ULTIMATE-GRADIENT SRF TEST CAVITY AND LOW LOSS TANGENT MEASUREMENTS IN ULTRA PURE SAPPHIRE*

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Abstract

A test cavity has been designed to test wafer samples of superconducting materials at 1.3 GHz. Operating in TE_{01} mode, this mushroom shaped cavity creates a unique distribution of surface fields. The surface magnetic field on the sample wafer is 3.75 times greater than elsewhere on the Niobium (Nb) cavity surface. This made possible by loading the cavity with an ultra-pure sapphire just above the sample wafer. The maximum field seen by the Nb wall is only 25% of the value deposited on the sample surface. Therefore, it should be possible to push the sample wafer well beyond the BCS limit for Nb while still obtaining a respectable Q.

The sapphire's loss tangent and dielectric constant must be measured to finalize the design for the Wafer Test Cavity. A sapphire loaded CEBAF cavity has been constructed and tested; these results on the dielectric constant and loss tangent will be presented.

INTRODUCTION

After decades of diligent research Nb cavities have made significant advancements. Alterations in polishing, materials, and chemistry have produced cavities of all grain sizes reaching near the fundamental breakdown limit. The ability to reach this boundary is a phenomenal success. However, the frequency at which multi-cell cavities reach high performance does not economically constitute a future collider. To fully comprehend the limitations of these cavities, a systematic and reproducible figure of merit must be established. Only in this manner are inhibiting characteristics methodically defined and removed from material specifications and processing operations.

The wafer cavity can be this short sample test where materials and processes are evaluated, by creating a reproducible environment. This allows for a more direct form of cavity evolution and as well as the possibility to test ideas that could cause a revolution. Such an idea is the heterostructure thin films described by Gurevich [1]. These layers effectively shield the Niobium substrate from the magnetic field, thereby potentially increasing the critical magnetic field limit by a factor of two while simultaneously enhancing the quality factor by four.

The Texas A&M group has designed a cavity to fit a "6 inch" wafer to provide adequate sample surface area and utilize the readily available deposition instrumentation from the chip industry. An ULVAC cluster tool has been obtained to facilitate the construction of these films to which the Wafer cavity will test their performance.

OTHER TEST CAVITES

Many (16 known to the author) cavities that test samples have been constructed in the past. Each of these cavities has its strengths and weaknesses. However there isn't a single one that has the ability to test large samples at high field with the sensitivity necessary to quantify the performance of advance heterostructures.

Three distinct cavities were major influences on the construction of the Wafer Cavity. The mushroom shape drew heavily from the group at SLAC [2]. Their cavity operates in a TE_{013} mode producing a field 1.75 times higher on the sample compared to the walls. Operating in a TE mode produces currents traveling azimuthally and thus avoids travelling across the joint between the walls and the sample. This copper cavity operates at 11GHz. This is well above the frequency space of future linear accelerators. Consequently, the wafer cavity design emphasized the necessity for a low S-band frequency near possible collider operating frequencies.

Slight alterations were made to the mushroom shape when a large sapphire was loaded into the center. Other TE cavities utilized sapphire but performed less than anticipated [3]. However research has shown the loss tangent can be as low as $2*10^{-10}$[4].

Two other cavities influenced the design through their coupling strategies. The Cornell cavity [5] inspired the coupling to the cavity with loops. This system was cemented in the design when a cavity P. Kneisel [6] worked on did not have many of the problems related to the coupling strategy which plagues many TE_{01} cavities.

WAFER TEST CAVITY DESIGN

The reentrant mushroom cavity design was combined with a large sapphire hung at the top of the cavities axis (Fig. 1). The sapphire acts as an electromagnetic lens focusing the field on the sample and pulling the field away from the Nb walls. Operating in the TE_{01} mode, the cavity's frequency is 1.3 GHz due to the dielectric loading. The size of the cavity and sapphire were determined to get the correct frequency and still be capable of utilizing the "6 inch" wafer as a sample medium.

In an effort to reduce complexity, the wafer test cavity components are simple or previously design pieces. The top of the mushroom is a half cell of a TESLA cavity. A cylinder comprises the walls with a circular ring

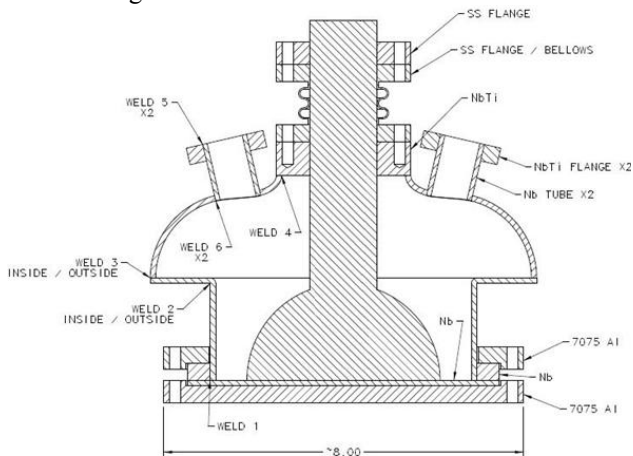connecting the walls and top together. A detailed sketch is shown in Fig. 1.

Figure 1: Wafer Cavity. The sapphire is hung a few mm's above the sample located at the bottom of the cavity. The sample is held by a mating bottom flange containing an array of resistors. The sapphire protrudes through the top, thus being submersed in the helium bath and stabilized by the pinch joint. The two side ports, located on upper part of the cavity, provide power and means for insertion of a probe antenna and vacuum port.
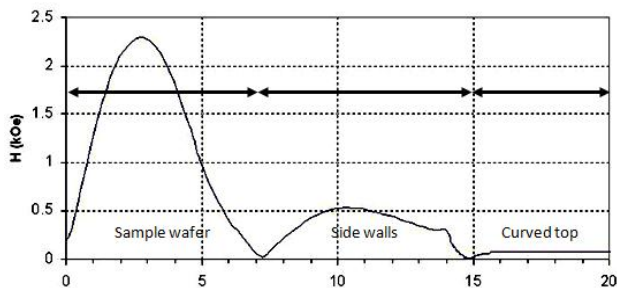

Figure 2: Wafer cavity magnetic field profile. The graph starts at the center of the sample and follows the contour of the cavity moving right across the joint, walls, and top.

The sapphire is suspended, using an indium "pinch" seal, above the sample surface by an adjustable Nb bellows. This secures the sapphire mechanically without the risk of fracture. The protruding sapphire is submersed in the superfluid helium bath keeping the sapphire, even at high field, cold. The indium seal not only holds the sapphire in place, but creates a barrier between the bath and interior of the cavity which is under vacuum.

To thermally map the heat generated from the sample an array of resistors will be located in the sample holder. This should allow the investigator to locate the areas of higher resistance and breakdown locations.

The sample field is 3.75 times the field seen by the wall surface (Fig. 3). The focused region is larger than any preceding cavity by an order of magnitude. At design capabilities (Nb walls reach BCS), the area held at BCS limit is 98 cm^2. At higher fields, the area reaching twice the BCS limit is 70 cm^2, and 49 cm^2 at 3 times BCS limit.

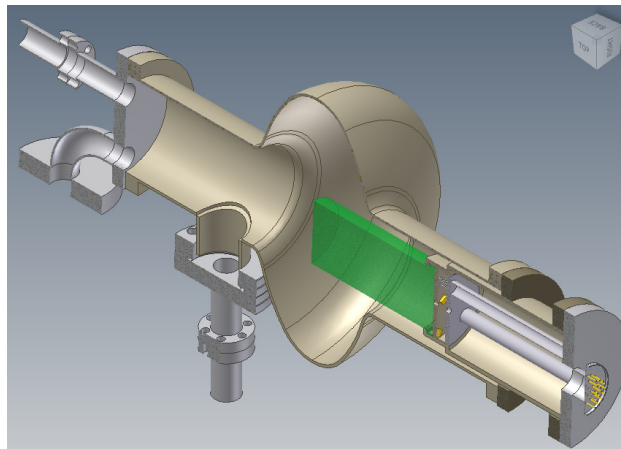Near the peak field, a large 17.5 cm^2 of sample area reaches 3.5 times the limit.

Figure 3: Sapphire Test cavity. The bottom face of the sapphire is located at the equator of the cavity and is held in place by a spring loaded disk pressing on the top of the sapphire. On the back of Nb disk are two resistors. These resistors are in thermal contact with the plate, sapphire, sapphire holder, and cavity walls using an indium ring seal for accurate internal temperature measurements.

SAPPHIRE MEASUREMENTS

The cavity performance will be highly dependent on the properties of the sapphire located at the heart of the cavity. Therefore a two inch diameter, four inch tall HEMEX ground finish (frosted appearance) sapphire was purchased from Crystal Systems. A CEBAF cavity and holder were constructed to suspend the sapphire inside the cell situated in the high field, as shown in Fig. 4.

The two ports, one on the side and another at the beam pipe, provided the entry for the drive and probe antennas. Over the course of the measurements, both ports were used for both antennas. A third port was attached to provide a vacuum line.

An initial test without the sapphire was performed to identify the TM_{010} mode with the drive port (hook) was located in the side port. The cavity had a Q_0 of $1.29*10^{10}$. The TE_{01} mode could not be found, but this test provided a background measurement for the cavity illustrating that any degradation is due to the loss tangent of the sapphire.

For the 2nd test the sapphire was cleaned with a recipe provided by NASA Jet Propulsion Lab and inserted in the cavity. The coupling was intentionally over-coupled to track the TE_{01} signal from room temperature to superfluid temperatures. This time the drive port (hook) was located on the end flange and the pick-up probe at the side port.

At 4.2 K the Q_0 of the cavity was $1.13*10^8$. This is a factor of 2.5 lower than the Q_0 of the empty cavity at the same temperature. At 2K the cavity began to multipact, but Q was measured to be $2.17*10^8$, which corresponds to a loss tangent of $4.6*10^{-9}$. NASA JPL produced a loss tangent of $1*10^{-9}$ on a crystal size approximately half the size of the one being tested [7]. Through modeling, the

frequency anticipated was verified experimentally, and determined dielectric constant used to be correct [8].

In the opinion of the author, the multipacting occurred due to an antenna extending to deeply in the cavity. The cavity antenna was removed and examined. The surface of the copper antenna exhibited sporadic speckling of black marks. The antenna was reduced by 2 cm, cleaned, and reinserted. The cavity was then closed without any cleaning for re-testing.

The 3rd test was worse ($Q_0=8.04*10^7$), however the multipacting ceased. Looking at the transmitted power signal, it was suggested by experts the problem was contamination. Such contamination could have been introduced by two different methods. The first pathway is during the coupler switch and the second could have been the off gassing of the varnish holding down the resistors, or the thermometers themselves.

In the 4th test, the cavity (no thermometry) was cleaned as well as the sapphire. The coupling was switched to the 1st test configuration and once again RF phase lock loop could not lock on the TE_{01} signal, it was too weak. The conclusion drawn is the driving antenna must be located on the end flange to obtain good coupling to the TE_{01} mode. The loaded Q could be measured with the network analyzer (NA). The NA had a limited resolution and therefore our loaded Q measurement beyond $1.8*10^8$ is highly unreliable. This does place Q once again in the same ballpark as the previous tests.
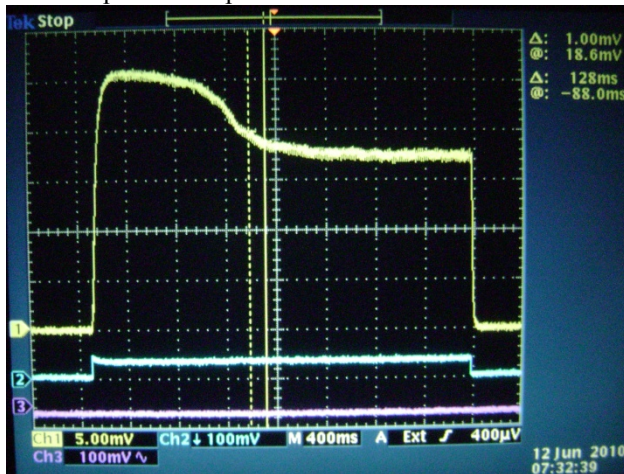

Figure 4: Above is a picture of the heating effect generated by the sapphire. The voltage, which is proportional to transmitted power, decreases as time progresses. This must be due to the sapphire heating. It takes approximately 400 μs for the heating to diminish the Q in this specific measurement.

The 5th test (no thermometry) produced a new phenomenon that was unexpected. At 2 K the sapphire began heating through the RF power being dissipated within. Once filled, the cavity's transmitted power decreases at around 400 ms, then levels off after 1.2 sec. Several measurements were taken at varying powers. On average the Q was $1.1*10^8$. As the power was gradually increased, the Q decreased as was the time required to heat the sapphire. It was quite difficult to obtain a decay measurement before the sapphire was able to heat. The equipment to perform such a measurement was not readily available.

The cavity was taken out and cleaned. Do to time constraints; the sapphire received only a BCP cleaning. The usual series of rinses with acetone, isopropanol, and ethanol were bypassed. After the high pressure rinse, the cavity was set out for drying and assembled in the same day. This time thermometers were attached to the backing plate using mechanical clamps. The 6th experiment was a failure. Using the NA, it was clear the Q was below $5*10^6$. No measurement was made with the RF system.

CONCLUSION

The first conclusion drawn is there is only one successful coupling strategy; hook at end flange and probe at side port. Second, the surface preparation on the sapphire is crucial. In general, runs where thermometry is present had lower Q. The 4th conclusion drawn is the dielectric constants of sapphire were confirmed accurate. Lastly, the loss tangent range is from $1.24*10^{-8}$ to $4.61*10^{-9}$. The most consistent value for the loss tangent of HEMEX sapphire measured was $8.7*10^{-9}$.

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