Medium-Beta Superconducting Cavity Tests at Los Alamos National Lab for High-Current, Proton Accelerators

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Abstract

Single-cell superconducting cavities are currently being evaluated for use in high-current proton accelerator applications being developed at Los Alamos National Lab. The designs that have been evaluated so far include 0.48 and 0.64 beta cavities. The parameters that have been checked are: peak surface electric field, magnetic quench field, multipacting levels, cavity Q, and propensity for Q disease. In limited tests to date, peak surface fields of 43 MV/m, and quench fields up to 103 mT have been achieved. Q_0 values have been typically $1x10^{10}$ at 2 K, with a reduction of about 30% after being held at 150 K for two hours. While some conditioning barriers were eliminated, no obvious multipactor zones were found.

Introduction

A high-energy, high-current, proton accelerator is being designed at Los Alamos National Laboratory for the Accelerator Production of Tritium (APT) project. The design goal is to have a 100 mA CW proton beam at 1700 MeV. The high energy section of the linac will be superconducting and increase the proton energy from 200 MeV to the final output level. An ED&D program is ongoing at Los Alamos in order to determine the performance of the cavities that are planned for use in the accelerator. This paper is a summary of the cavity tests done to date.

The superconducting cavities were made from 3 mm thick, RRR = 250, niobium from Teledyne-Wah Chang. The cavities were e-beam welded at LANL. Because of the 5 degree slope of the walls resulted in local yielding under vacuum loads at room temperature, mechanical stiffeners were added to rigidify the cavity structure. New designs with a 10 degree wall slope will be fabricated in the near future. The 10 degree slope will allow the stiffeners to be eliminated thereby saving material and manufacturing costs. Although the cavities which have been tested are not exactly the same as the proposed 5-cell cavities, a number of important questions about Q_0, quench field values, and multipacting behavior can be addressed.

Four single-call cavities have been made and tested thus far. Two were made at a β = 0.48, and the other two were made for a β = 0.64. The resonant frequencies are very close to the design frequency of 700 MHz. The radio frequency parameters for the two cavity types are summarized in the Table 1 below.

Table 1: Cavity parameters for the 0.48 and 0.64 beta cavities

Beta	Length	Iris Diameter	(2 R/Q)	E_{pk}/E_{acc}	B_{pk}/E_{acc}	G
	(mm)	(mm)	(Ω)		(mT/MeV/m)	(Ω)
0.48	102.79	100	18.81	3.52	8.43	129.6
0.64	137.05	130	33.52	2.90	7.36	151.2

An outline of the cross-sections of the cavities is shown below in Figure 1.

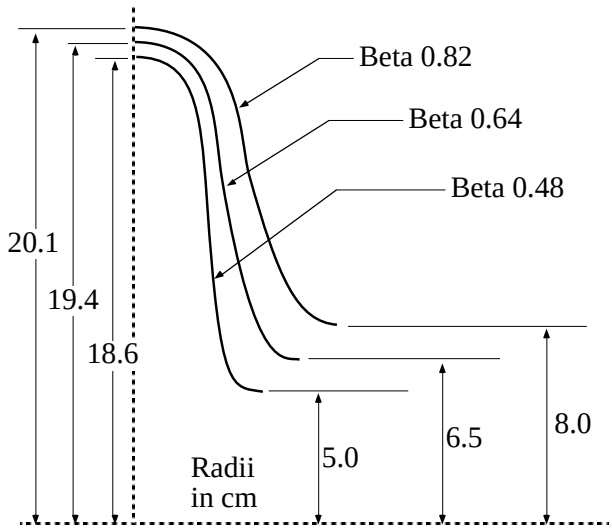

Figure 1: Cross-sectional view of cavities for different beta designs

The typical procedure for processing and testing a cavity is as follows:

1. Chemical polishing in HF:HNO_3:H_3PO_4 (2:2:3), bath temperature maintained below 20 °C.
2. Transporting the cavity to the lab in ultrapure water, then rinsing by overflowing ultrapure water in the clean room.
3. High pressure rinsing of the cavity and associated components in the clean room. Let dry.
4. Mounting of couplers and all flanges sealed in the clean room.
5. Mounting on the insert. Pumping for one night.
6. Moving the insert into the cryostat. Cooling down at 4 K. Test at 4 K.
7. Pumping on the helium bath. Test at 2 K.
8. Recovery of liquid helium from the cryostat.
9. Q-Disease test: Warm the cavity up to 130-150 K for two hours.
10. Cool again to 4 K. Test at 4 K.
11. Pump again to 2 K. Test at 2 K.
12. Recover remaining liquid helium from the cryostat.

By recovering the liquid helium in the cryostat, we were able to perform two tests at 2 K. Starting with 3 Dewars of 500 l each, we would have approximately 50% to 80% left in one Dewar which could be used in the following test.

Cavity Tests

The cavity tests will be presented in a chronological order so that the progression can be easily followed. A summary of the tests will be given at the end in tabular form for easy reference to each cavity.

Cavity 0.64-1, Test 1

This cavity was initially chemically polished to remove 100 µm. Tests at 4 K showed a pronounced Q_0 vs. E_{pk} slope near the end of the sweep due to heavy electron field emission. The low power Q_0 value is about 10^9 and the quench field of 48 mT was relatively low. A plot of the performance is shown in Figure 2 below.

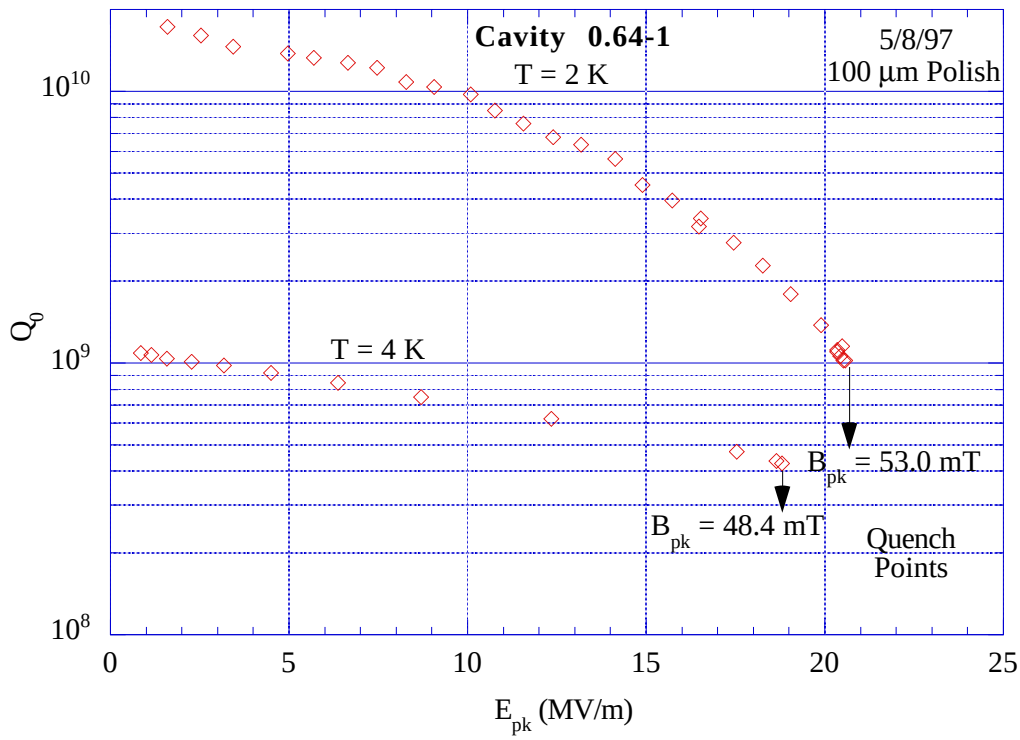

Figure 2: Performance curves for Cavity 0.64-1

At 2 K the Q_0 went to greater than 10^{10}. The steep slope above 10 MV/m from field emission is even more evident in this graph. No multipacting levels were observed. The cavity quenched at peak field of 20.5 MV/m (Eacc = 7.2 MV/m).

A test for Q-disease was done by allowing the cavity to warm up to 100-120 K for about an hour, and then was recooled to 2 K for increased sensitivity. Since there was only enough liquid helium to partially cover the cavity, only low power testing was done at this point. A plot of the surface resistance for both cases can be seen in Figure 3 below. The Q_0 value dropped about 30% because of the 5 nΩ increase in surface resistance.

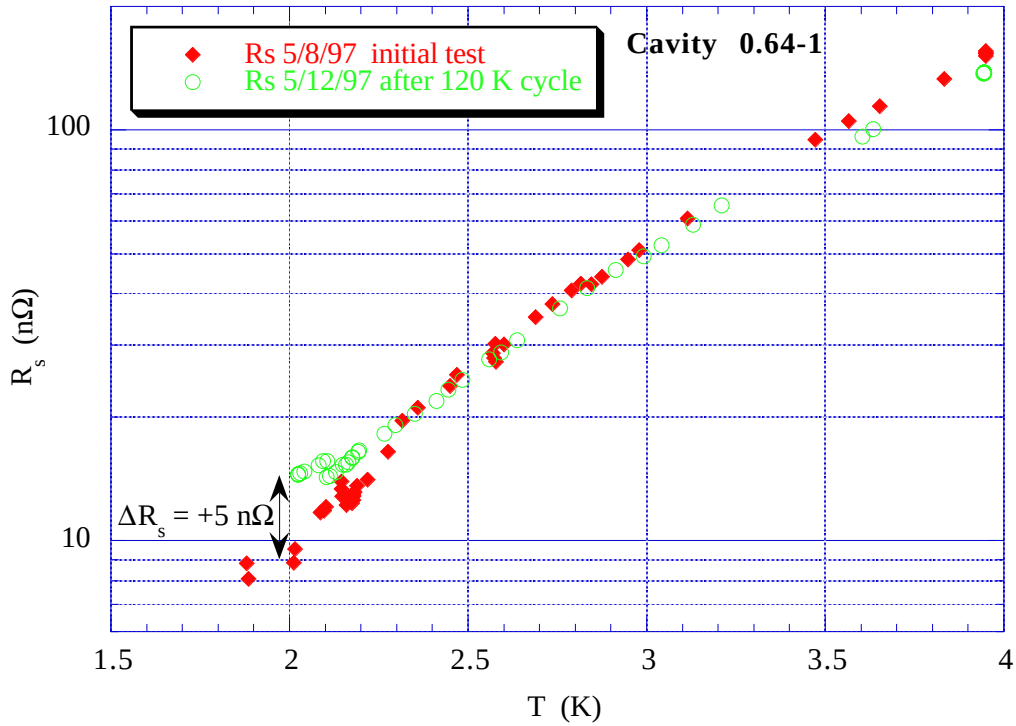

Figure 3: Q-disease test of cavity 0.64-1

Cavity 0.48-1, Test 1

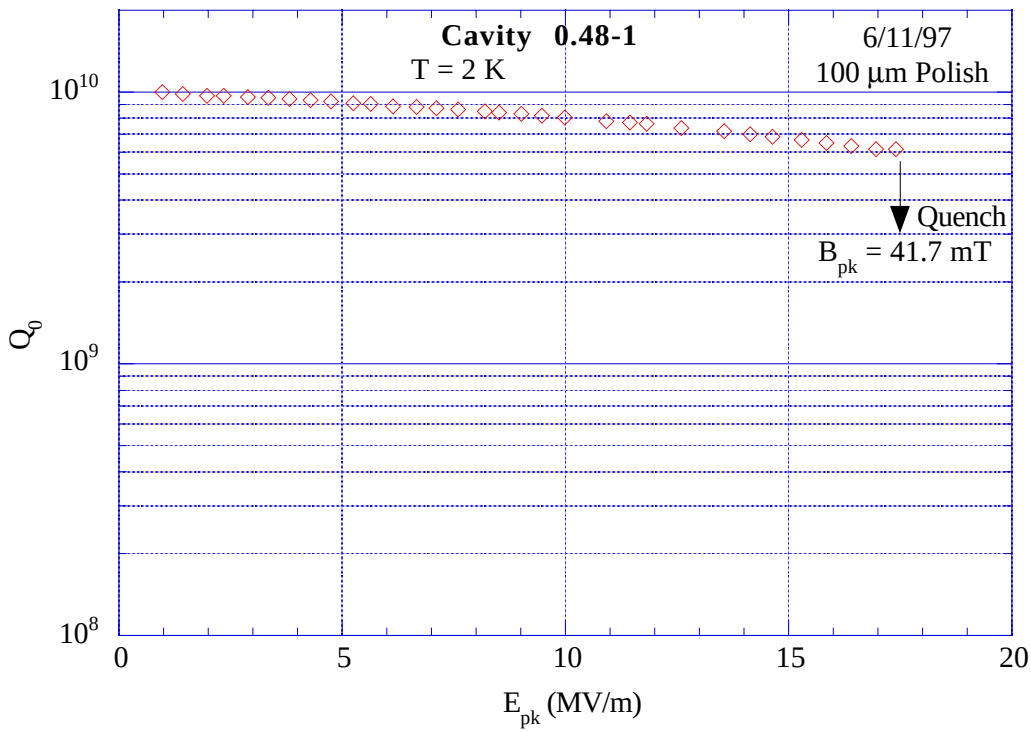

Figure 4: Test of cavity 0.48-1 at 2 K

After the problems with field emission that occurred in the first test, a more careful procedure for assembling the cavity in the cleanroom was devised. First, the high-pressure rinse

(HPR) was done with all flanges that could be in place. Then the cavity was allowed to air dry on the HPR stand under the clean down flow. The last of the flanges and the couplers were rinsed with ultrapure methanol and assembled on the cavity thus sealing the cavity. The rest of the assembly was done outside the cleanroom. A ring with five, equally-spaced, carbon resistors was placed around the equator of the cavity for basic thermometry measurements.

Due to a previous problematic test on this cavity (not reported here), the 4 K sweep was purposely stopped at a peak field of 7 MV/m (Eacc = 2 MeV/m). There was no electron activity.

The 2 K sweep can be seen above in Figure 4. The low-field Q_0 was near 10^{10}. The cavity quenched at 17 MV/m (Eacc = 5 MeV/m) and 42 mT. No electron activity or multipacting was observed for this cavity confirming that the cavity was very cleanly assembled. The five equatorial thermometers did not detect the quench location.

Cavity 0.64-2, Test 1

In previous cavity chemical polishes, the bath temperature was allowed to rise up to 30 °C. At this point, we started to use dry ice (frozen CO_2) to keep the bath temperature below 20 °C.

For the 4 K sweep, no x-rays were detected. The quench point was reached at E_{pk} = 15.2 MV/m (Eacc = 5.2 MeV/m). Both sweeps can be seen in Figure 5 below.

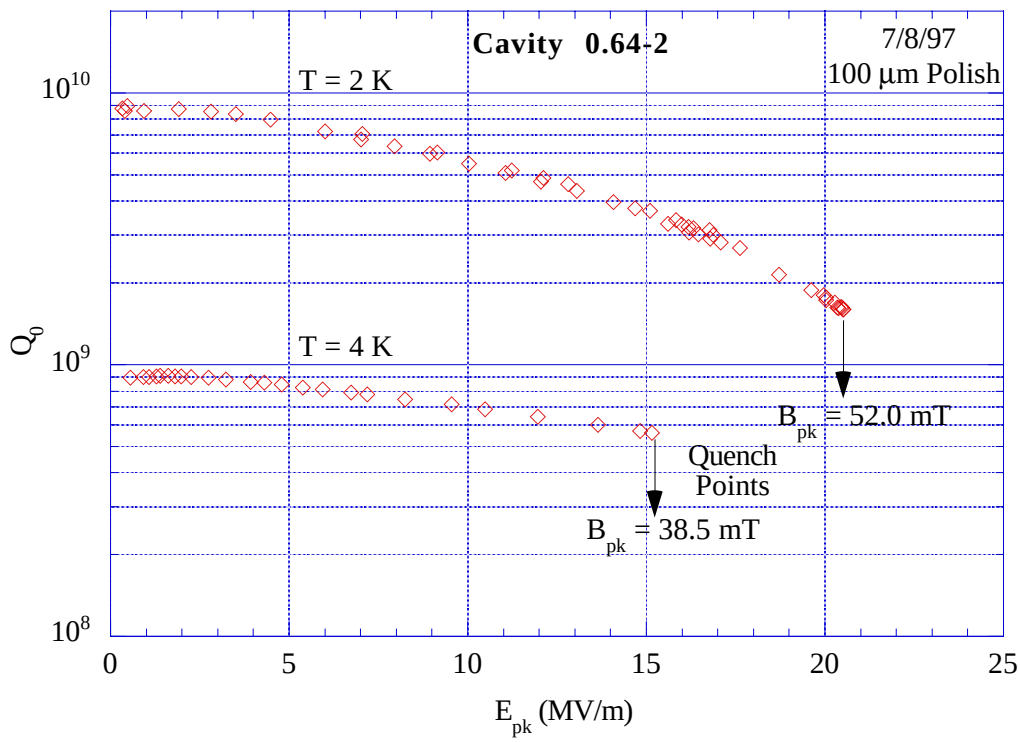

Figure 5: Performance of cavity 0.64-2 at 2 & 4 K

The 2 K sweep showed a slightly decreased Q_0 value (9.3×10^9) and a non-quadratic slope in the Q_0 vs. E_{pk} curve, even though there were no electrons detected up until 17 MV/m. At 17 MV/m, some field emission electrons were detected. Some improvement was seen after about 15 minutes of RF processing, but there were still electrons present up to the quench field of E_{pk} = 27 MV/m (Eacc = 7 MeV/m). One of the five thermometer resistors detected the

quench position on the equator ($\Delta T > 2$ K during the quench, but no detectable excess heat prior to the event).

This cavity was allowed to warm up to between 130 K and 150 K for more than two hours. After pumping down to 2 K, the cavity was measured again to determine any degradation in Q_0. The Q_0 dropped from 9.3 x 10^9 to 5.7 x 10^9, indicating an increase in surface resistance of +10 nΩ.

Cavity 0.64-1, Test 2

Since all previous tests indicated quench points at peak magnetic fields near 50 mT, it was decided to polish the surface further to remove most of the residual damage layer in the material that might be present from the deep-drawing process used to make the cavity halves. Cavity 0.64-1 was the first to receive the extra polish treatment. An additional 50 µm was removed from the surface to bring the total removed to 150 µm.

As can be seen in Figure 6, the 4 K sweep showed light x-ray activity starting near E_{pk} = 14 MV/m, but the cavity soon conditioned leaving no x-ray activity. The cavity quench was at Eacc = 5.4 MeV/m.

The 2 K performance was much improved. The quench field moved up to near 70 mT indicating that there was still some damage layer in the 100 µm to 150 µm regime that needed to be removed. Some x-rays started at 16 MV/m, but after light processing, there was no electron activity until 18 MV/m.

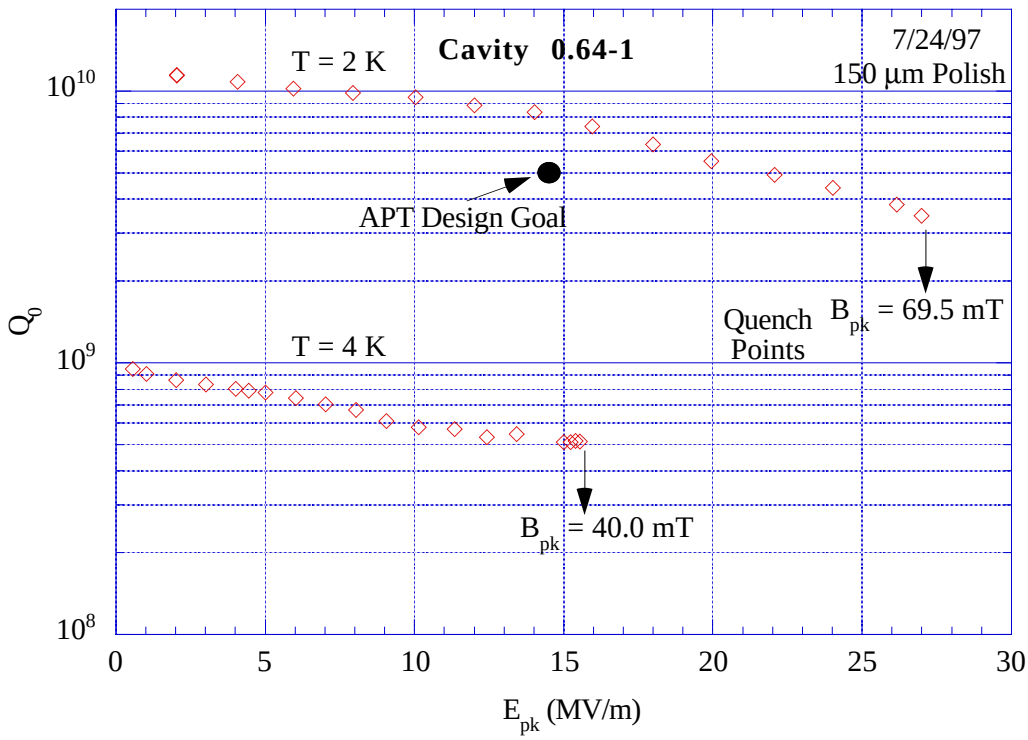

Figure 6: Performance curves for cavity 0.64-1 (150 µm polish)

Cavity 0.48-2, Tests 1 & 2

Cavity 0.48-2 had not yet been tested, so it was decided to test it first with a 100 µm polish, and then with an additional 50 µm polish. The results are shown in Figures 7 and 8 below.

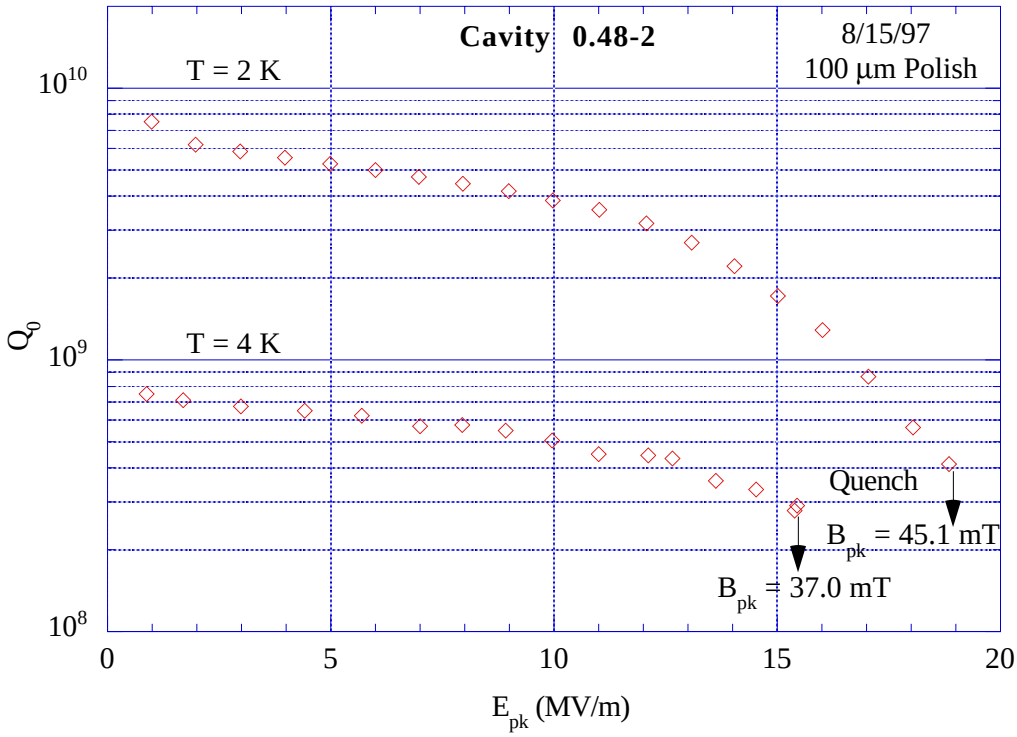

Figure 7: Performance of cavity 0.48-2 (100 µm polish)

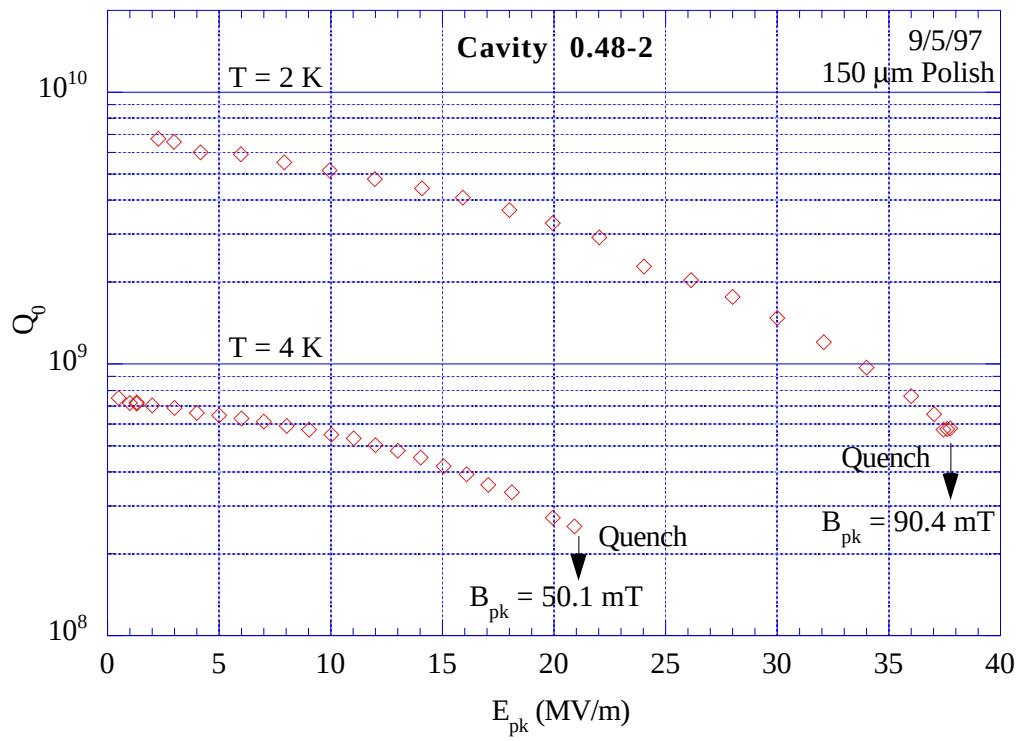

Figure 8: Performance of cavity 0.48-2 after a 150 µm polish

Once again, the cavity showed a low quench point with only 100 µm removed. After the additional polish had been completed, the 4 K quench moved to 50 mT, and the 2 K quench

went to over 90 mT. After some processing, electron activity would begin at about 20 MV/m and would increase up until the quench point.

Cavity 0.64-2, Test 2

In order to estimate the actual depth of the damage layer in the niobium, an additional 30 μm was removed from cavity 0.64-2 before it was retested. The 4K quench point moved to 82 mT, and the 2 K quench point occurred at 96 mT during heavy electron field emission. As before, electron activity would begin at about 20 MV/m once the cavity had undergone some processing.

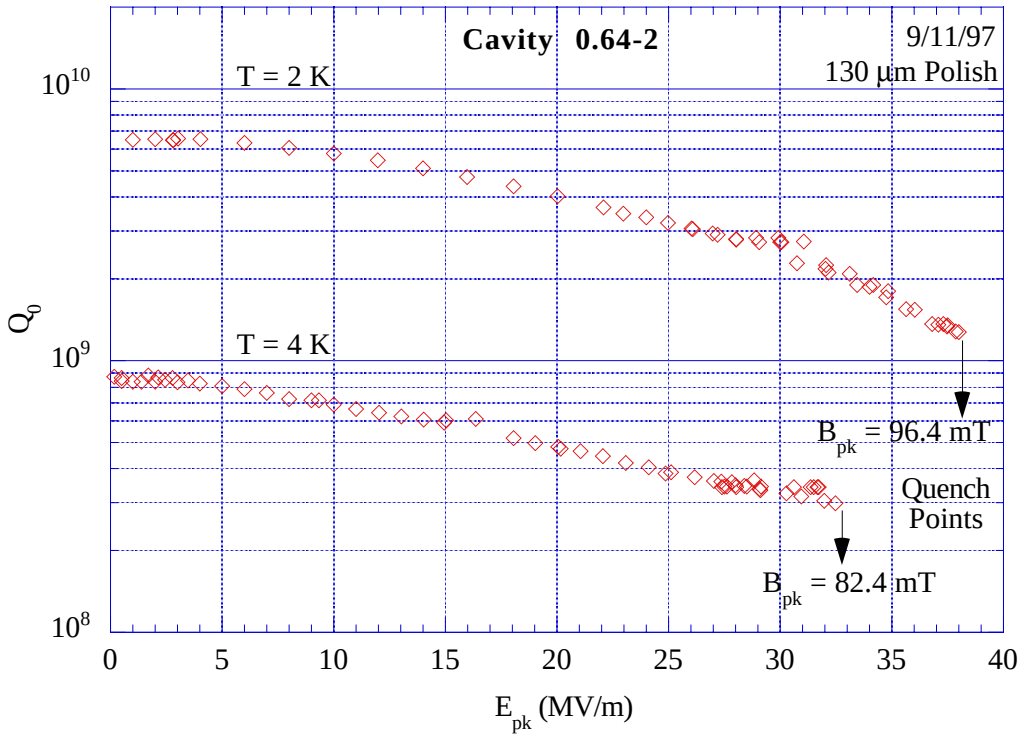

Figure 9: Performance of cavity 0.64-2

A puzzling aspect, of the more recent cavity tests, was the heavy electron field emission at higher gradients. Two possible reasons for this behavior were either the HPR jets were not reaching all of the cavity well, or that the HPR water was contaminated. Both possibilities were addressed concurrently. Two additional jet holes were drilled into the HPR nozzle in the horizontal plane. Previous jets were only at angles above and below the horizontal plane. Next, the 0.1 μm final filter for the HPR was removed and disassembled. Even though the filter had been specified for DI water use, the housing had been made of nickel-plated steel. The plating was not sufficient, and the housing had started to rust. In addition, the rust was on the output side of the filter and was contaminating the HPR water used for cleaning the cavity. Since a stainless filter replacement was not immediately available, the 0.1 μm filter assembly was left out of the water line, thus leaving only the 5 μm pre-filter. Using only the prefilter yielded a greatly improved result (as can be seen in the next test), thus further indicting the rusted filter housing.

Cavity 0.48-1, Test 2

Cavity 0.48-1 was polished an extra 38 μm, and high-pressure rinsed without the contaminated filter. The results of the test are shown in Figure 10 below. It is obvious that the previous cavity tests were contaminated by the rust in the final filter. At 4 K, the cavity started field emitting at about 19 MV/m and continued up to the 30 MV/m quench point. The 2 K

sweep showed no electron activity until 23 MV/m. Heavier field emission did not begin until 37 MV/m and continued up until the quench field of 43 MV/m (Eacc = 12 MeV/m). The results for all of the cavity tests are shown in Table 2 below.

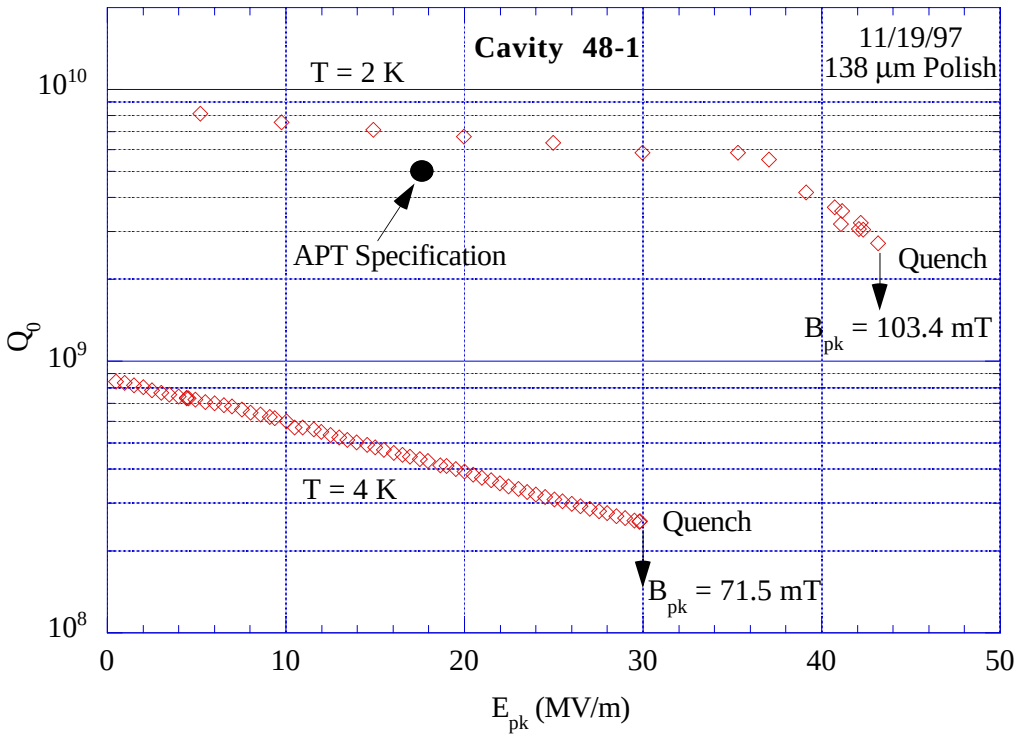

Figure 10: Test of cavity 0.48-1

Table 2: Summary of cavity tests

			QUENCH FIELD			
T = 4 K	**Q_0**	**R_s**	**E_{acc}**	**E_{pk}**	**B_{pk}**	**Q_0**
	(Low Field)	(nΩ)	(MeV/m)	(MV/m)	(mT)	(at Quench)
100 µm polish						
0.48, #1	1.4E+09	92	4.4	15.4	37.0	
0.48, #1	8.0E+08	164				
0.48, #2	7.5E+08	175	4.4	15.4	37.0	2.9E+08
0.64, #1	9.8E+08	153	6.5	18.8	48.4	4.2E+08
0.64, #2	9.0E+08	169	5.2	15.2	38.5	5.6E+08
>130 µm polish						
0.48, #1	8.4E+08	172	8.5	29.8	71.5	2.6E+08
0.48, #2	7.5E+08	179	5.9	20.9	50.1	2.5E+08
0.64, #1	1.1E+09	138	5.4	15.7	40.0	5.2E+08
0.64, #2	8.8E+08	180	11.2	32.5	82.4	3.0E+08

			QUENCH FIELD				
T = 2 K	**Q_0**	**R_S**	**E_{acc}**	**E_{pk}**	**B_{pk}**	**Q_0**	**Q_0**
	(Low Field)	(nΩ)	(MeV/m)	(MV/m)	(mT)	(at Quench)	(Eacc= 5MeV/m)
100 µm polish							
0.48, #1	1.0E+10	13	5.0	17.4	41.7	6.2E+09	6.2E+09
0.48, #2	7.5E+09	19	5.4	18.9	45.1	4.1E+08	7.0E+08
0.64, #1	1.5E+10	9	7.2	20.5	52.8	1.0E+09	5.0E+09
0.64, #2	9.3E+09	16	7.0	20.4	52.0	1.4E+09	3.7E+09
>130 µm polish							
0.48, #1	8.2E+09	17	12.3	43.2	103.4	2.7E+09	6.9E+09
0.48, #2	6.8E+09	19	10.7	37.8	90.4	5.8E+08	3.9E+09
0.64, #1	1.1E+10	14	9.3	27.0	69.5	3.5E+09	8.0E+09
0.64, #2	6.6E+09	23	13.1	38.0	96.4	1.3E+09	4.9E+09

Figure 11 compares all cavity tests done at 2 K. The outline markers are used for all initial tests (100 µm polished) while the solid markers are used for the second tests (>130 µm polished).

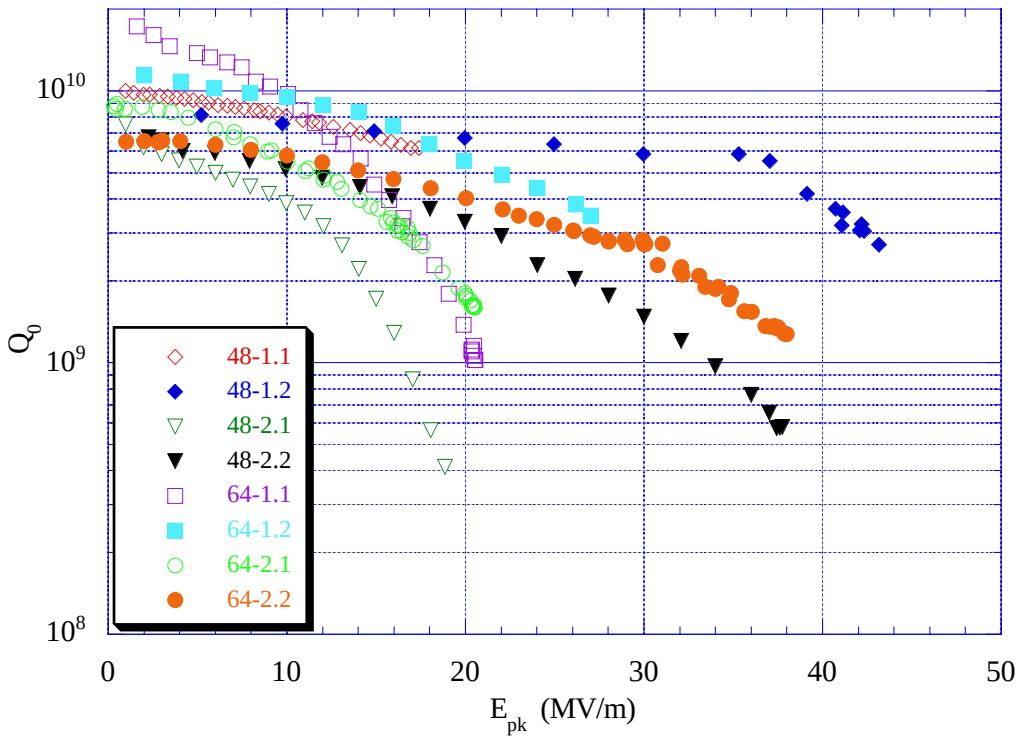

Figure 11: Summary of all results at 2 K

Conclusions

Since no cavities of this shape and frequency had been previously tested, one of the major questions to be answered by these tests was whether the altered elliptical cavity was prone to multipacting. During testing, there were various degrees of conditioning that each cavity

needed, but there were no specific bands where electron activity was consistently a problem. With this result, one must conclude that these cavities do not have any multipactor bands.

The 100 K effect (Q-disease) tests indicated that the cavity material has a small amount of dissolved hydrogen, but not enough to be a major problem for cavity performance. However, since the cryogenic load in the APT accelerator design is already large, it would be best to heat treat the cavities at 800 °C for two hours to remove the bulk dissolved hydrogen.

The Q_0 at low fields remains the last problem to be dealt with. Although the surface resistance values are respectable, they could be significantly improved. The majority of the problem is with residual magnetic field in the cryostat of about 30 mGauss. Better shielding will be installed on the cryostat in the near future. In the $\beta = 0.64$ cavities, an additional 1 nΩ is due to losses on the stainless steel flanges due to the larger beam tube apertures.

Magnetic quench fields were initially low (about 50 mT) with only 100 μm polished off the cavity surface. With at least 130 μm polished off the surface, the majority of the damage layer was removed and the quench field values moved up past 90 mT, with one value above 100 mT.

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