COMPARISON OF BUFFERED CHEMICAL POLISHED AND ELECTROPOLISHED 3.9 GHz CAVITIES*

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Abstract

Five 3.9 GHz 9 cell cavities have been measured for the DESY FLASH module. These cavities were BCP processed and reached gradients of typically about 25 MV/m with Q drop starting at about 20 MV/m. Recently a few one cell cavities have been processed with EP and at least one has tested to a gradient of 30 MV/m with Q drop starting at about 25 MV/m. We will compare the results and give an update to the thermal analysis in relation to global thermal breakdown at 3.9 GHz.

INTRODUCTION

The FNAL 3.9GHz cavity program for a module to be installed at DESY in FLASH is reported at this and prior conferences [1,2]. A number of 9cell 3.9GHz cavities have now been measured in vertical dewar tests and data can be compared. These cavities were prepared by the BCP process. More recently single cell cavities reported here have been used in the development at Fermilab of a small EP system that is presently being used at a local vendor. [3]. Vertical tests of one of these cavities is presented.

The test results from the two processing methods can be compared. In addition results can be compared with global thermal models and with what might be expected for medium field Q slope and high field Q drop. The question arises as to whether the measured data is or is not consistent with global thermal predictions or with medium field Q slope and high field Q drop.

CAVITY PARAMETERS

The 3.9GHz 9 cell cavities were designed and built for use in the DESY FLASH-FEL. A module of four 9 cell cavities has been shipped to DESY and will be installed at the end of the FLASH injector this winter. They will be used for bunch energy linearization in conjunction with bunch compression in order to control bunch pulse length and intensity uniformity. These cavities have input coupler ports and high order mode (HOM) couplers similar in design to those of TESLA.

The one cell cavities do not have coupler ports or HOMs. Because they are “end cell” design they have slightly different cavity parameters with a high ratio of surface magnetic field to accelerating gradient.

The cavity parameters of the two types are given in Table 1.

Table 1: 9 Cell and 1 Cell 3.9GHz Cavity Parameters

Parameter	3.9 GHz 9 cell	3.9 GHz 1 cell
Ep/Eacc	2.26	1.99
Bp/Eacc(mT/MV/m)	4.86	5.86
G1 (ohm) (=Rs*Q)	275	317
Active length (m)	0.346	0.0384
R/Q (ohm)	750	50.5
Input coupler port & HOMs	yes	no
Wall thickness (mm)	2.6	2.6

PREPARATION PROCEEDURE

The 9 Cell Cavities

The general cavity preparation steps after fabrication up through vertical testing were:

- A light (20micron) outside BCP etch followed by ultra sound-UPW rinse.
- A heavy (100 micron) inside BPC etch followed by UPW rinse.
- A 800C vacuum bake held for two hours.
- A light (20 micron) inside BCP etch followed by ultra sound-ultra pure water (UPW) rinse and high pressure rinsed (HPR) for ~ 4 hours.
- The cavity was then dried by slow vacuum pumping.
- And mounted on the vertical test stand.

If additional vertical tests were necessary the cavity was usually just re-rinsed and HPRed again. Further BCP was usually not done as there was worry over the thickness of the HOM cans.

The One Cell Cavity

The cavity preparation steps were:

- No outside etch, a UPW rinse.
- A heavy (125 micron) inside EP process, initial rinse in de-ionized (DI) water, followed by a ultra sound-UPW rinse.
- A 800C vacuum bake held for two hours.
- A light (20 micron) inside EP process, initial DI water rinse, followed by a ultra sound-UPW rinse and HPR for ~ 4 hours.
- The cavity was then dried by slow vacuum pumping.
- And mounted on the vertical test stand.

As before, for the cavity reported here (1c#2), preparation for further vertical tests was just re-rinsing and HPR. After the 2nd test the cavity was baked at 120C for 48 hours.

No special treatment was carried out to ameliorate sulphur contamination.

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CAVITY RESULTS

9 Cell Cavity Vertical Test Results

The 9 cell vertical dewar tests are shown in Figures 1 and 2.

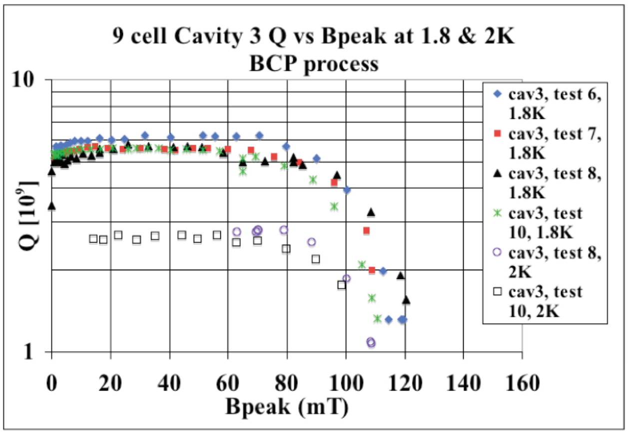

Figure 1: 3.9 GHz 9 cell cavity #3 vertical dewar tests showing reproducibility of results.

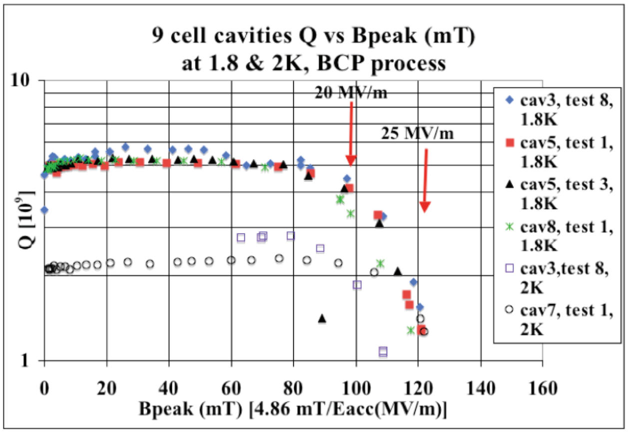

Figure 2: 3.9 GHz 9cell vertical dewar tests at 1.8 and 2K. Data from cavities #3,#5, #7, #8.

The tests that are displayed are for measurements taken without HOM pickup antennae installed. Figure 1 shows the reproducibility of a number of tests on cavity 3, Figure 2 shows the reproducibility between different cavities at 1.8 K and 2.0 K. The Q is very flat up to about 90mT (18.5 MV/m). There is not a big difference between end points at 1.8 K and 2.0 K.

1 Cell Cavity Vertical Test Results

The 1 cell vertical dewar tests are shown in Figures 3 and 4.

The tests shown are of only one cavity. A second cavity (#1) has been tested but its residual resistance is very high It was used of the first attempt at EP and the temperature got very high during processing. It will not be discussed here.

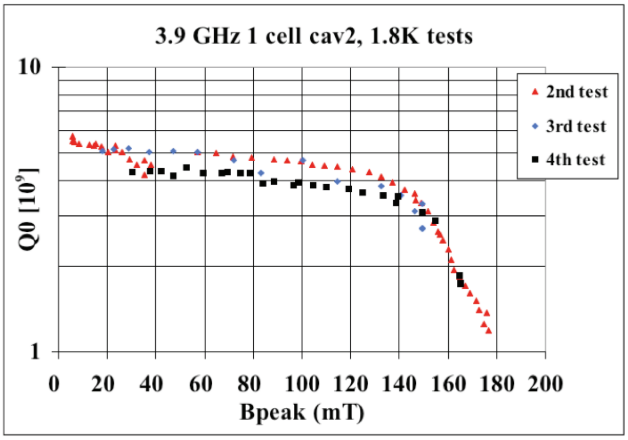

Figure 3: 3.9GHz one cell cavity tests at 1.8K.

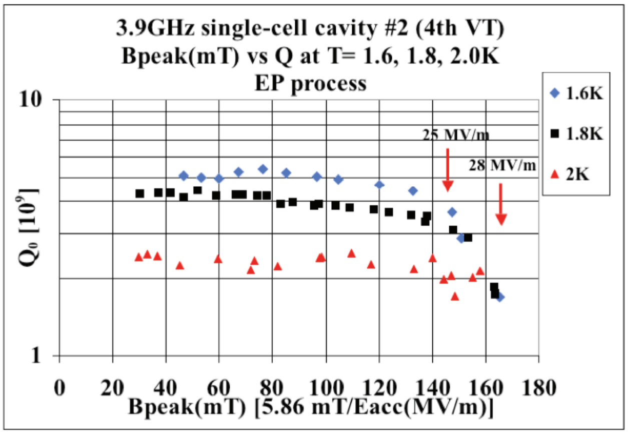

Figure 4: 3.9GHz one cell cavity tests at 1.6, 1.8, 2.0 K.

The test reproducibility at 1.8 K is good and the field extends much higher than for the 9 cell cavities. A low temperature bake was preformed between tests 2 and 3. The data as a function of temperature shows a very similar field end point for all three temperatures. The lack of significant Q improvement at 1.6 K is probably due to residual resistance.

CALCULATIONAL MODEL

The Model

Thermal models have been developed over the years. Some of these models go far beyond what is done here and incorporate local hot spots and defects [4,5]. Discussions of "medium field Q slope" following basic thermal models are given in [6,7,8]. The goal here is to have a simple calculation of heating from basic "global" thermal properties and rf surface resistance to try to compare with the measured Q vs B_{Peak} data. The steps of the calculation proceed from the helium bath to the inner Nb rf surface in a simple static one dimensional model as a function of heat flux transported in a range up to 0.1 W/cm^2. The parameters of particular interest are the Kapitza conductance at the helium-niobium interface, h_{Kap}, the thermal conductivity of the niobium, k, and the rf surface resistance $R_s=R_{BCS}(T)+R_{res}$. All are functions of temperature. The two conductance numbers are properties of the specific niobium material and processing preparation and are not well known. The basic steps in the calculation are:

- Starting from the helium bath temperature and heat flux (power/cm^2) find the temperature of the outside cavity wall using a particular h_{Kap} model.
- Using a model for k, find the temperature at the rf surface and the surface resistance Rs.
- Form this one can compute Q and
- From the power and the Rs one obtains B for that power level.

Kapitza Conductance

Measurements of the Kapitza conductance are limited. A simple scaling of h with T^3 given by

$$h_{Kap}\left[\frac{W}{cm^2 K}\right] = 0.05T^3_{Bath}$$

is a typical assumption [2] but we believe it does not fit our data well.

Instead we use two measurement references here, Mittag [9] and Amrit et al [10]. Mittag gives two sample measurements, Amrit gives four. We select the Mittag measurement of annealed and etched reactor grade Nb (Nb2), and the Amrit measurements #1 and #3 for etched RRR 178 (#1), and then annealed to RRR 647 and etched (#3).

The measured data has been characterized in the form

$$h_{Kap}\left[\frac{W}{cm^2 K}\right] = A\left(T_{bath}\left[K\right]\right)^B f$$

Mittag uses a correction form factor, f given by

$$f\left(\frac{\Delta T}{T_{bath}}\right) = 1 + \frac{3}{2}\left(\frac{\Delta T}{T_{bath}}\right) + \left(\frac{\Delta T}{T_{bath}}\right)^2 + \frac{1}{4}\left(\frac{\Delta T}{T_{bath}}\right)^3$$

where ΔT is the temperature difference between the bath and the cavity outer surface. The three sets of measurement parameters are given in Table 2.

Table 2: Kapitza Conductance Parameters Used Here

	identify	A	B
Mittag anneal Nb2	Mittag ann	0.020	4.65
Amrit etch #1	Amrit#1	0.0935	3.55
Amrit anneal, etch #3	Amrit#3	0.062	3.95

These three values of h_{Kap} are plotted in Figure 5 as a function of bath temperature. The predicted Nb outer surface temperature as a function of heat flux is shown in Figure 6. The form factor "f" produces a nonlinear slope of the curves (e.g. Mit_ann at 1.6K) and had a significant effect on the ΔT drop. For the higher conductivities it is less significant as can be seen by comparing the 2nd and 3rd curves at each temperature. (For the 1.6 K case this is about a 0.5 degree correction to a 2.5 K ΔT drop at 0.1 W/cm^2.) In the Q vs B calculations presented below this term has not been included but probably should be in further work.

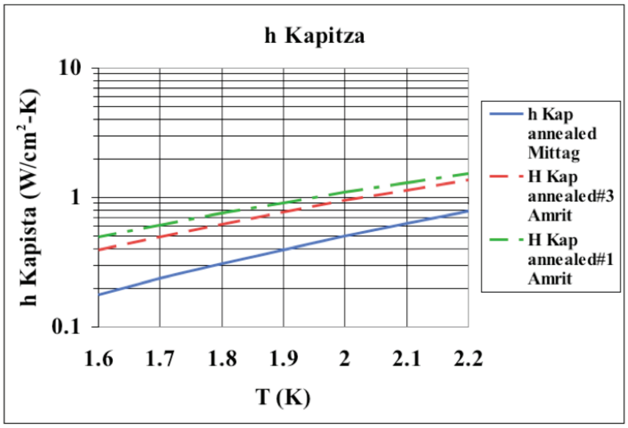

Figure 5: Kapitza conductance based on references [9,10].

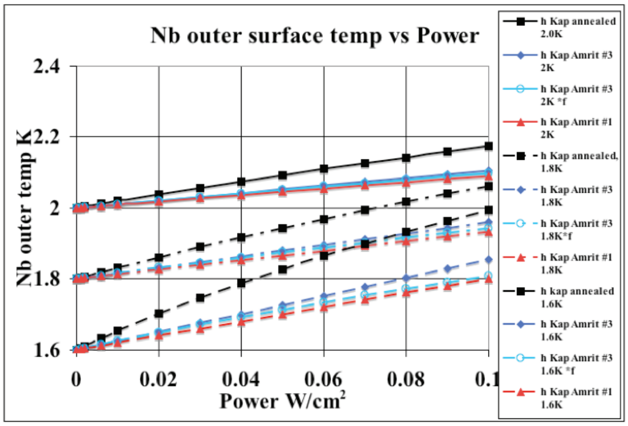

Figure 6: The outer surface temperature of the niobium as a function of helium temperature and Kapitza conductance model. From top to bottom for each temperature are: "Mittag_ann*f term", "Amrit#3", "Amrit#3*f term", "Amr#1".

Thermal Conductivity

Considerable effort has gone into measuring thermal conductivity of niobium material used in cavities [11]. The thermal conductivity assumed for these calculations is for two values of k, 0.3 and 0.5 W/cm-K. Constant temperature dependence has been assumed for the range of temperatures predicted by the calculation. The constant k approximation would be consistent with some phonon peak as might be expected with cavities baked at 800C. These rather high values were chosen for annealed cavities and to make the model most consistent with the observed measurements.

Surface Resistance

The rf surface resistance is represented approximately by

$$Rs[nohm] = A\frac{1}{T}\exp\left(-(B/T)\right) + R_{res}$$

where A= 1.35*10^5 and B=17.67 are the coefficients in reference PKH [12] equation 4.43. A possibly better fit to our 9 cell data over a wide temperature range would have

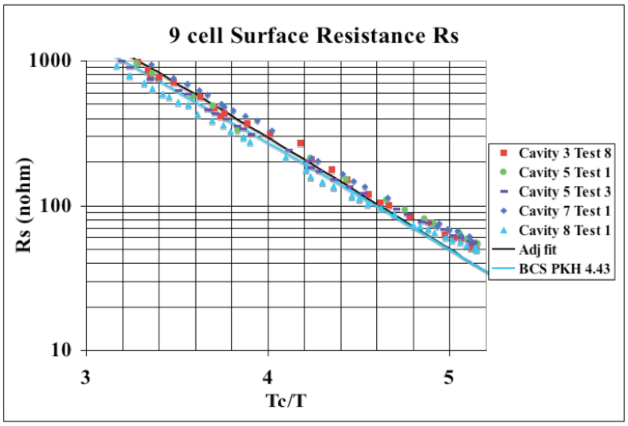

Figure 7: 9 cell cavity measured surface resistance as a function of Tc/T. BCS PKH 4.43 is from reference [12].

$A=1.96*10^5$ and B=18.3. The 9 cell data and fits are shown in Figure 7.

Numerical Results

Q vs Bpeak at different bath temperatures have been calculated for the parameters of the 1 cell cavity (G1, Rs). The curves would only be slightly different with 9cell parameters. For two different residual resistance values, 7 and 30 nOhm, three curves are calculated. The one with the highest Bpeak uses h=Amrit#1 and k=0.5 W/cm-K. The lower two curves use k=0.3 W/cm-K, the middle for Amrit#3 and the lowest for Mittag_ann.

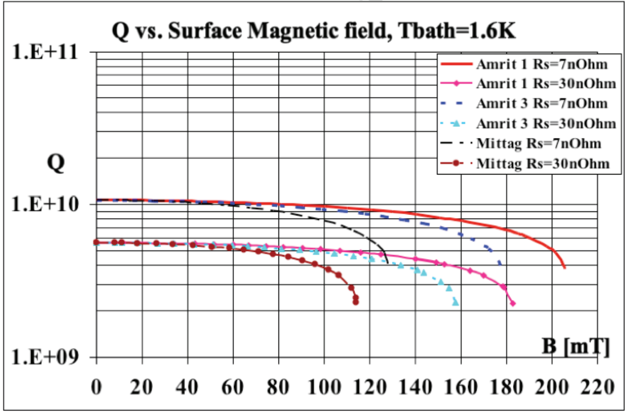

Figure 8: 1.6 K Helium bath calculation. The two curve families are for Rr=7 ohm (upper) and Rr=30 ohm (lower). In each family the Kapitza (h [W/cm^2-K}) and thermal (k [W/cm-K]) conductance is varied. From highest to lowest curve: h=Amrit#1, k=0.5;h=Amrit#3, k 0.3; h=Mittag ann, k=0.3. See text for h and k discussions.

COMPARISON OF DATA AND MODEL

Discussion of the Data

There is risk in trying to compare the 9 cell and one cell cavities and draw too strong conclusions. The cavities are different in shape and have different end configurations. Only results from one 1 cell cavity are reported here. The correct calibration constants are a constant worry. Even so we report the apparent differences.

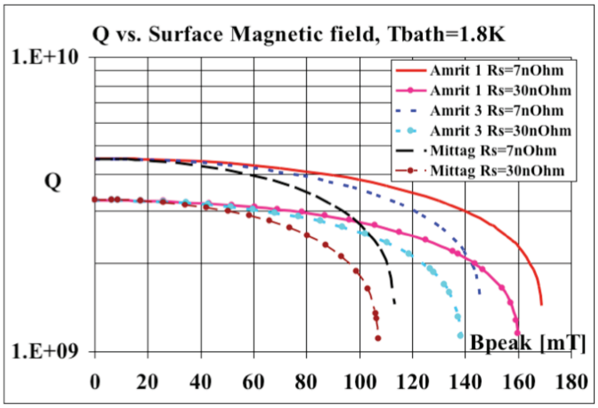

Figure 9: 1.8 K Helium bath calculation. See Figure 8 for curve parameters.

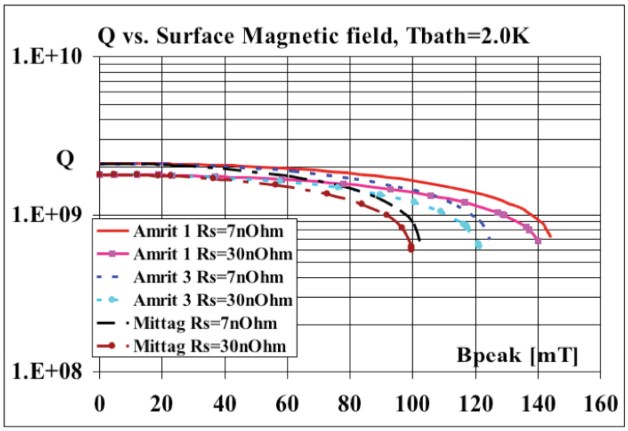

Figure 10: 2.0 K Helium bath calculation. . See Figure 8 for curve parameters.

The 1 cell EP processed cavity shows dramatic improvement in Bpeak over the 9 cell BCP cavities. The gain is of order 40 mT.

Both 1 cell and 9cell data show flat or almost flat "midfield slope" followed by a knee or break in the slope where apparent "high field Q drop" seems to take over. This is at about 100 mT for the BCP cavities and 140mT for the EP cavity.

This behavior was unexpected as we had been assuming the 9 cell cavities were operating near a "global thermal limit". The observed behavior is much like what is seen at lower frequency (1.3GHz) where global thermal heating is not expected to limit cavity behavior.

There was no strong dependence of end point field with helium bath temperature in either the 9 cell-BCP or the 1 cell-EP.

A low temperature bake (120C) did not significantly change the measurement results, but it may not have been done for sufficient time.

In general for the 9 cell cavities there was some field emission at the higher gradients.

The Data and the Model

Measurements are compared with the model in Figures 11, 12, and 13. The 1 cell 1.6K data agrees well with the Amrit#3 h and k=0.3. High residual resistance, 30 nOhm, is necessary to explain the low Q. The Q slope is greater in the model. The 1 cell 1.8 K data agrees well with the highest curve, but the 9 cell does not, indicating an other reason for the Q drop. The 2K data does not agree with the models.

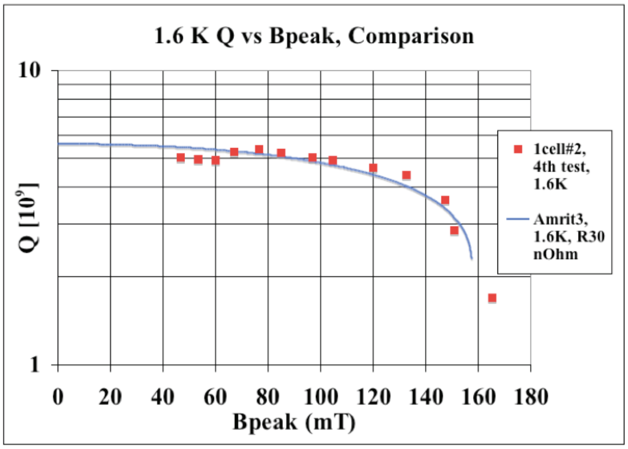

Figure 11: Comparison of the 1.6 K 1 cell data with the model for 30 ohm residual resistance, Amrit#3 h, and 0.3 k.

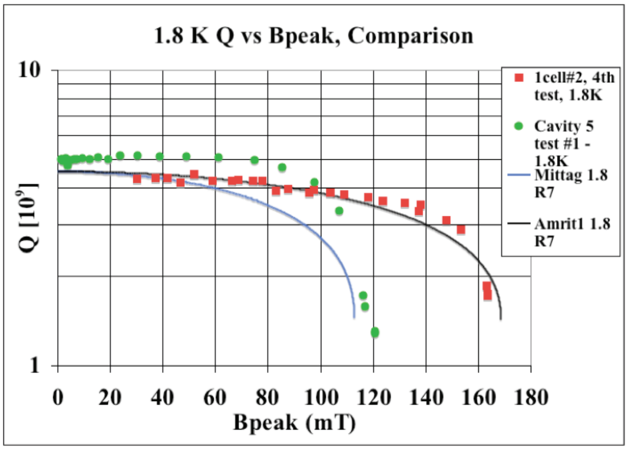

Figure 12: Comparison of the 1.8 K, 9 cell and 1 cell data with models for 7 ohm residual resistance. The two extremes, Amrit#1,h=0.5 and Mittag, h=0.3 of the model are plotted.

One of the first things one observes is that much the data does not show the strong quadratic slope behavior of the calculation, though in the 1 cell 1.6 and 1.8 K cases the agreement is quite good. The comparison would be even worse if a model with "nonlinear field dependent BCS resistance" were used [7,8].

Inclusion of the function f in the h, if appropriate, would tend to flatten the Q slope on the model and extend the end point of B.

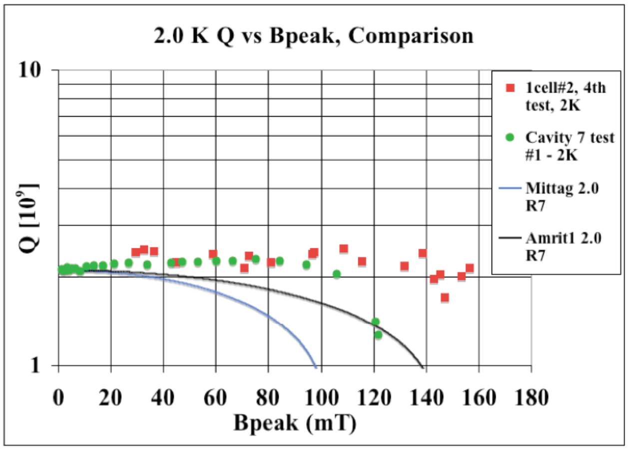

Figure 13: Comparison of the 2.0 K 9 cell and 1 cell data with models for 7 ohm residual resistance. The two extremes of the model as in Figure 12 are plotted.

SUMMARY

An EP 1 cell cavity has been measured to higher Bpeak fields than BCP 9 cell cavities. The difference is similar to that seen for 1.3 GHz cavities.

Thermal models with high Kapitza and thermal conductivity indicate the potential for reaching high Bpeak in 3.9 GHz cavities.

There is some indication that the thermal model has greater Q slope than the measured cavities.

More EP data and a direct cavity comparison with BCP and outside surface preparation is necessary.

Better thermal property data for the specific cavity material used is needed.

The thermal model needs refinement. Is the one dimensional model a reasonable one?

The 3.9 GHz cavities lend themselves to interesting study in thermal transport as well as RF surface properties.

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