A MEASUREMENT OF THE LOSS TANGENT AND HEAT CAPACITY OF A LARGE SINGLE CRYSTAL AND THE IMPACT ON THE DESIGN OF WAFER SAMPLE CAVITY*

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Abstract

A large single crystal of sapphire was inserted into a CEBAF cavity, operating in the TE_{01} mode, to measure the sapphire's loss tangent and the heat capacity. These values were measured at cryogenics temperatures. The dielectric constant, heat capacity, loss tangent were calculated based on the experimental data and models produced by RF modelling software. The motivation for these measurements was to determine the performance capabilities of the Wafer Test Cavity. The Wafer Test Cavity uses the sapphire as a dielectric lens to focus the magnetic fields onto the sample wafer up to 3.75 times higher than the surface of the cavity to test characteristics of sample materials. The tentative design the Wafer Cavity will be presented.

INTRODUCTION

Current Niobium SRF single cell cavities can nearly achieve the fundamental magnetic field limit on a routine basis. Even though the ability to reach such fields is achieved, the reasons as to why most cavities do not attain such a limit are not well understood. These limiting phenomenon are known, but the manner and degree in which they affect the performance is not understood.

It was hoped that such a relationship could be established by creating a sample test system that can place consistent conditions on sample materials. These samples could have all the individual processes used in cavity manufacturing, or combinations thereof, and assesses each process on the performance of the cavity.

A second reason for such a system is to test materials that would be a SRF revolution rather than tweaking procedures causing an evolution. Gurevich [1] stated that alternating layers of insulators (such as Al_2O_3) and type-II superconductors (such as Nb_3Sn) could create a heterostructure capable of shielding the magnetic field from the bulk Niobium. This allows the cavity to withstand magnetic field twice the critical limit while simultaneously enhancing the Q-value (quality factor) by factor of four. The significance of this statement is an accelerator whose energy is doubled for the same power cost. If the concept is proven true then it will truly be a revolution in accelerator physics.

The Wafer Test Cavity (WTC) is designed to produce field 3.6 times higher field on the sample compared to the surface of the cavity which allows one to investigate heterostructures to their capabilities in a reproducible

environment, as well as the current techniques used for conventional cavity production. It is the hope that the Wafer Test cavity will become a powerful analytical tool for present and future research.

RESULTS FROM THE SAPPHIRE TEST CAVITY

A crucial aspect to the high performance parameters is the sapphire located at the heart of the cavity. The loss tangent has been measured low enough by calorimetry to allow the Q of the cavity to be on the order of 10^{10}. The heat capacity of the sapphire must also be known for the losses generated by the sapphire will increase the temperature of the sapphire. The loss tangent is temperature dependant and therefore as the temperature gets larger the loss tangent increases leading to an ultimate limitation of the field on the sample for a given input power.

A CEBAF cavity was loaded with a sapphire about half the size of the crystal designed for the WTC and its properties were tested, see Figure 1. This Sapphire Test Cavity (STC) was tested 8 times producing varying results each experiment.
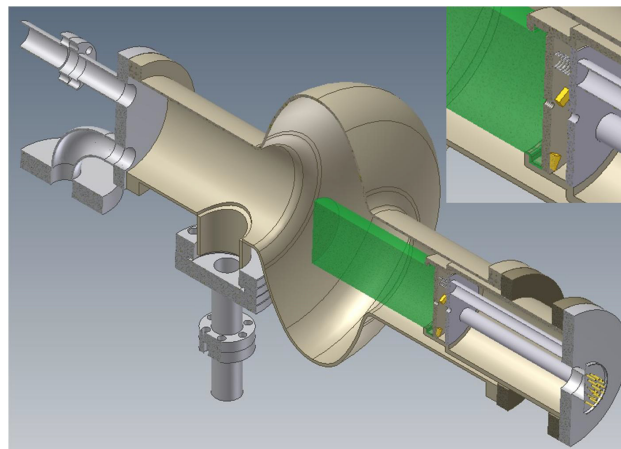

Figure 1: Drawing of the Sapphire Test Cavity. The sapphire's (green) end face is parallel with the equator. The side and end ports were the locations of the probe and input couplers. The end flange also included the vacuum line. The sapphire is held in place by a Nb holder with an indium seal that acts as a thermal bridge between the sapphire, backing plate with resistors attached, and the holder which is the pathway to the Helium bath. The backing plate is spring loaded ensure consistent contact with the seal.

The loss tangent and heat capacity have been measured in the STC but results were not as high as expected. The best measured loss tangent was $3.52*10^{-9}$ at 2 K and $9.1*10^{-9}$ at 4.2 K. For comparison, using calorimetry Buckley [2] found the loss tangent to be $2*10^{-10}$ at 4.2 K and the loss tangent trend shows decrease below this temperature. There were several problems with the STC design. In order to get the sapphire in the center of the cavity a fixture was inserted into one of the cavity's beam tube. Hence the couplers had to be put on the same side. To eliminate the potential cross talk a side port was inserted. This inadvertently caused a large asymmetry that perturbed the field down the beam pipe to the couplers.

There were several unique design features that may have led to errors in measurement accuracy and limiting the cavities performance. At the same time some of the procedure performed to the sapphire may have slightly damaged the crystal.

The protruding holder may have caused inadvertent losses as well as leaked field through small vacuum holes to the resistors. The varnish used may have out gassed during thermal cycling leading to poor Q, because the varnish would have to pass through the cavity to be pumped out. The varnish was replaced with clamps that were seen to change the calibration of the thermometry, which could lead to altered heat capacity values. An indium seal was inserted to act as a thermal bridge to the bath but it was seen that sapphire heated significantly and was therefore difficult to ascertain the values of the loss tangent and heat capacity at specific temperatures.

The sapphire could also have been damaged by performing a BCP on the crystal. It is not anticipated to do so but it is a possibility. The logic behind the crystal not being damaged and the cavity being the limiting factor is the crystal surface was polished and never BCP before test 7 and the same result occurred, in actuality worse performance.

Using the values measured, the parameters of the WTC were calculated. As seen in Figure 2, with a long pulse from the 500 W (largest amplifier at Jlab for 1.3 GHz), the cavity could only reach at most 21 mT in 2 ms. This is an order of magnitude less than hoped. If one needed to get to the BCS limit it could be achieved but the amount of power inserted into the cavity would have to be 35kW in .25 ms, which is unreasonable. However if we use the values that were taken by calorimetry, the cavity would be able to reach the BCS limit in 20 ms with a 500W amplifier. This is reasonable. So it is necessary to achieve a better sapphire measurement.

WAFER TEST CAVITY DESIGN

The design of the Wafer Test Cavity has radically changed since original inception. The top part of the cavity is a mushroom shaped piece comprised of half a TESLA cell, a disk, and a cylinder as shown in Figure 3. On the top of the mushroom are two ports that contain the coupling loops to insert power and measure the Q of the cavity. These two loops will be recessed to eliminate line of sight and cross talking. If required additional dummy ports can be inserted on the top of the cavity to reduce the asymmetry of the cavity. Most of the field is located near the sample but this is a provision to correct for the problem if it arises.

Energy in Cavity using Best Fit Equation for Loss Tangent Data

- Reality Fit, 500 W, long pulse
- Fit, Full BCS, 35000 W, pulse=3.5E-4
- Fit, 1/2 BCS, 11500 W, pulse=5.2E-4
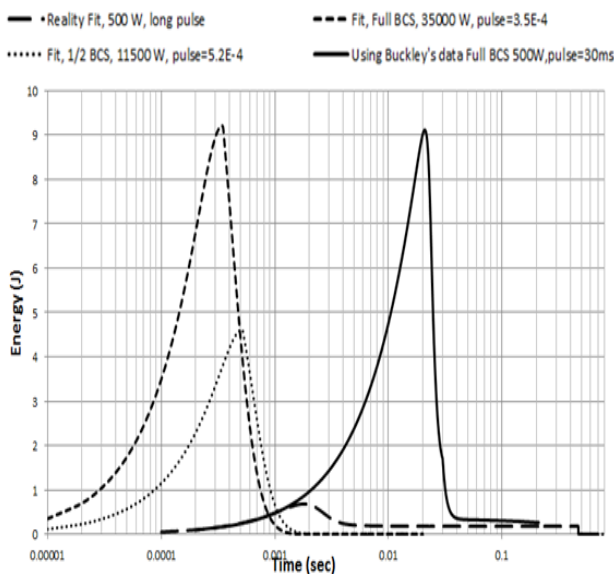- Using Buckley's data Full BCS 500W, pulse=30ms

Figure 2: This figure illustrates the ramifications of the STC tests. Long dashed line shows that at the maximum power that can be provided (500 W); the cavity cannot reach above 21 mT. However if the same results were to be achieved as those measured by calorimetry, then the cavity would respond as designed with 500W of power as the solid line shows.
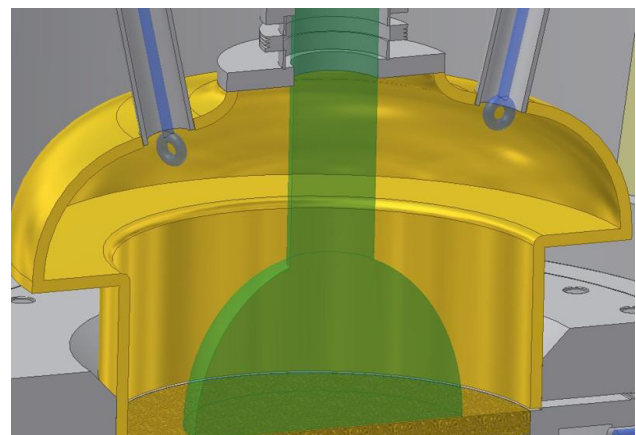
Figure 3: The top half of the cavity. The mushroom is a half TESLA cell that's connected to a cylinder. The sapphire (green) is held by a bellows with an indium pinch seal at the top of the cavity. It allows adjustment of the sapphire above the sample. There are two ports located at the top: one probe and one input coupler. The two loops can be adjusted to get the optimal coupling. If necessary, dummy ports can be inserted to symmetrize the system.

The sapphire is suspended by an indium pinch seal connected to a bellows to allow for height adjustment. The indium provides a mechanism to make a superfluid helium tight seal on the sapphire while not damaging the sapphire during compression. The shape of the sapphire can be of three different flavors. The first is an optimized ellipsoid attached to a cylindrical stem as shown in Figure 3. This shape optimizes the field concentration on the sample while holding the frequency of the cavity at 1.3 GHz.

The second model creates the same shape as the ellipsoid using a series of cylinders of varying diameters. This is also one single piece of sapphire. However a third design has the exact same shape as the second but is comprised of a set of washers that sit on top of a sapphire mandrel, Figure 4. The second model is the least difficult to machine and will be the most cost effective. The ellipsoid will optimize the field, and the third will allow the most versatility in frequency and field magnitude as Figure 4 illustrates.

Cavity with the different amounts of sapphire

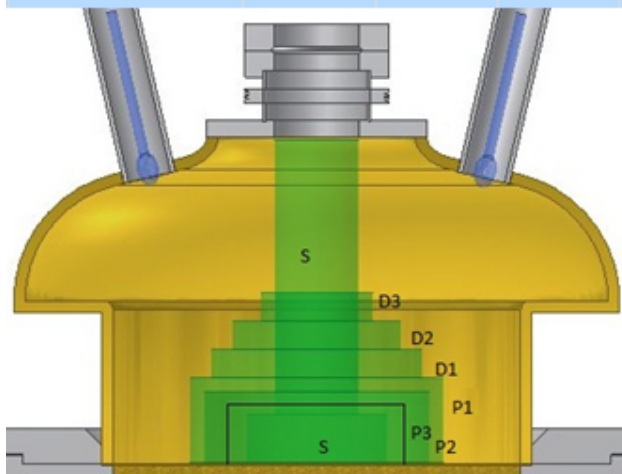|	freq (GHz)	sample to wall ratio
No sapphire	2.78228	-
S only	-	-
Full sapphire	1.32	3.56
remove D3	1.3332	3.63
remove D3, D2	1.3727	4.13
remove D3, D2, D1	1.487	4.91046
Just S, P2, P3	1.682	7.265
Just S, P3	1.936	8.455
Just S and P3 are the maximum ratio obtainable		

Figure 4: The cylindrical pyramid that can be made into one or several pieces. The table above shows the frequency and sample to wall ratio of the cavity if only certain pieces of sapphire are placed in the cavity. Using just the stem (S) and pedestal 3 (P3), the maximum ratio is obtained. Using a smaller sapphire decreases the ratio, as does a larger sapphire.

Using the washers the maximum ratio of the magnetic field on the sample to that of the cavity surface is 8.5 times. The cost of the larger ratio is a higher frequency. It must be determined which sapphire will best suit our needs based upon cost of manufacturing and the end goal of the testing device.

The newest piece is an improved sample holder. The sample is directly cooled by the superfluid helium on the back surface. With 6 inch diameter wafer, the sample has to be stabilized against atmospheric pressure during the leak checking phase of cavity testing. It must also withstand the Lorentz force generated during testing up to the BCS limit. Taking data from the RF model of the cavity, the Lorentz pressure on the sample wafer is approximately the same magnitude as atmospheric pressure except in the opposite direction.

To counteract these forces, a symmetric 6 beam cross bracing mount was designed to only allow the wafer to deflect 22 microns due to both pressures. The inch thick cross member fully support the Lorentz force while supporting 9 counter-bored #2 screws bond the sample to the bracing mount. The 9 stainless screws are able to support the 2400 N force with only a 2 mm penetration into the sample. The mount is shown in Figure 5.
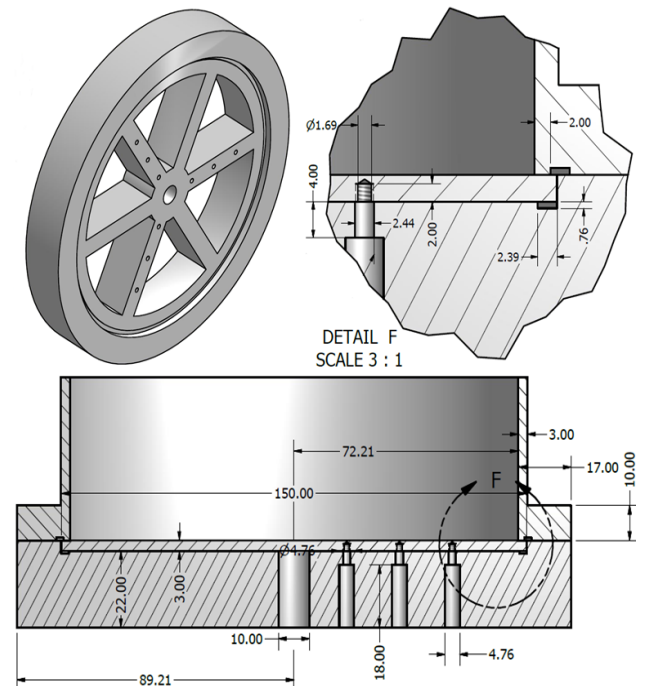

Figure 5: 6 spoke wafer mount. Top Left: shows the design of the mount with 6 inch thick spokes with a hole in the center and 9 counter-bored holes for #2 socket head screws. It also shows the recess for placement of the wafer. Bottom: Gives a cross section of the mount and wafer with dimensions. Top Right: An enlarged view of the two indium joints providing the helium seal and the counter-bored holes. It also shows the tapped holes in the wafer. Each 3mm thick wafer must have the 9 holes drilled and tapped.
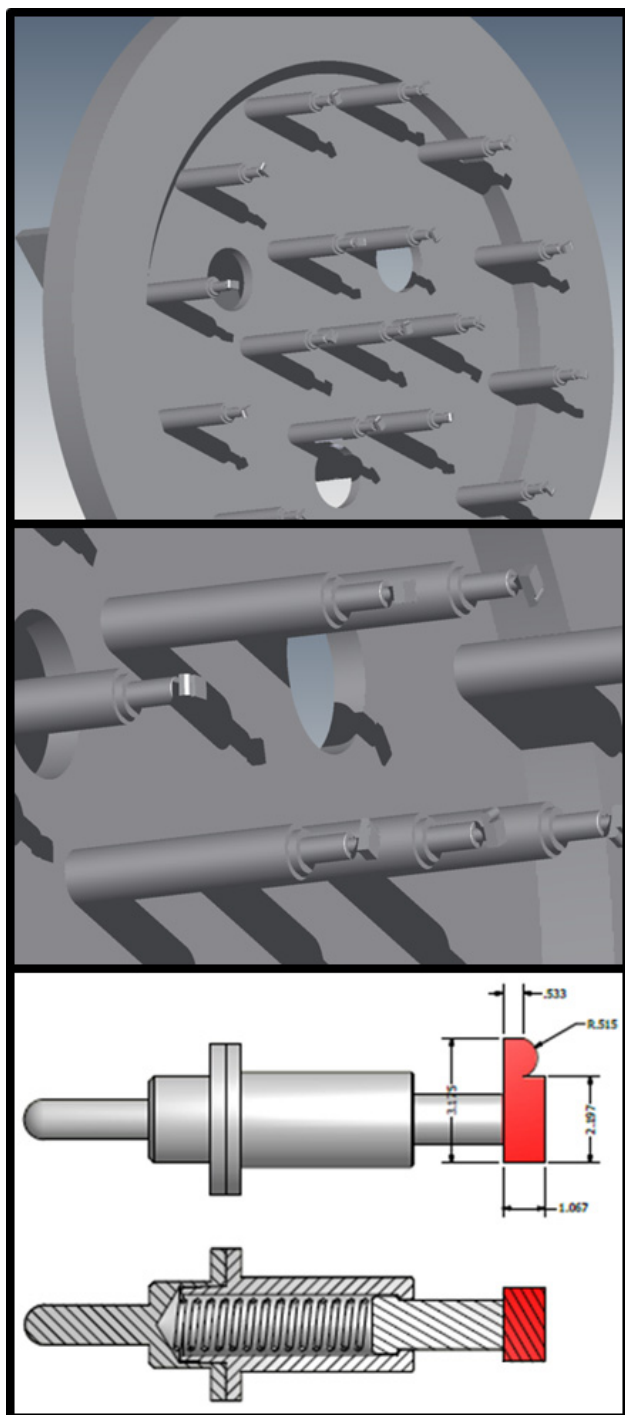
regions between cross beams and a single resistor in the center. It should be possible to identify the location of a quench site and provide an accurate value of heat generated during operation. The flange has three holes inserted for the leads to escape and to let the superfluid helium have direct contact with the thermometers and the sample. Each resistor sits on spring loaded pin that provides at most 1.15 N of force on the resistor keeping the resistor in direct contact with the cavity at all times.

In addition, another two resistors will be placed on the top of the exposed stem of the sapphire. This I will allow us to get a direct measurement of the sapphire compared to the STC where the heat had to pass through the indium thermal bridge and Nb backing plate. This will give us a vast improvement in our measurements of heat capacity of the sapphire.

The entire assembly should provide the instrumentation and mechanical support necessary for the testing and operation of the Wafer Test cavity. It should also provide an environment for accurate testing of samples and the sapphire itself.

CONCLUSIONS

The WTC is a much more suitable environment to test the properties of sapphire. The STC was not a loss, important procedures, properties, and information was obtained during the eight experiments that helped create the design of the WTC. The STC accomplished this with a minimal investment, whereas if the WTC was used initially and the sapphire was damaged, the loss in cost would be much greater in comparison. The STC experiments enhance the WTC's design. The WTC will now being a substantially better at measuring the properties of sapphire and it is hoped that samples could be test up to the BCS limit of Niobium.

ACKNOWLEDGEMENTS

REFERENCES

[1] A. Gurevich," Appl. Phys. Letters 88, pp. 012511-012513 (2006).

[2] S. N. Buckley, P. Agnew, and G. P. Pells, J. Phys. D: Appl. Phys., 27, pp. 2203-2209, (1994).

Figure 6: Top: Shows the hex pattern of the resistors and the three holes for leads and helium inlet. A back fin contains two 41 pin connectors for easy attachment to the outside world while in the dewar. Middle: Shows the close up view of spring loaded pins inserted into the extending cylinders and anchors them into position. Bottom: The view of the spring loaded pin and resistor, as well as a cross sectional view.

Underneath the wafer support mount is another flange that contains the thermometry bank that is shown in Figure 6. This bank consists of 19 Cernox resistors distributed evenly in a triangular part in each of the six