GHz cavities.

Epk(CW) = (0.6 -0.7)xEpk(pulsed). A very clean cavity can be further improved, even more so because the lower field emission loading allows higher Epk with the same power.

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