WAFER TEST CAVITY

Linking Surface Microstructure to RF Performance: a ‘Short-Sample Test Facility’ for characterizing superconducting materials for SRF cavities

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The Wafer Test cavity was designed to create a short sample test system to determine the properties of the superconducting materials and S-I-S hetero-structures[i]. The project, funded by ARRA, was successful in accomplishing several goals to achieving a high gradient test system for SRF research and development. The project led to the design and construction of the two unique cavities that each severed unique purposes: the Wafer test Cavity and the Sapphire Test cavity. The Sapphire Cavity was constructed first to determine the properties of large single crystal sapphires in an SRF environment. The data obtained from the cavity greatly

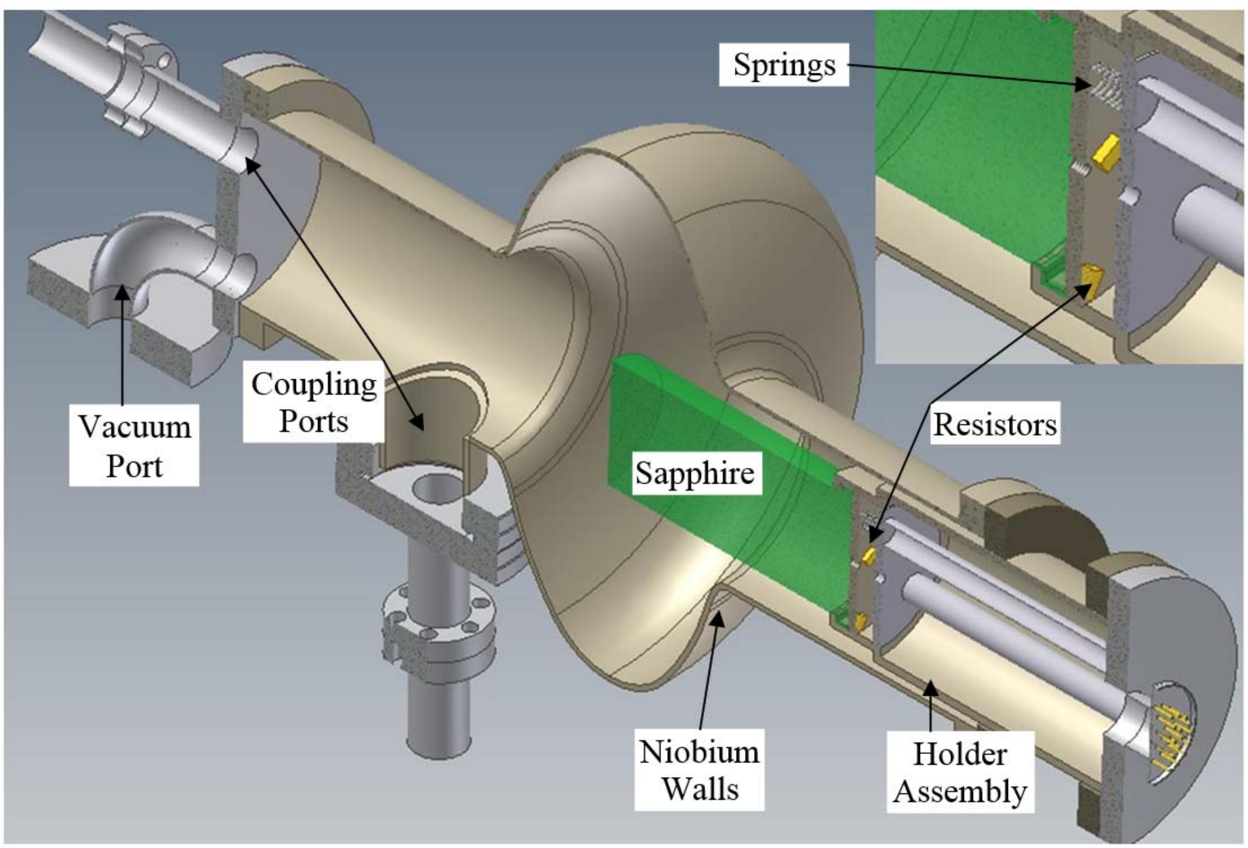

Figure 1: The design of the sapphire test cavity. The sapphire (protruding cylinder) was inserted up to the cavity’s equator. The sapphire is firmly anchored in the holder by a spring loaded backing plate as shown in the upper right corner. The resistors (blocks near the springs) are held on the backing plate to allow the internal temperature to be measured.

altered the design of the Wafer Cavity and provided the necessary information to ascertain the Wafer Test cavity's performance.

The Sapphire Cavity

Construction Design

The HEMEX sapphire acquired from Crystal Systems was two inches in diameter and four inches tall in length. The surface was precision ground and had a frosted finish. A Nb holder suspends the sapphire end face at the equator of a CEBAF cavity. The complete assembly is shown in Figure 1.

The sapphire is completely surrounded by the CEBAF shaped Nb cavity and Nb holder. The only non-niobium material in contact with the sapphire is an indium seal that provides the thermal contact between the sapphire, the backing plate, and the holder. This thermal bridge allows the sapphire to be cooled through the holder which is cooled directly by the superfluid helium. The two ports on the cavity provide the means for the input power to be inserted and transmitted power to be probed. The vacuum/port flange is the only non-superconducting material in the system other than the copper antennas.

Experiments Performed

With this experimental design, several experiments were performed. The initial experiment was to operate the cavity in the TM_{010} mode without the sapphire to ensure that the cavity was operating within the normal parameters. The cavity had a Q_0 of $1.29*10^{10}$ at 2 K. The cavity performed as intended and therefore any degradation should come from the sapphire, however the TE_{011} mode was not found.

The sapphire was cleaned by a recipe provided by the NASA Jet Propulsion Lab, with some slight alterations. The alteration included not putting the sapphire in boiling nitric acid; rather it was placed in buffered chemical polish (BCP) mixture for a few seconds. After cleaning, the crystal was loaded into the cavity where the coupling was over-coupled to ensure that the TE_{01} signal could be found. The signal was found at room temperature and tracked down to 4 K, taking Q measurements via network analyzer periodically.

The second test was somewhat successful. The Q_0 was $1.13*10^8$ at 4.2 K which is a factor of 2.5 lower than the Q_0 of the empty cavity at the same temperature. When the cavity was cooled to 2 K the cavity started to multipact. The Q was measured to be $2.17*10^8$. The corresponding loss tangent is $4.6*10^{-9}$ which is higher than originally hoped, but might be due to the multipacting (caused by the antennas protruding into the cavity), which decreases the decay time and therefore increase the loss tangent. The test did tell us the frequency was predicted accurately by the model.

The third test performance was worse than test 2, but the multipacting stopped. The transmitted signal showed evidence of contamination. The contamination could have come from two sources: opening of the cavity to reduce the antennas or the varnish holding the resistor out gassed during the thermal cycling. For the 4th test the cavity and the sapphire were cleaned again and assembled. The coupling was altered and the TE_{01} signal could not be found because the signal was too weak. However a measurement could be made with the network analyzer. The error in this measurement is high but it produced a Q_0 of $1.8*10^8$ at 4 K (same as the previous test) and Q_0 of $3.4*10^8$ at 2 K. This was the best measurement.

Heat Capacity (J/(kg*K)) as a function of Temp.			
Temp (K)	Model Fit	Fugate	Cryocomp
2.29	1.06E-03		2.25E-04
2.35	1.15E-03		2.55E-04
2.49	1.36E-03		3.76E-04
2.69	1.72E-03		5.72E-04
3	2.39E-03	2.34E-03	9.62E-04
3.54	3.92E-03	3.87E-03	1.91E-03
3.75	4.66E-03		2.50E-03
4	5.66E-03	5.61E-03	3.30E-03
4.2	6.55E-03	6.49E-03	4.00E-04
5	1.10E-02	1.10E-02	7.96E-03
5.5	1.47E-02	1.46E-02	1.14E-02
6	1.91E-02	1.89E-02	1.54E-02
8	4.53E-02	4.49E-02	4.06E-02
10	8.84E-02	8.83E-02	8.30E-02

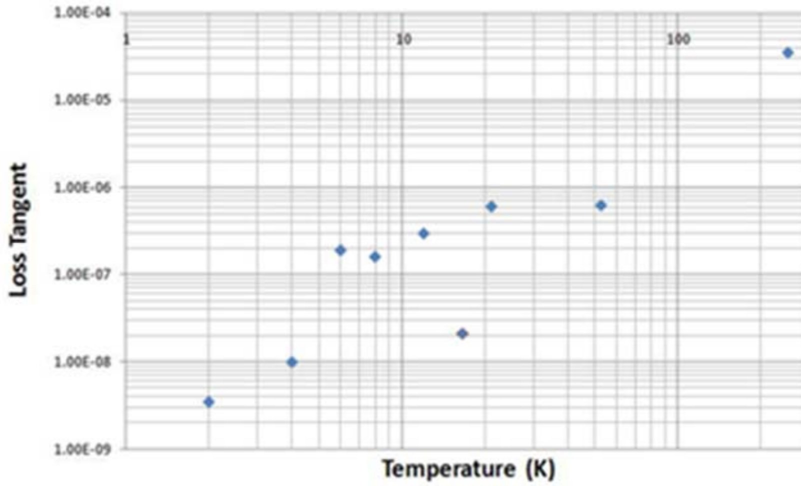

Figure 2: Left: The four top left measurements are the values of the heat capacity that are produced by an extremely close fit trend line from data acquired during Test 7 and compared to data to previously taken by other researchers. Right: Loss tangent measurements from 2K to 250K based on models and Nb resistance.

The 5th test produced an interesting phenomenon- heating. Sadly we were not able to quantify the heating effect since the thermometers were removed to ensure no contamination or interference was produced during the Q measurements. As the RF power was increased, the heating increased, and therefore the Q decreased as expected.

For the 6th test the crystal was given a BCP etch and mechanical clamps were used to fix the resistors to the backing plate. The cavity was cleaned and assembled in the same day. This test was a major failure producing a Q below $5*10^6$. After the 6th experiment, sources of bad Q were investigated. Talking with experts at NASA JPL it was found that water can severely hinder Q. Since the cavity was cleaned, rinsed, and assembled all in the same day, there was some water in the cavity that could attach itself to the sapphire surface. The water can attach to exposed crystal edges which causes losses. The frosted sapphire was polished to reduce the surface area and reduce the sites were the water could attach.

The 7th test began by cleaning the sapphire and storing it in a pot of ethanol until assembly. Once the rest of the cavity was assembled, the sapphire was dropped in the holder and sealed. The cavity was then put on the vacuum pumping station as quickly as possible to pull moisture out of the system. The test was average in that the Q at 2 K was around $1.15*10^8$. However we were able to quantify the heating. This allowed us to make both loss tangent measurements and heat capacity measurements.

In the last test the entire cavity was filled with superfluid helium in an attempt to get a Q measurement directly at 2 K without any increase in temperature from dissipation while filling the cavity with energy. However the Q was lower than in the seventh experiment. This was unexpected since the loss tangent of helium is negligible. Other outside sources of contamination or parasitic modes must have caused the problems.

Results

From these experiments useful data were extracted. The loss tangent for the sapphire can be given a temperature dependence using a best fit curve as well as the heat capacity. Figure 2 (right) shows the best values of the loss tangent measured from 2 to 250 K. The heat capacity was measured in experiment 7 and was given a best fit curve as well.

The results of the curve compared to known data and extrapolated data from Cryocomp for heat capacity are compared in Figure 2 (left). The results for the heat capacity look to be reasonable compared to other data[ii]. The loss tangent data is much higher than previous work[iii,iv]. The 4.2 K measurement made in this set is slightly better than previous work using RF cavities, except for one measurement where Q was measured to be 10^{-9} [3]. However it is much higher than $2*10^{-11}$ measured using calorimetry at 4.2 K by Buckley[iv].

The 2 K measurement of loss tangent is an order of magnitude higher than expected. There are several possible causes for this. One is contamination arising from water on the sapphire. Another is the indium ring may be playing some role. However it is suspected that there is a parasitic mode being generated in the cavity and is dissipating energy in on the stainless steel flanges and antennas. The other possible problem is the antenna's coupling (most likely). In this design the fields don't have to enter the cavity's cell before going back to the probe. The antennas could be talking directly to each other, bypassing the loaded cavity's cell and not seeing the TE mode.

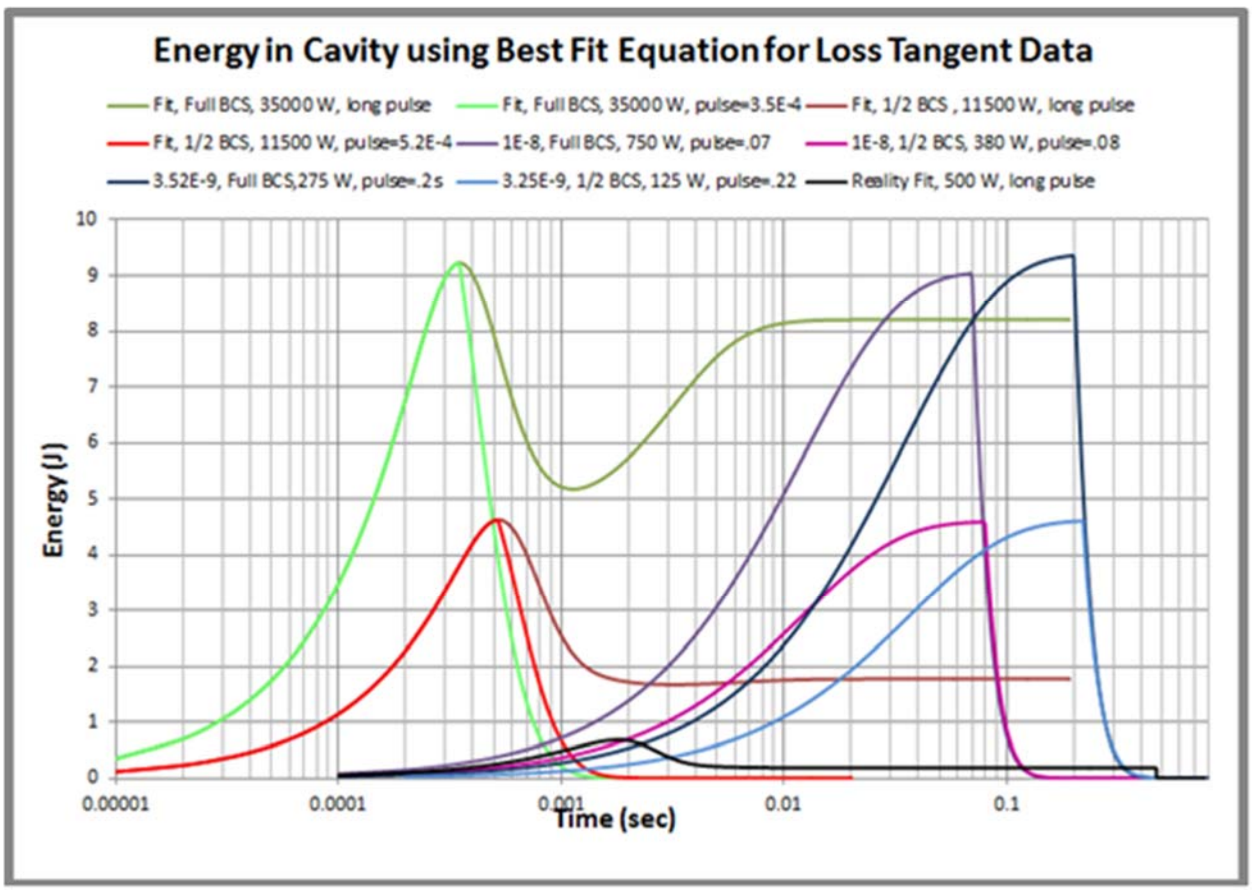

Figure 3: The stored energy that is possible to be stored in the Wafer Test Cavity as initially designed for a wide variety of parameters.

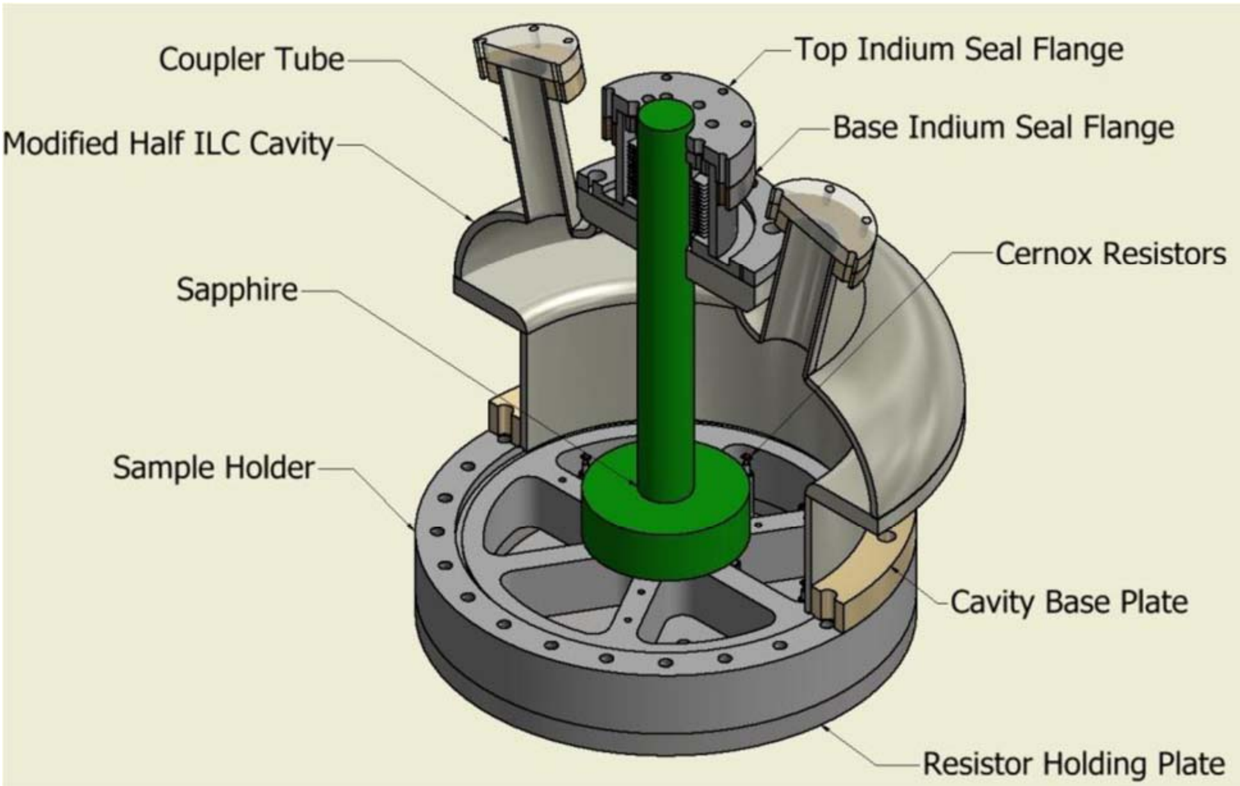

Figure 4: Schematic of the final design of the Wafer Test Cavity.

The Impact of these results on the Wafer Test Cavity

The ramifications of these recorded values of loss tangent and heat capacity are that the wafer test cavity cannot operate within the parameter space for which it was initially designed. The loss tangent produces heat at a much higher rate than anticipated. The heat dissipated is large enough to change the temperature of the sapphire quickly which increases the loss tangent, and exacerbates the problem.

Therefore the most field that can be placed on the sample surface is 21 mT, more than an order of magnitude lower than hoped if the initial design was used. At 2 ms the cavity reaches its maximum stored value, after this time the sapphire heating increases the loss tangent, reducing the stored energy until and it reaches equilibrium at 6 mT. The cavity as it is designed requires 9 J of stored energy, and this will not be achievable, thus the frequency of the Test cavity must be changed and create a higher ratio on the surface. By increasing the surface field from 5 to1 to a higher ratio of to 9 to 1 and reduce the crystal size to reduce the required stored energy by a factor of 4, making our ability to achieve 200 mT achievable.

The black curve in Figure 3 is what would occur if nothing changed; thus we would not get above .7 J with a 500 W input. By decreasing the stored energy in the cavity by using a smaller sapphire that creates a higher sample to wall ratio, we can get the cavity to operate with a minimum of 85 mT. We anticipate that these values for the sapphire will get better. The cooling of the sapphire was also altered to allow direct cooling. Thus show hinder the heating of the sapphire significantly.

The Wafer Test Cavity

Introduction

The Wafer Test Cavity was designed to evaluate RF materials and heterostructure to more easily identify what properties lead to better performance. The cavity was designed to use flat samples that place high field upon them without using edge effects. Flat geometries are the easiest to characterize and for deposition of thin films. The cavity was originally designed by Dr. Nathan Pogue, Dr. Peter McIntyre, Dr. Dior Sattarov and Dr. Charlie Reece[v] and draws on several other test bed designs, but most notably from the Surface Impedance Characterization Cavity[vi] and the Stanford TE_{013} test cavity[vii].

The TAMU cavity is a dielectrically loaded, “mushroom” shaped cavity, consisting of a half ILC accelerating cavity, with a cylindrical bottom. The bottom plate serves as the sample material, as can be seen in Figure 1. The combination of the cavity geometry and the dielectric loading, concentrates the magnetic field on the sample. The ratio of the magnetic field on sample versus on the cavity walls is roughly a factor of 5 to 9, depending on crystal position, above the sample. The electric and magnetic field simulation results are shown in Figure 5 respectively, for a crystal height of ½” above the sample.

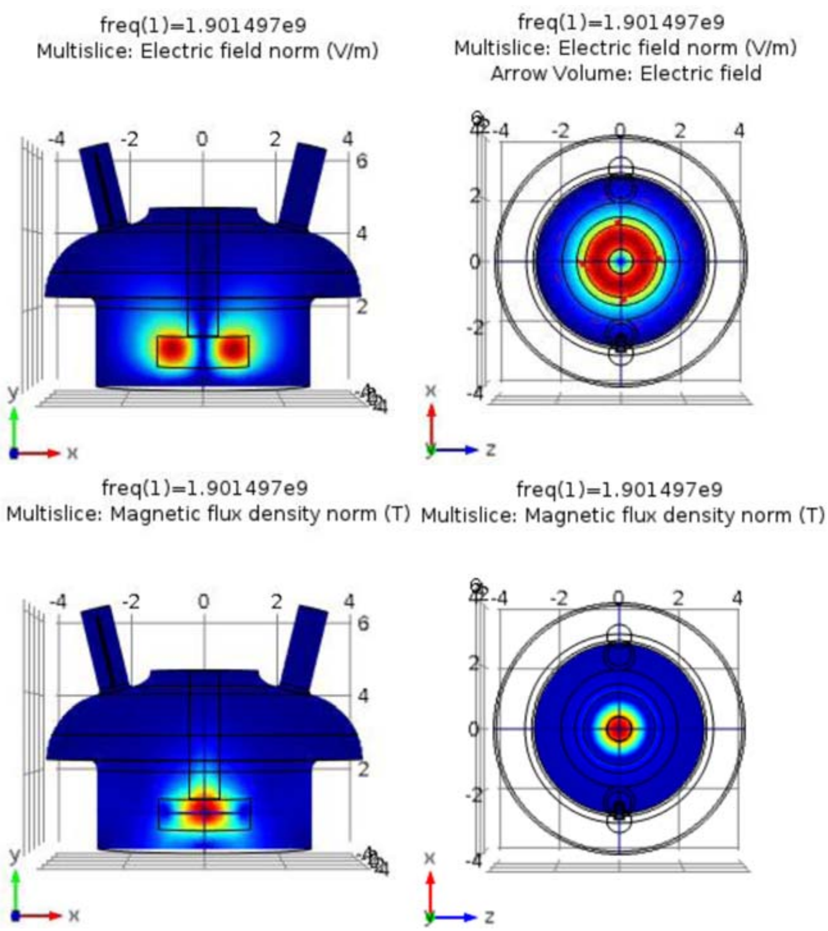

Figure 5: Top – Electric Field of the crystal in the cavity sitting .5 inches above the sample surface. Bottom – Magnetic field of the same the cavity with the same conditions.

Cavity and Component Fabrication

The fabrication of the cavities main components had been supervised by Larry Turlington. The details of the fabrication can be derived from the JLab and TAMU engineering prints and it is sufficient to say that the materials used were RRR niobium, NbTi and 304 stainless steel. The issue of the SS will be discussed shortly. A plate of 3/8" RRR niobium was used to fabricate a 7.024" diameter base plate for the cavity. This was done to prevent unnecessary deflection due to pressure differences between the cavity and dewar. A length of 316L stainless steel tubing, 316LN mini-conflat flanges and custom feed through flanges for the cavity were acquired for the fabrication of the feed-throughs. The custom flanges were machined by the main JLab machine shop. The mini-conflat flanges were sourced from Anne-Marie Valente and later replaced. The stainless steel tubing was acquired from McMaster-Carr and cut and notched by Ari Palczewski. The welding of the feed-throughs was done by Aaron Auston. The 4-way feed-through that was machined at JLab had one issue, when the welded flanges were not attached in the right order. There were two short pieces of tubing and one long piece, for the coupler to follow. Since these were switched, the coupler was not going down a straight tube, which was later complicated by the fact that the feed throughs used ceramic insulators that were not straight.

Figure 6: Image of the Wafer Test Cavity.

The main issue with machining of the components for the cavity was the use of 304 stainless steel, which was found to have a permeability of greater than 1.1, in certain places. This issue was brought up during a group meeting with the SRFPMA group at JLab, where it was estimated that a large amount of money in operational cost was wasted due to high permeability parts in the cryomodules for CEBAF. This issue was deemed to be insignificant due to the time constraints of this project, but should not be ignored in the future. Another issue with the stainless steels used, was the 316L from the JLab machine shop being just as bad as the 304L from McMaster. Again these issues were largely ignored.

Cold Testing

The first cold test was performed to find the frequency of the TE011, check the coupling, and get a rough Q measurement. The test was successfully performed with the following the results: β =1.725, Q_L= 3.5x10^7, Q_{ext1} = 5.4x10^7, and Q_0= 9.4x10^7. The second cold test was performed in two parts; first the cavity was cooled to 5 K and monitored with a network analyzer. At 5 K the cavity was then switched over to the R&D RF system and was monitored from 4.23 K to 2 K. From room temperature to 5 K the frequency, Q_L, T_{cavity}, $T_{sapphire}$ and resonant peak width of TE_{011} mode were measured on an Agilent 5071C network analyzer, via a Labview program provided by Ari Palczewski. During this portion of the cool down, the Q_L and frequency rose as the temperature fell.

The sapphire crystal cooled considerably slower than the cavity as a whole. There are two reasons for this, the cavity is cooled from the bottom and the crystal is only exposed on the top of the cavity and the crystal has a large thermal mass within the vacuum of the cavity with only a small portion being exposed to the cryogenic bath.

The RF test from 4 K to 2 K was performed by hand and entered into the standard spreadsheet used for doing RF testing in the VTA. For Q vs. T measurements, low-level RF was used from 4 to 2 K. It was very difficult to get a lock on the cavity with the PLL to take measurements.

After a considerable amount of effort, Grigory Eremeev suggested adding an amplifier to the transmitted power. A 35 dB amplifier was added to the transmitted power input, but there was still considerable difficulty in getting a lock on the cavity. The Frequency Modulation on the signal generator was then adjusted from 1 MHz to 10 MHz, which made locking the cavity much easier in conjunction with the amplified transmitted power line.

There is a large error in the measurement, partly due to a mismatch in the input coupler Q_{ext} and cavity Q_0, and partly due to very low power levels at which the measurements were done. This makes the Q_0 of the cavity is effectively flat between 4K and 2 K, with a value of 2-3 x 10^8. An

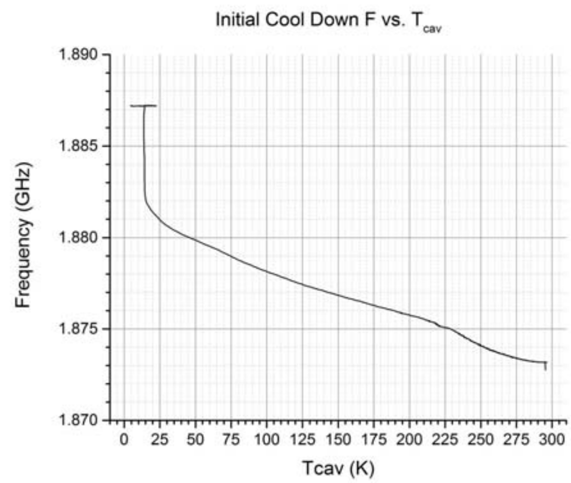

Figure 7: Frequency vs. T – Room Temperature to 5K.

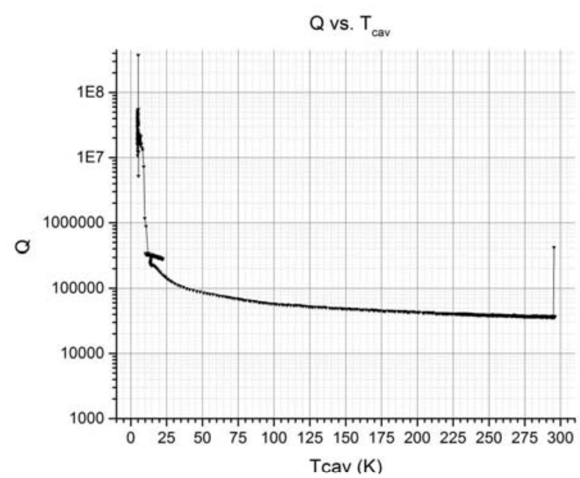

Figure 8: Q vs. T (RT to 5 K)

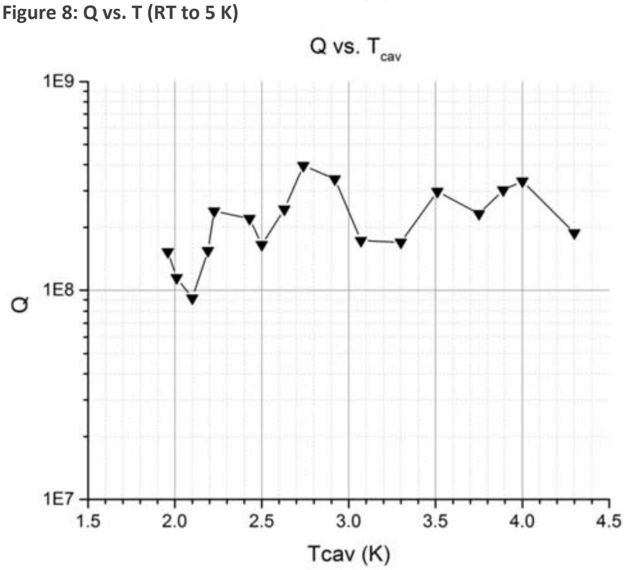

Figure 9: Q vs. T (4 K to 2 K)

interesting result was the frequency going down between 4 K and 2K, which is likely attributed to the pressure change when going below 4 K.

At 2 K, the power was raised and it was noticed that the cavity was quenching at a low power level. Looking at the transmitted power, it could be seen that before the cavity could fill, it would quench. The filling was occurring on a short time scale 2-3 ms, with the quench taking on the order of µs. In the pulsed mode, even with a period between pulses of 8-10 ms the cavity was quenching. This led us to believe the cavity was quenching and then cooling again very rapidly and then quenching again.

At the power levels close to quench, the quality factor of the cavity would degrade on the time scale of a few seconds. This is likely due to losses in the crystal, where the crystal is heated and does not have time to dissipate the heat through the top of the cavity. Again this effect is attributed to the time that it takes the crystal to transfer the heat dissipated due to RF heating. This effect takes roughly 4-6 seconds to begin, with a power level on the order of 100 mW.

Aside from the already discussed results of the test there were several other derived values and confirmed quantities. The RF measurements helped confirm the Q_{ext} values of the couplers and the coupling coefficient, β. During this test the cavity is over-coupled and an average value of β_{ext1} of 6.06. The input coupler for the cavity was set at $5x10^7$ on the test bench in the RF Structures Lab and the transmitted power coupler was set at $6x10^9$. The measured values of Q_{ext1} and Q_{ext2}, were $3.6x10^7$ and $4.6x10^9$, both of which are well within the errors caused by setting them with a loop coupler. It also worth noting that during the Q degradation, β went from above 1 to below 1 during the Q change. As the Q_0 went down due to the crystal heating, the Q_0 approached the Q_{ext1} of the coupler.

With several legitimate possibilities as the cause for the issues that the cavity is experiencing, a clear, concise and systematic path forward is necessary for the third experiment. Eliminating simple possibilities first is the obvious choice, due to constraints on time and money. The following recommendations were made during the meeting at JLab:

- Change the loop couplers out for L-shaped or “hook” style couplers (simulations provided by Haipeng Wang)
- Attempt to model multipacting situations based on perturbations to cylindrical geometry in the cavity and seek solutions by modifying the cavity
- Adjust the position of the crystal to perturb the fields to identify and change the dynamics of the quenching

Again, the elephant in the room is time and money, so changing the couplers and retesting is the fastest and cheapest way to identify problems with the cavity.

The third test was completed and several of the same issue remained. The coupler was changed but still the amount of power that was transmitted was small. A large portion of the ingoing power was reflected. Since the reflected power varied non-linearly with input energy, energy was being lost in the coupler itself. The result of the third experiment was the best yet, producing 6.5 mT of field at 1.76 W on the flat sample. After only 3 tests and the cavity reached a level of success and demonstrated the cavity can operate as anticipated.

Summary

The outstanding issues currently are that we experienced unexplained low level quenching and low Q. At a short meeting at the conclusions of the summer, a discussion between the staff at JLab revealed several possible causes for the quenching and low Q.

- Deviation from cylindrical geometry introduces normal fields in the cavity and causes multipactoring
- Using long coaxial line to make loop couplers causes RF field to be introduced to non-superconducting parts of the cavity
- Discoloration of the coupler could indicate that the coupler itself is multipacting or experiencing some form of field emission
- Possible exposure of indium to RF field could be causing low field quenching
- The sapphire crystal can be out of symmetry with the rest of the cavity and could be causing anomalies in the RF fields

Based upon the over coupled test of Justin Comeaux, the lowest loss tangent obtained was $4.71*10^{-9}$ which matches the pulsed measurement of Nathaniel Pogue in the Sapphire test cavity of $4.61*10^{-9}$. So the two are quite similar, however the Wafer Test cavity has lower fields in the cavity and has direct cooling keeping he sapphire at lower temperature longer. Sapphire being and excellent thermal conductor – 10,000 W/m – has a relaxation time of around a microsecond. Thus we are confident that the Wafer Cavity would greatly outperform it previous field values (6.5 mT) once coupling is perfected and additional investigation into the other possible sources of loss. Justin Comeaux, for his masters thesis, will perform a thermal model of the cavity operating with a sustained power load while being actively cooled by helium.

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