

SUPERCONDUCTING THIN FILM TEST CAVITY COMMISSIONING

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Abstract

A radiofrequency (RF) cavity and cryostat dedicated to the measurement of superconducting coatings at GHz frequencies was designed to evaluate surface resistive losses on a flat sample. The test cavity consists of two parts: a cylindrical half-cell made of bulk niobium (Nb) and a flat Nb disc. The two parts can be thermally and electrically isolated via a vacuum gap, whereas the electromagnetic fields are constrained through the use of RF chokes. Both parts are conduction cooled hence the cavity halves are suspended in vacuum during operation. The flat disc can be replaced with a sample, such as a Cu disc coated with a film of niobium or any other superconducting material. The RF test provides simple cavity Q-factor measurements as well as calorimetric measurements of the losses on the sample. The advantage of this method is the combination of a compact cavity with a simple planar sample. The paper describes the RF, mechanical and cryogenic design, and initial commissioning of the system with notes on how any issues arising are to be addressed.

CAVITY DESIGN

A use of a double-choked pillbox-type cavity for surface resistance measurements was described in [1].



Figure 1: A three-choked 8 GHz test cavity.

The main advantage of this setup is that it is not harmful to the sample or cavity as there is no need to provide a good electrical contact between the pillbox-like cavity and the studied surface because the electromagnetic field leakage is mitigated through use of RF chokes. A new three-choked cavity with improved leakage mitigation was used for this work and can be seen in Figure 1.

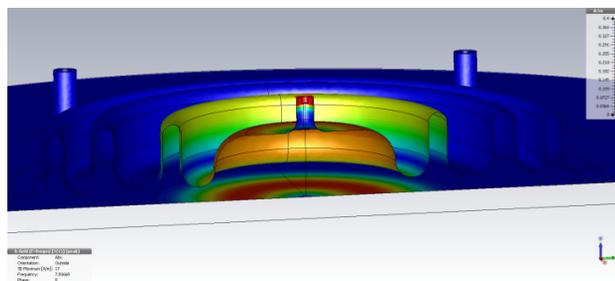


Figure 2: H-field distribution on the surface of the three choke cavity (top) and sample plate (bottom) simulated using CST [2].

The H-field distribution in the cavity can be seen in Figure 2. Final optimization of the chokes was done via measurement across the cavity diameter of the electric field in the cavity/sample gap (Figure 3.). The cavity was manufactured by Niowave Inc. [3].

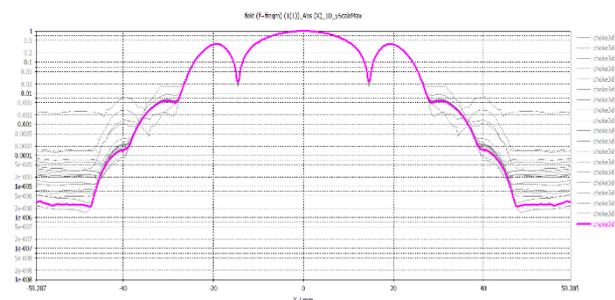


Figure 3: Optimisation of the 3rd choke depth using the normalised E-field amplitude as measured across the gap.

CRYOSTAT DESIGN AND ASSEMBLY

Cooling is provided by concentric LHe and LN₂ chambers, suspended from the steel top plate by thin-walled tubes (as shown on Figure 4). The ‘cradle assembly’ holding the test cavity and sample is bolted onto the bottom face of the LHe chamber, and covered by a steel vacuum can. A long neck passes through the centre of the LHe chamber, leading to warm ports for the RF cables and thermometry wiring. An aluminium thermal shield is attached to the LN₂ chamber, and both are covered with 30-layer aluminised Mylar MLI. The whole assembly is

covered by an aluminium outer vacuum chamber (OVC) at room temperature.

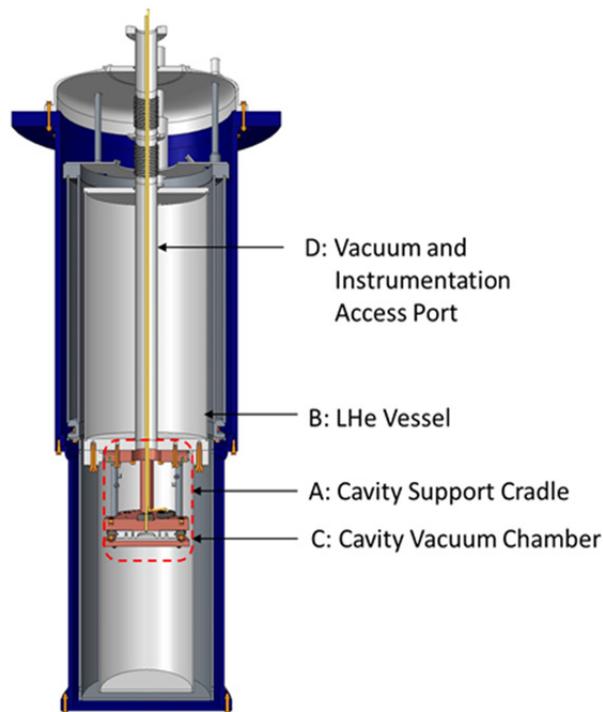


Figure 4: Schematic of the cryostat showing the helium vessel (B), access port for vacuum, tuner rod and instrumentation (D), and cavity attached to its support cradle (A) in the cavity vacuum chamber (C).

The OVC and sample chamber can be pumped separately or in tandem. There is also the capacity to pump on the LHe chamber to achieve temperatures of less than 4.2K, which has yet to be verified on our system.

In the cradle assembly (see Figure 5), the thermal contact has been improved between metal parts by placing indium foil at all joins – including that between the top plate and LHe chamber wall which is then compressed as the connecting bolts are tightened. The same is done between the cavity and its supporting plate. The exception is the sample, which because of the importance of good thermal contact between it and the sample plate has been prepared more thoroughly. Here, indium foil was placed between it and the sample plate and then pressure was applied with a heavy weight, placed on top of a gasket to evenly distribute the load around the outside of the sample plate. The sample was then heated to around 160°C using an electric hotplate, until the indium melted and thoroughly wetted both faces of the join. To prevent oxidation of the sample and/or seal, this was performed in a glovebox containing a high-purity N₂ atmosphere.

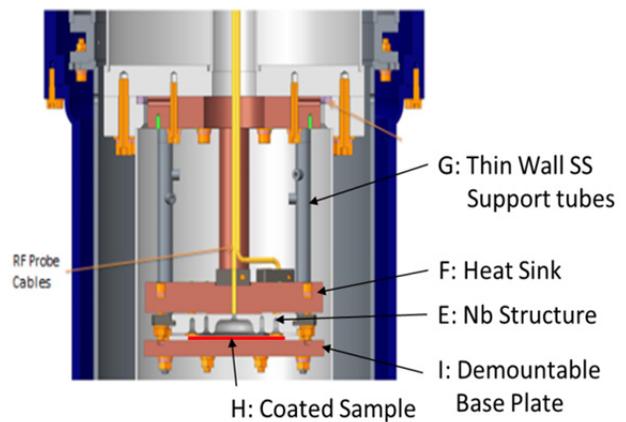


Figure 5: Schematic of the cradle showing the cavity (E) supported by the heat-sink (F). This is strongly coupled to the cold mass. The base-plate (I) supports the sample (H) and is weakly thermally coupled to the cold mass through the thin-walled supports (G).

To minimise heat leak via the RF cables, the majority of their length is made from semi-rigid UT-85 cable with stainless steel outer and inner surfaces. RF losses in this cable remain significant (~10dB per metre length), though its performance appeared to improve during the cryogenic test. A short loop of copper braid-coated RG402 cable connects to the warm RF ports, the input probe is made from copper-walled semi-rigid RG402 cable and the cavity probe from aluminium-walled RG405 semi-rigid cable connected with a short length of copper braid-coated RG405 cable.

MEASUREMENT METHOD

The RF power dissipated in the sample is to be measured via an adapted version of the power compensation method described in [4].

Silicon diode temperature sensors are placed on the top plate, cavity plate, sample plate and the sample itself. Although it may not be possible to attach a temperature sensor to the coated copper samples without compromising the film, for now it will help us map the heat flow through the assembly under power inputted from the heaters and/or RF, and tell us to what extent their effects can be assumed equivalent.

Resistive heaters (Four 12 Ω resistors wired in series) are screwed onto both the sample and cavity plates, evenly spread around a ring coaxial with the central axis of the assembly. At the warm end, these are connected to variable DC power supplies. It is intended that a small amount of current will bring the sample to an equilibrium temperature slightly above 4.2K. Applying RF input power will also cause the equilibrium sample temperature to rise due to dissipative losses at its surface. By turning the RF power back off and finding the increase in heater power needed to achieve the same equilibrium sample tempera-

ture, the RF power dissipated in the sample at that input level can be calculated.

The surface resistance R_s of a material may be defined via the power dissipated in it, P_s , and the magnetic field strength H at its surface. [5]

$$P_s = \frac{1}{2} R_s \iint |\mathbf{H}|^2 \cdot dS$$

Knowing this, and having a direct method of measuring the power dissipated in the sample via the power compensation method, an estimate of the surface resistance can be made. Reference [6] details how the surface resistance of the sample can be calculated via a measurement of the input and reflected power, (calculating power in the cables via off-band losses) the decay time of the induced resonance once the power is switched off (or the loaded Q-factor, measurable by e.g. the 3dB bandwidth of the transmission peak) and some material-independent geometrical cavity constants calculable using e.g. CST Microwave Studio.

RF Circuitry

The bandwidth of the cavity with a superconducting sample is expected to be extremely narrow at LHe temperature ($Q_0 > 10^6$). Therefore, a phase-locked loop will be necessary to keep the cavity on-resonance regardless of small fluctuations in its resonant frequency caused by mechanical vibrations. A custom-made RF circuit has been assembled to the design on page 161 of [5], using a field-programmable gate array (FPGA) and capable of forward, reflected and transmitted power measurements. Accurate power measurement is, as mentioned above, central to the accurate calculation of R_s . Currently, losses in the cables between the RF circuit and cavity (especially the steel-walled cables) and directional couplers look to be a major limit on its precision so the RF circuit is in the process of being upgraded with improved directionality and low loss input cables.

FIRST COOL-DOWN

A test run of the cryostat was carried out this August, using a copper sample plate to ensure there were no radiation concerns, as the testing bunker was still in preparation. A picture of the cryostat and controls is shown on Figure 6. A data logging application ensured all thermometer read-outs were monitored, as will the vacuum gauges when commissioning is complete. All chambers were vacuum-tested successfully. The cryostat was found to perform well, with minimal heat leak between the LN₂ shield and the inner volume as evidenced by very little (~1-2K) change in the temperature of the inner volume when the LN₂ volume was cold.

What may make the current assembly impractical for high-throughput use is the length of time required for initial cool-down of the sample and sample plate (>10 hours), due to the extremely long thermal path along the thin-walled steel supports. An attempt to accelerate the cooling by adding low-pressure GHe to thermalize it to the chamber walls created a thermal short to the warm ports and resulted in rapid LHe boil-off. In the future, the

whole assembly will initially be thermalized to LN₂ to minimize the cooling work required of the LHe. A cold valve would be needed to make thermalizing to LHe feasible, and while this is worth considering for the future it can only be a longer-term solution. In the meantime, a shorter thermal path between the sample and top plates – via thermal strapping, different support pillars, or both – looks to be the most immediate way of addressing the issue. However, this would result in a lower limit on the sensitivity of the calorimetric measurements.

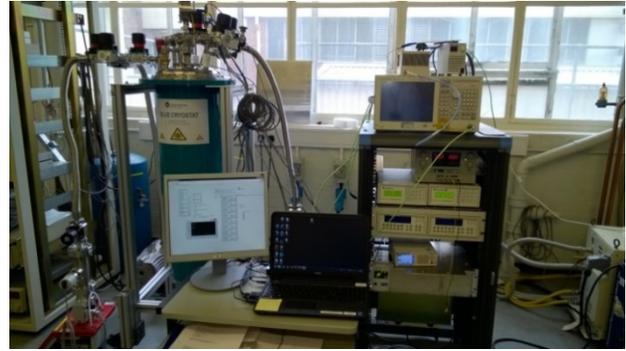


Figure 6: Experimental set-up in the cryogenics lab (un-shielded area).

Tuning

As the cavity and probe cool and their conductivities increase, the strength of coupling between the two increases. The intention is that the depth of the input RF probe can be adjusted in situ when cold, so that the cavity resonance can be tuned to near the point of critical coupling and it can be known whether it is under- or over-coupled at any given position. To achieve this, one of the warm ports holds a Vernier gauge which drives a rigid central ‘stalk’ of thin-walled steel tube aligned coaxially with the cavity and the various chambers. The RF input cable was initially clamped to this stalk slightly off-axis, and then given two 45° bends to position the probe as nearly coaxial as possible. However, the fact that the force was being applied off-axis meant that at a certain depth the probe jammed in position and was then bent by any subsequent force rather than moving further. The design has therefore been altered to clamp the input probe coaxially with the stalk, which should resolve the problem. For future developments, a small piezoelectric stage is being considered as an alternative.

FUTURE PLANS AND CONCLUSION

The commissioning will progress through October, and it is planned that a number of features will be added. The radiation-shielded area will be ready shortly, allowing the experiment to be relocated and a full niobium structure to be tested. The full phase-locked loop circuit will be tested on the cold cavity.

The next assembly will be performed in a cleanroom environment using a horizontal laminar flow, which provides an ISO 4 (class 10) atmosphere around the sample plate. Working to this cleanliness level will add a signifi-

cant level of complexity to the assembly but will be required to reach the higher Q-factors being aiming for.

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