# A SAPPHIRE LOADED $TE_{011}$ CAVITY FOR SURFACE IMPEDANCE MEASUREMENTS – DESIGN, CONSTRUCTION, AND COMMISSIONING STATUS*

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*Abstract*

In order to measure the superconducting surface properties of niobium that are of interest to SRF applications, a facility which utilizes a Nb cavity operating in the $TE_{011}$ mode at 7.65 GHz which provides a well-defined RF field on a disk shaped sample has been designed and fabricated. The RF losses due to the sample's surface impedance are determined by using a calorimetric technique. The system has the capability to measure such properties as $R_s$,(T), and penetration depth, which can then be correlated with surface properties and preparation processes. The design, fabrication, and results from initial commissioning operations will be discussed, along with the near term sample evaluation program.

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## INTRODUCTION

The RF surface impedance ($R_s$) of niobium at surface magnetic fields in the range of 90 – 180 mT is a subject of much interest. Anomalous "Q-drop" is observed to occur frequently in this region in SRF cavities. That the onset of "Q-drop" is often increased or eliminated by mild thermal processing suggests that it is partially due to some aspect of surface chemistry perhaps in combination with surface roughness and other factors. It would be of great value to be able to subject a surface to microscopic analysis after having measured its RF performance with respect to superconducting properties as a function of surface magnetic field. The closed geometry of SRF cavities makes detailed analysis of the relevant surface very difficult.

A new RF test apparatus has been designed and constructed at JLAB for the express purpose of presenting high RF magnetic fields to flat sample surfaces under controlled cryogenic conditions so as to calorimetrically measure the surface impedance and allow correlations with surface analytic measurements of the same surface.

The apparatus uses a sapphire-loaded cylindrical niobium $TE_{011}$ cavity with a non-contacting endplate (Figures 1 and 2). Niobium coupons and niobium films, as well as interesting compound superconductors prepared by arbitrary techniques may be mounted and subjected to high RF fields and the thermal dissipation measured as a function of temperature. The apparatus has been constructed and is presently being commissioned.

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## DESIGN FEATURES

The $TE_{011}$ cavity mode has been chosen for two reasons:

- There are no RF currents crossing the joint (gap) between the end plate and cavity wall.
- There are no electric field lines terminating on cavity or sample surfaces simplifying the multipacting problem.

The cavity is sapphire loaded to keep the sample size small. RF fields are confined to a region of 10 mm radius from the center of the sample coupon. Sapphire has a high permittivity, high heat conductance, and low dielectric loss, making it possible to design a small RF cavity with a reasonably low frequency (7.5 GHz.).

RF losses are measured only on the flat sample plate which is easily bonded to the calorimeter and can later be detached for surface analysis. The thermal conductance of this bond must be such that the difference in temperature between the sample and the calorimeter is negligible. The attachment is made using gallium as the bonding agent ( m.p = 30 C.). This works well between two copper surfaces. For bulk niobium samples, the back of the sample is first ion etched and coated in-situ with 100 nm. of palladium before wetting with gallium. This measurement technique is sensitive to the sample surface only while being insensitive to other cavity losses. The calorimeter sub-system offers the following design features:

- Thermally isolated non-contacting endplate / sample holder
- Independent temperature control of sample holder and cavity
- Cu sample plate and Cu ring function as calorimeter allowing the temperature of the measurement (Cu ring) to be set at any desired value.
- Cernox® sensors (2 ea) on sample holder and Cu ring, readout using Lakeshore Model 218 Temperature Monitor
- Heaters (25W) on sample holder and Cu ring, independently operated, controlled using Lakeshore Model 332 Temperature Controller

Demountable samples can be examined by various forms of analytical instrumentation, and treated by any surface chemistry techniques.

Sample edges are not exposed to the RF fields through the use of a choke joint preventing anomalous heating from vortex entry at film edges.

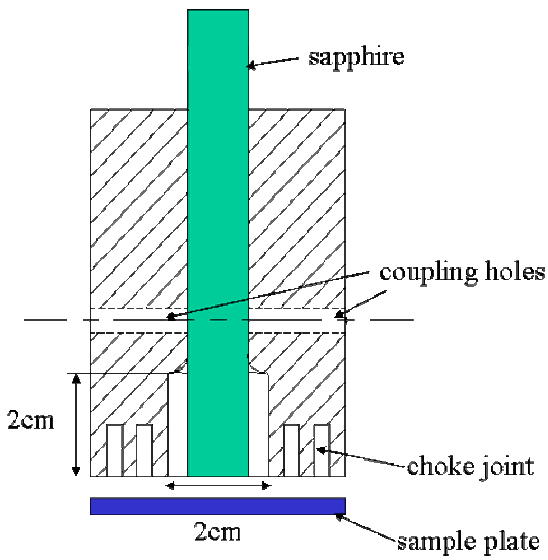


Figure 1.) Schematic of the $TE_{011}$ cavity geometry.

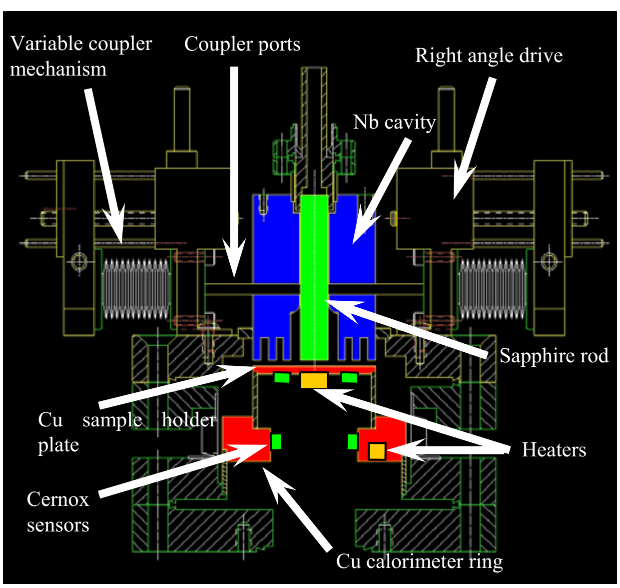


Figure 2). Schematic of $TE_{011}$ cavity and variable input coupler mechanisms.

## MEASUREMENT CAPABILITIES

It is highly desirable to measure the superconducting and RF properties of small samples subjected to highly localized processing or deposition conditions, the effects of which would otherwise only be known through an averaged contribution to a cavity test result.

It is also useful to be able to subject those same samples to surface analytical techniques in order to correlate those specific preparation conditions with RF performance, microstructure, and surface chemistry. A number of small sample test cavities have been developed for this purpose having differing features and range of application [1,2].

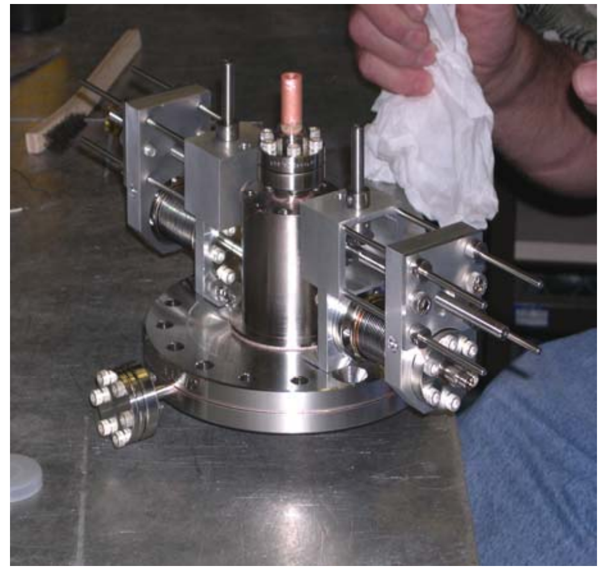

Figure 3.) $TE_{011}$ cavity and variable input coupler mechanisms.

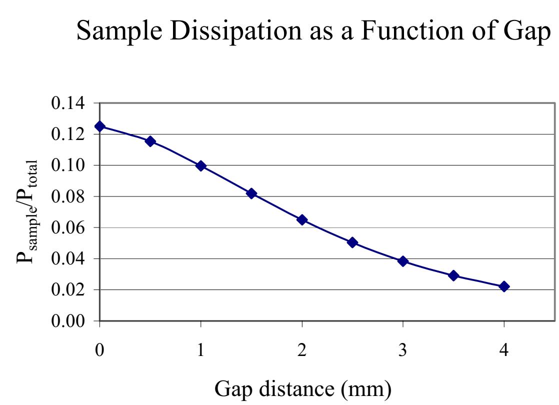


Figure 4.) The plot above gives the fraction of RF power dissipated in the SC sample, as a function of distance between sample and cavity, for fixed field.

Surface impedance can be measured as a function of temperature and field. The temperature of the copper calorimeter ring ( Figure 4) is set at a desired temperature and the duty cycle of the pulsed RF source is set to provide a small but accurately measured temperature rise for the field value selected.

The calorimeter sensitivity can be selected by the design of its support structure to operate at low values of field and $R_s$. In order avoid excessive excursions in temperature at high fields, the RF source is pulsed and the duty factor accurately measured.

The specific power dissipated by the sample, in Watts, is given by:

$$P_s = 3.7 \times 10^7 R_s B^2 \qquad (1)$$

where $R_s$ is in W, and B is in Tesla .

The temperature dependence of the penetration depth can be measured by choosing a low bath temperature for the cavity in order to saturate its penetration depth and sweeping the sample temperature near Tc while measuring the change in cavity frequency using a low field value. The sensitivity of this method is about 3 Hz. per Angstrom. The sample temperature can be swept rapidly many times over the same temperature range for data averaging without changing the bath temperature.

Provisions have also been made to apply a magnetic field parallel to the sample surface to look at surface impedance near Hc1. This requires the cavity to be in the normal state (~ 10 K) in order to get good field uniformity over the sample surface which can assume a temperature which is independent of the cavity. In this mode the calorimeter is not used other than to set the sample temperature and the cavity Q and FM noise is measured at low RF field levels as the applied DC field is varied through the onset of vortex entry into the surface. Surface roughness and a locally depressed Hc1 at the surface due to contamination can smear the onset. In the regime of vortex penetration a hysteresis effect in surface impedance can be seen with respect to increasing and decreasing field [4, 5]. The intent is to examine magnetically induced surface loss which are not affected by the vortex nucleation time at microwave frequencies. This method will be limited by the relatively low cavity Q and the magnitude of the surface impedance.

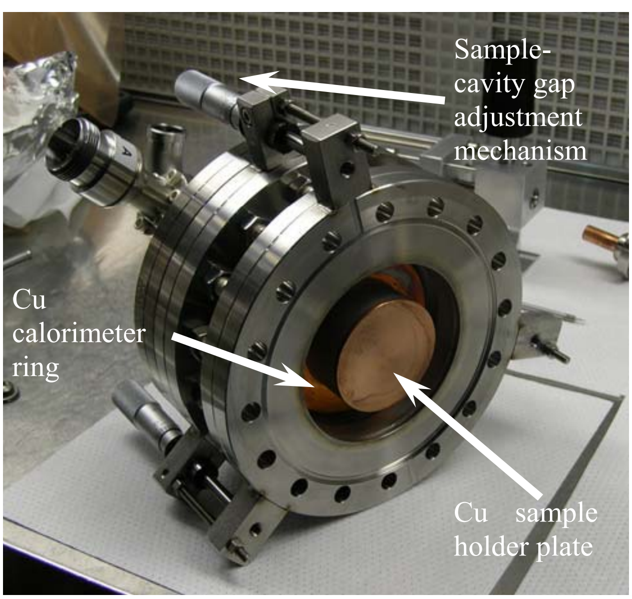


Figure 5.) Sample holder plate showing gap adjustment mechanism and Cu calorimeter ring.

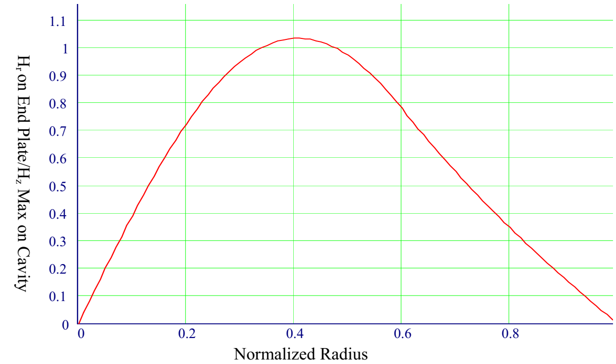


Figure 6.) Radial magnetic field (scaled by the maximum magnetic field of the cavity), whose integral over the sample surface gives the total power dissipated.

## CURRENT STATUS

The cavity and calorimeter have been completed and are currently being commissioned. One of the original concerns was that of coupling to other modes than the $TE_{011}$ due to deviations from azimuthal symmetry. The sample plate was made larger than the cavity in order to accommodate a double choke joint at the gap between the two. The $TE_{011}$ mode is well cut off in the sapphire rod exiting the cavity. A dipole mode has been found in the sapphire rod which is induced by the coupling ports and is not cut off. Its cutoff frequency can be shifted by grinding down a portion of the rod to eliminate the problem. In addition we also plan to couple to the cavity symmetrically through an annular gap instead of the existing coupling ports.

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