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UPDATE ON CORNELL HIGH PULSED POWER SAMPLE HOST CAVITY*

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Abstract

The Cornell High Pulsed Power Sample Host Cavity (CHPPSHC) is designed to measure the temperature-dependent superheating fields of future SRF materials and thereby gain insights into the ultimate limits of their performance. Theoretical estimation of the superheating fields of SRF materials is challenging and mostly has been done for temperatures near the critical temperature or in the infinite kappa limit. Experimental data currently available is incomplete, and often impacted by material defects and their resulting thermal heating, preventing finding the fundamental limits of theses materials. The CHPPSHC system allows reaching RF fields in excess of half a Tesla within microseconds on material samples by utilizing high pulsed power, thereby outrunning thermal effects. We are principally interested in the superheating field of Nb_3Sn, a material of interest for the SRF community, and present here the current fabrication and assembly status of the CHPPSHC as well as early results.

INTRODUCTION

One of the major limitations on accelerator technology is improving the efficiency of Radio-Frequency (RF) cavities [1]. For superconducting RF (SRF) cavities, one of the paths of interest is alternative materials such as Nb_3Sn. The current standard niobium (Nb) SRF cavities have a critical temperature of 9 K and typically operate at 2 K in superfluid helium. The ultimate limit of Nb's accelerating gradient is ~ 55 MV/m in TESLA-geometry cavities. This value is determined by the superheating field of Nb, H_{sh}, which is approximately 200 mT at 2 K [2, 3]. In type II superconductors, the superheating field, H_{sh}, is the maximum magnetic field at which is the metastable state can exist.

Nb_3Sn, on the other hand, has a critical temperature of 18 K and can operate equivalently at 4.2 K in liquid helium. Operating in liquid helium at 4.2 K instead of in superfluid helium at 2 K would significantly reduce the construction and operational costs of an accelerator due to the reduced requirements in cryoplant facilities. It also opens up the possibility of conduction cooled cavities [4, 5] which would make small-scale accelerators more accessible for medical and industrial applications.

In addition to the exciting implications of a material with a higher critical temperature, Nb_3Sn has a predicted superheating field of ~ 440 mT at 4.2 K [6]. This corresponds to an accelerating gradient of ~ 100 MV/m – nearly double that of Nb.

The value of H_{sh} quoted for Nb_3Sn has not been confirmed experimentally yet. Previous tests have attempted to measure it before, but have run into various limitations [3, 7]. The Cornell High Pulsed Power Sample Host Cavity (CHPPSHC) is a sample host cavity designed for the specific purpose of probing the superheating fields of different Nb_3Sn recipes and other candidate SRF materials. It utilizes a 1 MW klystron and is geometrically optimized for high magnetic fields on the sample with the ability to reach up to approximately 0.5 T. Design, machining, and assembly of CHHPSHC have been completed and a commissioning test with a Nb sample has been performed.

COMMISSIONING

Design

A sample host cavity presents several benefits over standard single-cell TESLA geometry cavities. Single-cell TESLA cavities have a large surface area and complicated geometries. A sample has a much smaller surface area and a simpler geometry making it easier to test different materials. Another limiting factor is that while single-cell TESLA cavities can reach sufficiently high fields, they require tens of µs to fill with energy. The longer the filling time, the more likely that thermal effects will cause a premature quench. A custom designed cavity geometry would allow us to optimize for fast filling and high magnetic fields.

In order to ensure that CHPPSHC can reach high enough magnetic fields on the sample, it is optimized for a high ratio between peak magnetic field and the square root of energy stored in the cavity, or $\frac{B_{pk}}{\sqrt{U}}$.

Reaching high fields alone is not enough. The CHPPSHC also needed to be able to reach these fields on a timescale smaller than the spread of thermal effects to ensure that the sample quenches observed were due to fundamental material limits and not heating due to defects. The best way to do this is to ensure that the cavity charges, or "fills", with energy as quickly as possible [8, 9].

These design challenges are achieved through 3 main features: host structure geometry, sample geometry, and strong RF input coupling.

The CHPPSHC operates in a dipole mode. The magnetic field pattern and magnitude can be seen in Fig. 1a and the surface magnetic fields can be seen in Fig. 1b.

The sample is an ellipsoid shape with a sharp knife-edge that is oriented perpendicular to the magnetic fields in the cavity. This knife edge exploits field enhancement, a phenomenon where magnetic fields are magnified at sharp fea-

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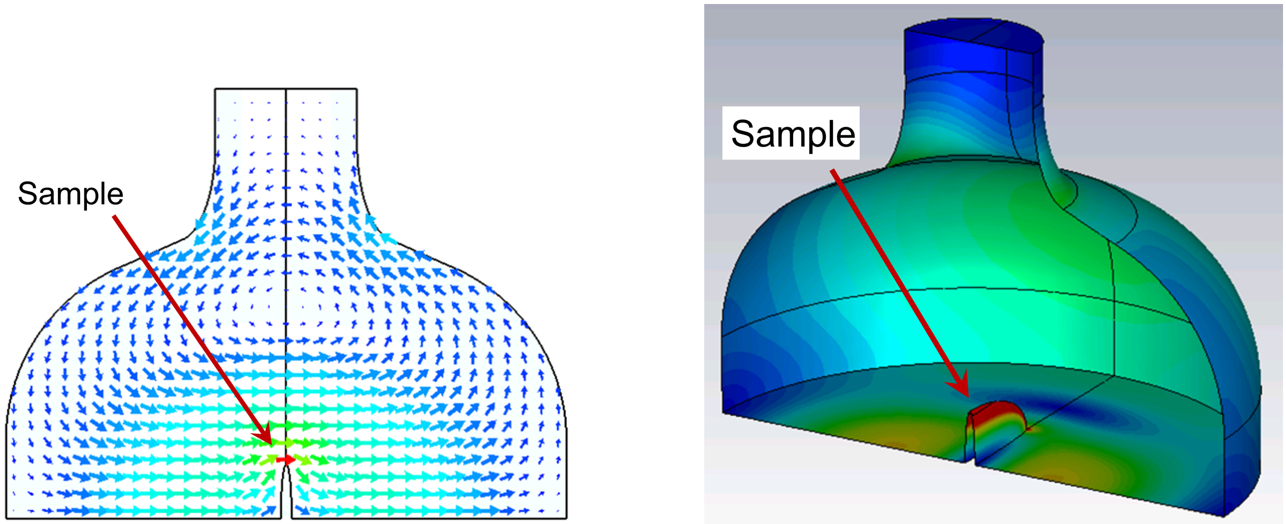

(a) Magnetic field simulations inside the CHPPSHC main cavity volume.

(b) Surface magnetic field simulation of the CHPPSHC.

Figure 1: Magnetic field simulations of the CHPPSHC [2].The cavity operates in a dipole mode and is optimized for high fields on the sample's surface. The design exploits field enhancement to reach higher fields on the sharp edge of the sample.

tures [10, 11]. The combination of optimized host structure and sample geometries ensures the highest possible field on the surface of the sample.

The third major design consideration, strong input power coupling, allows the cavity to fill faster. The klystron we have access to can put out pulses on µs – ms timescales. Thermal effects spread on the ms-timescale [2]. We are aiming to fill the cavity on the µs timescale. A coupling factor of 1 corresponds to the highest efficiency of energy transfer from coupler to cavity, however, by increasing the coupling above 1, the inital fill rate can be increased. This comes at the detriment of a lower maximum stored energy. The CHPPSHC was designed to have an adjustable coupling factor between 1 and 20. The final CAD model of the host cavity, sample, and coupler can be seen in Fig. 2.

The final design challenge to consider was how to detect sample quench. The solution we chose was to attach two Cernox cryogenic temperature sensors to the sample. These monitored small temperature fluctuations on the sample. A sample quench would be followed by a rise in temperature. However, the timescale of this temperature event would be several ms. The Lakeshore temperature monitors we had access to could not sample at a high enough rate to reliably detect a quench. We chose to use an oscilloscope to measure the small temperature fluctuations. The signal went through an amplifier of gain 10 and a 100 kHz low-pass filter to reduce noise.

Machining and Assembly

The main parts of the cavity were turned out of a solid copper block instead of forming them out of copper sheet due to the expensive and time-consuming process of making dies that would only be used once. The cavity parts were electron beam welded as shown in Fig. 3. Four Nb samples were fabricated. These will serve as the bases for different

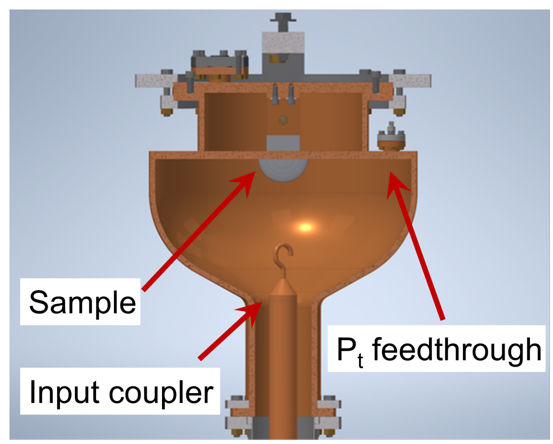

Figure 2: Finalized CAD design of full host structure, sample, and coupling antenna.

types of Nb_3Sn coatings in the future. One has already been coated using the standard Cornell coating of 3 µm Nb_3Sn as a witness sample to a cavity coating.

All components were cleaned and prepared for assembly in a class 100 cleanroom environment. Prior to final cleaning, the Nb samples were electropolished and baked at 800 C. In the cleanroom, all RF surfaces were cleaned in an ultrasonic and rinsed with methanol except for the main cavity "bell", which was high-pressure rinsed with deionized water and dried with high-purity nitrogen to mitigate oxidation.

A Nb sample was assembled to the top plate as shown in Fig. 4. Two Cernox cryogenic temperature sensors were adhered to the sample with a thin layer of indium to increase thermal contact.

The cavity was assembled to a test insert with a waveguide for pulsed power operation. The insert and waveguide were both pumped down and held at a vacuum on the order of 10^{-8} Torr. The insert was verified to be leak tight and

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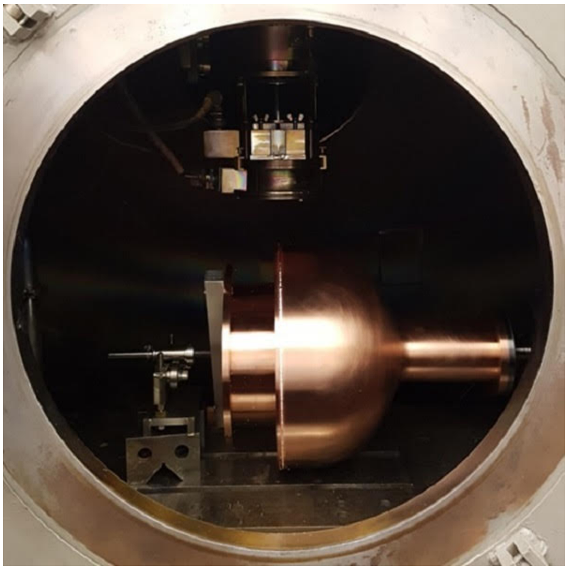

Figure 3: A photo of the cavity host structure in our electron beam welder after the final seam was finished.

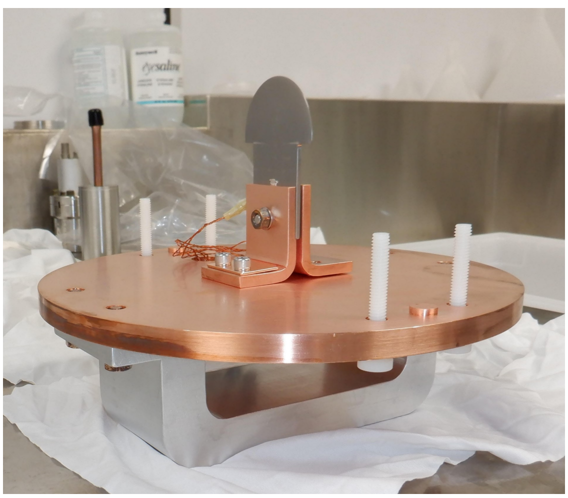

Figure 4: A photo of the Nb sample assembled to the cavity top plate in the cleanroom in preparation for final cavity assembly. A small amount of indium is used to adhere two Cernox cryogenic temperature sensors (not shown) to the sample to monitor absolute temperature and temperature fluctuations on the ms timescale.

removed from the cleanroom for final preparations. External instrumentation was attached to the insert, most notably two Cernox cryogenic temperature sensors for monitoring the temperature of the helium bath.

The final assembly of the insert before being lowered into the cryostat can be seen in Fig. 5.

FIRST PULSED POWER TEST

Measurements

The goal of the first test was to validate the CHPPSHC's functionality. A Nb sample was chosen for this test because the superheating field is reasonably well known, which would allow us to identify any problems with the system if the results did not align with our expectations.

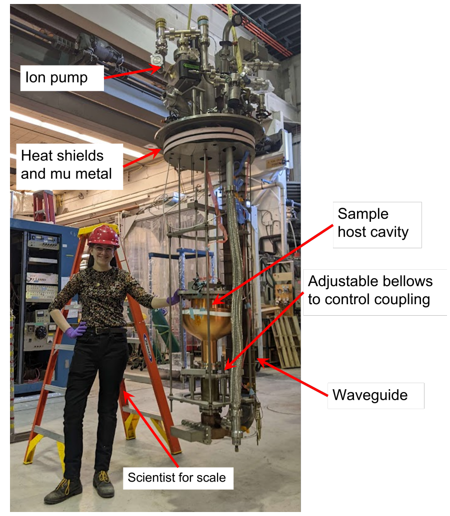

Figure 5: The final assembly of the CHHPSHC with all external instrumentation before being lowered into the cryostat for cold RF testing. The cavity and waveguide vacuum volumes are kept at pressures on the order of 10^{-8} Torr with ion pumps. The insert is designed for variable coupling and has a waveguide that directs pulsed RF power to the cavity. Scientist for scale.

After preparation was complete, the assembled insert was transferred to a cryostat. This cryostat was filled with liquid helium (LHe) to maintain a testing temperature of 4.2 K. The klystron was used to send pulses of power to the cavity. These pulses were set to be of 10 µs to 20 µs long with amplitudes starting at a few kWs. The amplitude of the forward power was gradually ramped up to values as high as 150 kW. This value is far lower than the maximum 1 MW output of the klystron, however these forward powers were sufficient for a commissioning test with a Nb sample.

Forward power from the klystron, power reflected from the cavity, and power transmitted through the cavity were recorded using Boonton power meters. Absolute temperatures of the LHe bath and Nb sample were recorded on a Lakeshore temperature monitor. An oscilloscope was used to measure ms-scale temperature changes of the Nb sample.

Several decay curve measurements were done with the CW system to determine the coupling factor and loaded quality factor.

Analysis

Using the forward and transmitted powers (P_f and P_t respectively), we can calculate the peak magnetic field on the sample (B_{pk}) and energy stored in the cavity (U). We know from simulations [2] that

$$\frac{B_{pk}}{\sqrt{U}} = 450\,\frac{\text{mT}}{\sqrt{\text{J}}}\,. \quad (1)$$

Simulations were run to determine how much sample position affected the peak fields on the sample surface [2].

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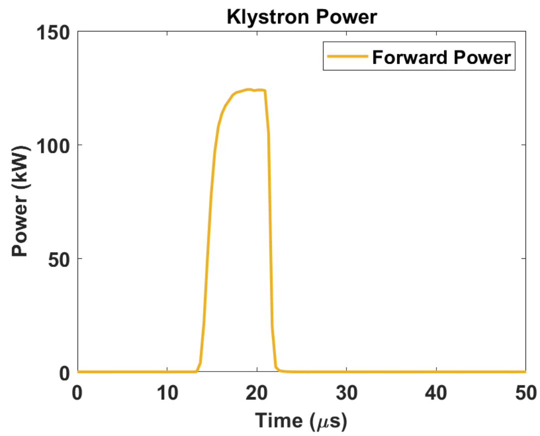
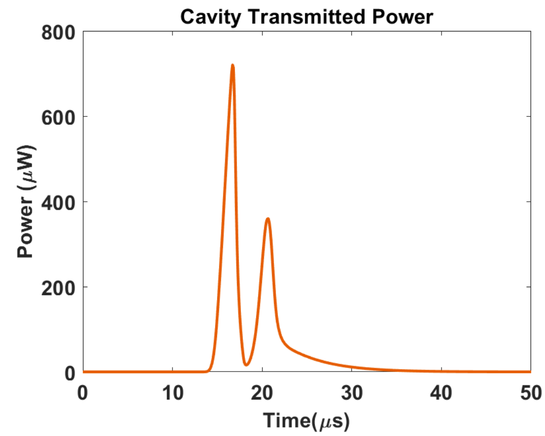
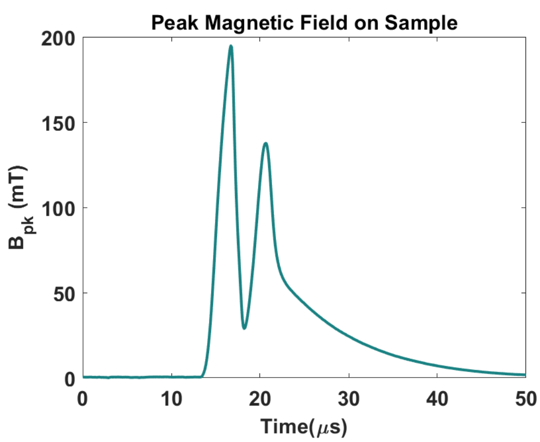


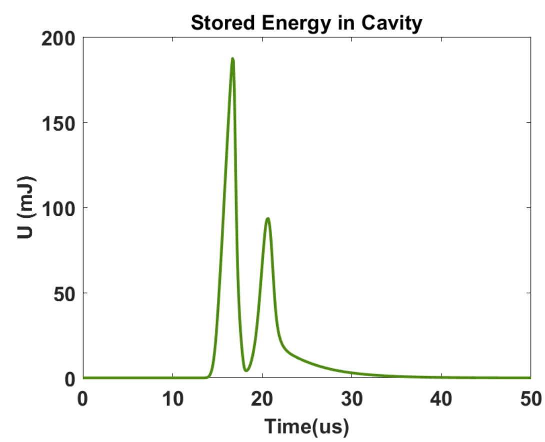
(a) Forward power from the klystron. Maximum power is approximately 124 kW and duration is approximately 15 µs.



(b) Transmitted power through the cavity. The transmitted power is proportional to the stored energy in the cavity and the peak magnetic field squared.



(c) Peak magnetic field (B_{pk}) on the Nb sample. It reaches a maximum value of 195 mT before quench occurs.



(d) Energy stored in the cavity over the course of an RF pulse.

Figure 6: Power measurements from an RF pulse at 4.2 K and calculated peak magnetic field and stored energy. Quench occurs on the sample at $t = 16.7$ µs characterized by the sharp drop in P_t, B_{pk}, and U.

450 mT is a conservative value based on these simulations We also know that the stored energy at steady state is given by [1]

$$U_{\text{steady state}} = \frac{4P_f Q_L}{\omega_0}\,, \tag{2}$$

where Q_L is the loaded quality factor and ω_0 is the cavity resonant frequency. The ratio between B_{pk} and $\sqrt{P_t}$ is also constant:

$$\frac{B_{pk,1}}{\sqrt{P_{t,1}}} = \frac{B_{pk,2}}{\sqrt{P_{t,2}}}\,. \tag{3}$$

We can combine Eqs. (1), (2), and (3) to get a relationship between B_{pk} in mT and P_t at an arbitrary time:

$$B_{pk}(t)[\text{mT}] = 450\left[\frac{\text{mT}}{\sqrt{\text{J}}}\right]\sqrt{\frac{4Q_L}{\omega_0}\frac{P_{f,cal}}{P_{t,cal}}P_t(t)}\,, \tag{4}$$

where $P_{f,\,cal}$ and $P_{t,\,cal}$ are power values from a pulse where the cavity filled to steady state and did not quench.

Returning to Eq. (1), we can use $B_{pk}(t)$ to find $U(t)$:

$$U(t) = \left(\frac{B_{pk}(t)}{450\;[\text{mT}/\sqrt{\text{J}}]}\right)^2\,. \tag{5}$$

The forward and transmitted power for an example pulse can be seen in Fig. 6a and Fig. 6b respectively. The corresponding B_{pk} and U are shown in Fig. 6c and Fig. 6d. Sample temperature data from the same pulse is shown in Fig. 7.

Discussion

Examining the plots shown in Fig. 6, we see that there is a clear drop in transmitted power, and thus B_{pk} and U, at approximately 16.7 µs. This indicates a quench on the Nb sample. The peak magnetic field on the sample before quench is approximately 195 mT. This falls within the expected range for Nb shown in Fig. 8 that has been electropolished and baked at 800 C [3].

In Fig. 7, there is a sharp spike when the RF is on and then a gap before the actual temperature rise of the sample

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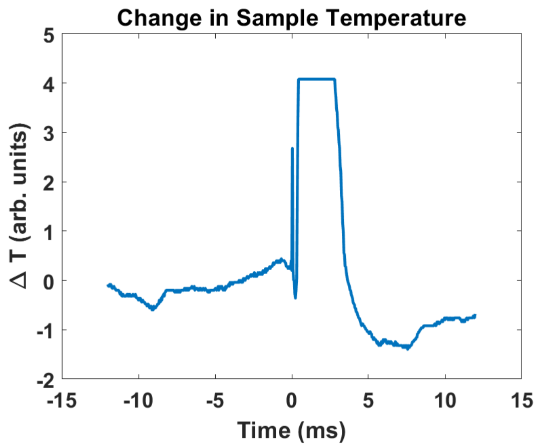

Figure 7: Sample temperature change over several ms. There is a small spike due to the RF pulse before the larger spike due to actual temperature fluctuations. The upper limit of the temperature event is cut off due to the amplifier in our system

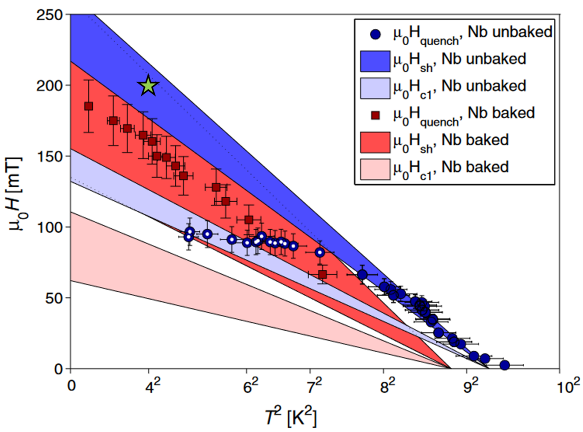

Figure 8: Critical magnetic fields for baked and un-baked Nb [3] including theoretical ranges (solid ranges) and experimental data. The peak magnetic field on the sample for the RF pulse shown in Fig. 6 is marked with a green star.

happens, which allows us to see the delay in thermal events. This is a promising result – it shows that the CHPPSHC is capable of fulfilling its purpose of quenching a superconducting sample with magnetic fields on timescales short enough to outrun thermal effects.

An additional consideration that must be made is for "overfilling" the cavity, meaning that the cavity (or in this case, the sample) quenches, but the RF pulse continues putting power into the system [8]. Looking for drops in the intrinsic quality factor as a function of time will determine if this phenomenon is affecting the RF data. This investigation is underway but not yet completed.

CONCLUSION

The first test of the CHHPSHC was a success. The system met all of it's design goals including high magnetic fields on the sample, fast filling time, and outrunning thermal effects to achieve its goal of sample quench due to the fundamental magnetic field limit of the sample. After many months of design, machining, and assembly, the cavity was tested with pulsed power at 4.2 K for the first time with a Nb sample. This sample underwent the standard preparation of electropolish and bake at 800 C. The test indicated a quench field of 195 mT which is within the established range for Nb [3].

FUTURE WORK

The commissioning test of the CHPPSHC with Nb is only the beginning. The system was designed with Nb_3Sn in mind from the start. Several follow-up tests with the Nb sample are needed to corroborate the results of the first, including tests at varied temperatures from 2 K up to Nb's critical temperature. With a solid foundation of Nb tests, the CHPPSHC will be used to test different Nb_3Sn coatings, including variations on thermal vapor deposition, electroplating, and chemical vapor deposition. The modular design of a sample host cavity will also allow us to test other SRF candidate materials in the future.

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