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REBCO SAMPLE TESTING AT HIGH POWER X-BAND

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Abstract

SRF materials such as niobium have been extremely useful for accelerator technology but require low temperature operation ~2 K. The development of high temperature superconductors (HTS) is promising due to their operating temperatures being closer to that of liquid nitrogen ~77 K. This work aims to determine the high-power RF performance of such materials at X-band (11.424 GHz). We have tested two kinds of REBCO coatings, a film deposited by electron-beam physical vapor deposition and coated conductors soldered to the copper substrate. Testing was done in a hemispherical TE mode cavity due to its ability to maximize the magnetic field on the sample and minimize electric field. We will report on conductivity vs temperature measurements at low and high power. We have only observed quenching at temperatures above 80 K, very close to the material's critical temperature.

INTRODUCTION

Superconducting materials such as niobium (Nb) have been extremely useful for RF cavity technology but require low temperatures for operation ~ 2-4 K [1–3]. The development of high temperature superconductors (HTS) is promising due to their transition temperature in excess of 80 K. HTS cavities could be cooled by liquid nitrogen versus liquid helium which is expensive to operate and much more expensive to build due to the additional cryogenic infrastructure. Nb structures have been able to show conductivity >10 GS/m [4] at 4 K compared to room temperature normal conducting copper structures that typically have conductivity $\sigma \approx 100$ MS/m [5].

The drawback of using any superconductor are limitations on the induced surface magnetic field which can cause the structure to quench. This normally limits the gradient of Nb structures to gradients on the order of 35 MV/m [1–3]. This is close to an order of magnitude less than their normal conducting counterparts that can operate at gradients in excess 200 MV/m [6,7]. Structures coated with HTS materials could be used as high Q devices such as linearizers, deflector cells, axion cavities, and pulse compressors [8]. Rare earth barium copper oxides (REBCO) are particularly interesting because their critical temperature of approximately ~90 K which exceeds the 77 K operating range of these devices. Furthermore, REBCO is commercially available as 2G coated conductors (CC) and in constant development in form of other coatings, making it suitable for resonant structures. Thus it is vital to understand the quench limitations of REBCO in order to utilize them for RF cavities.

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SAMPLE FABRICATION

Two distinct REBCO samples with different coating techniques and surface treatments were subjected to testing. The first coating technique, illustrated in Figure 1, utilized commercially available 2D coated conductors from Fujikura that were 12 mm wide. In this scenario, numerous CCs were initially soldered onto a copper disc, followed by delamination between the REBCO and buffer film [9]. This approach resulted in the REBCO being the topmost layer.

For the second sample, the REBCO was deposited via electron-beam physical vapor deposition with inclined substrate deposition, covering the entire surface of the copper disc. A MgO buffer layer was first thermally evaporated and reactively grown on the copper substrate, which was tilted by approximately 30°. The REBCO then nucleated on the inclined MgO plane, resulting in the REBCO *c*-axis having an inclination angle of approximately 30°, as depicted in Figure 1 [10].

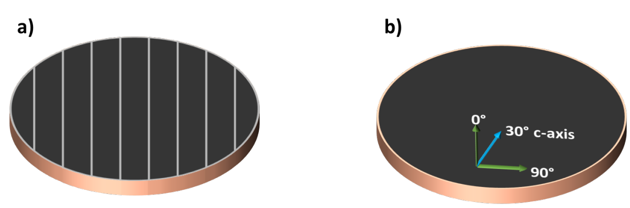

Figure 1: Sketch of the samples: (a) soldered REBCO-CCs on copper and (b) directly grown on copper with a MgO buffer layer.

HIGH POWER CRYOGENIC TEST STAND

Samples were tested at low and high power in a hemispherical cavity designed to have a TE_{023} mode so that the electric field on the sample surface is negligible while the magnetic field is maximized across the sample to better induce quenching within the sample. The hemispherical cavity is coupled into a TE_{01} circular waveguide that can also be connected to a 2.5 kW X-band traveling wave tube (TWT) that can provide up to 8 µs pulse length. A schematic of the hemispherical cavity installed in the experimental high bay can be seen in Fig. 2. The measurement plane is approximately 3 m away from the sample [4].

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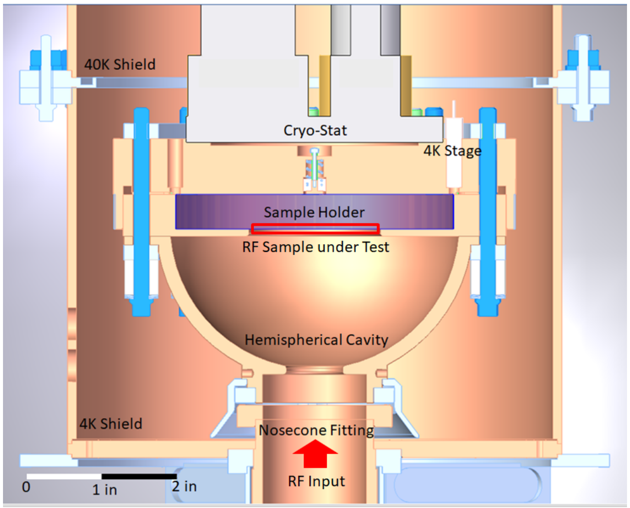


Figure 2: Schematic of Test Stand.

HIGH POWER MEASUREMENTS

The quality factor of the REBCO sample (Q_s) can be obtained from previous cold test measurements which experimentally determined the intrinsic quality factor of the cavity (Q_{cav}) [11]. These measurements also showed that the external quality factor (Q_e) is fairly constant throughout the temperature range of interest. This means for a given reflected pulse on resonance with total quality factor Q_t, Q_s can be determined based on the following equation:

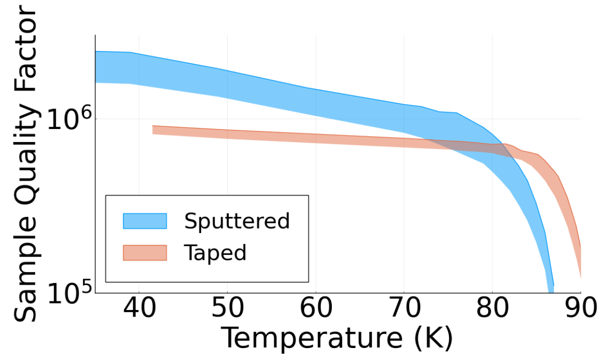
$$\frac{1}{Q_s} = \frac{1}{Q_t} - \frac{1}{Q_{cav}} - \frac{1}{Q_e}. \tag{1}$$

Where Q_s can be used to derive the RF conductivity of the sample (σ_s) by using a reference conductivity σ_{ref} and then using HFSS simulations to determine a reference $Q_{s,ref}$ for the cavity. Based on the fact that Q $\propto \sqrt{\sigma}$, we can find the equivalent sample conductivity from

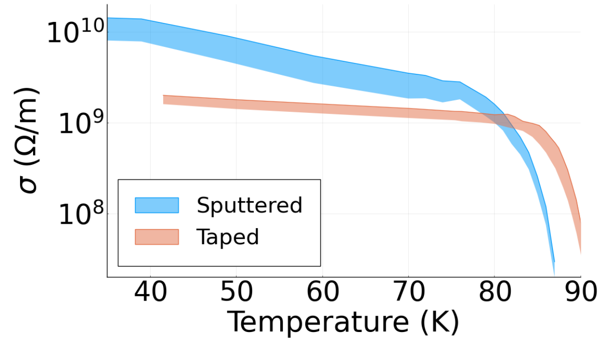
$$\sigma_s = \sigma_{ref}\left(\frac{Q_s}{Q_{s,ref}}\right)^2. \tag{2}$$

Due to the use of the TWT's isolator, the high power RF measurements were limited to only 1.6 kW of maximum power. However this proved sufficient to see evidence of quenching occurring while operating within a few degrees of the critical temperature. Measurements were conducted by slowly heating the sample up from 4 K and measuring the forward and reflected power through Keysight N1912A power meters. These power meters could be used to measure the magnitude of the forward power, as well as record the reflected power pulse shape in order to measure the total quality factor of the cavity. Forward power was ramped up at each temperature step from 100 W to 1600 W, in order to better ascertain how quickly the REBCO samples would quench as a function of applied power.

To determine the total quality factor of the cavity, the tail end of the reflected pulse in dBm was fit to a line, with slope of the line m being inversely proportional to the quality factor



(a)



(b)

Figure 3: Plots of sample quality factor (a) and conductivity for both REBCO samples, with the shaded regions showing range of values for forward powers between 100 W and 1600 W.

based on $Q_t = -\pi f_0/m$, where f_0 is the resonant frequency of the cavity in MHz, and based on this total quality factor we can extract the contribution of the superconducting sample and conductivity as shown in Equations 1 and 2. These results are summarized in Figures 3a and 3b. While the sputtered samples are able to reach higher conductivities closer to the bulk values, they also are more drastically affected by forward power and hit a critical limit closer to 86 K instead of the expected critical temperature of 89 K. However in order to properly understand the quenching mechanism for these samples, we would need to study in more detail how quickly quenching begins within the samples.

Quenching occurs as regions of the superconductor revert back to normal conducting, causing a dramatically sharp decline in conductivity and quality factor. This is seen as a increase in time constant of the reflected power's exponential decay, as shown in Figure 4, where quenching is observed at higher forward powers. However another earlier sign of the onset of quenching can be found by looking at the first peak of reflected pulse. As quenching begins to occur the slope of this line deviates from linearity, implying that the quality factor of the cavity is changing as a function of time. Indeed if we fit this slope with a time dependent term for Q_0, we are able to fit these anomalous decays. By identifying

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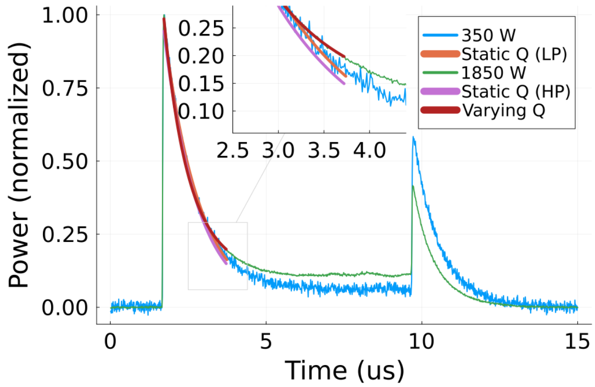

Figure 4: Comparison of reflected power trace with and without quenching. At low power (blue), the reflected trace has a lower decay time constant as compared with the high power trace (green). The assumption that the quality factor is constant fits this decay accurately (orange). However in the high power case, the static assumption (purple) undershoots the reflected power (insert) requiring the fit to account for a time-varying Q model to fit correctly (red).

at which powers and temperatures these deviations become significant, the minimum power for quenching for a given temperature can be identified, as shown in Figure 5.

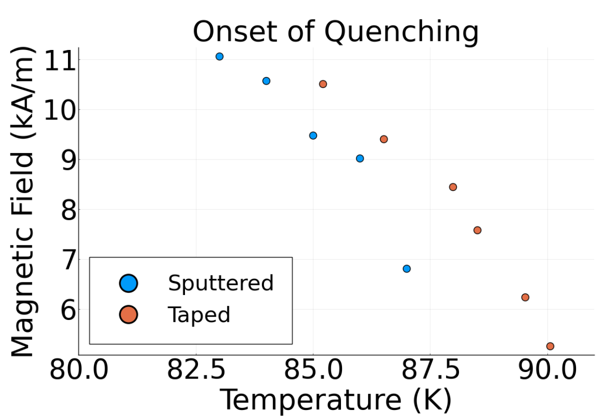

Figure 5: Scatter plot showing the minimum surface magnetic field needed to begin the onset of quenching withing each REBCO sample.

As with Figure 3 above, the sputtered sample reaches a critical limit sooner, but the overall slope is similar for both samples. This implies that the relation between surface current and quench temperature may be linear. This would mean that the quench was occurring primarily to the samples reaching a critical current limit, as opposed to a critical temperature limit. Based on pulsed surface heating models, we expect the average temperature rise within the sample to be no more than 0.1 K [7]. However, this does not account for any hot spots that may occur from gaps, surface impurities, or areas of bad electrical or thermal conductivity. Understanding these limits and mechanisms behind them will be the subject of future study as these experiments continue to higher power levels.

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