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REBCO SAMPLE TESTING FOR A HTS HIGH Q CAVITY

M. E. Schneider*, G. P. Le Sage, A. Dhar, E. A. Nanni,
SLAC National Accelerator Laboratory, Menlo Park, California, USA
J. Golm, P. Krkotić, W. Wuensch, S. Calatroni, CERN, Geneva, Switzerland
J. Gutierrez , ICMAB-CSIC, Barcelona, Spain

Abstract

This work aims to explore the high-power RF performance of high temperature superconducting materials at X-band (11.424 GHz). We tested two kinds of rare earth barium copper oxide (REBCO) coatings. One was applied with a film deposition and the other with a soldered tape, both on a copper substrate. Testing was done in a hemispherical cavity with a TE mode due to its ability to maximize the magnetic field on the sample. These REBCO samples has conductivity on the order of 10 GS/m which was more than an order of magnitude greater than copper samples. These measurements were then used to find the design parameters for a full 3D cavity that is to be coated with REBCO.

INTRODUCTION

Superconducting materials such as Niobium (Nb) have been extremely useful for RF accelerator 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 accelerators 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 Nb is that, unlike copper room temperature structures where the gradient is limited by breakdowns caused by high peak surface fields, the limiting factors in superconducting accelerating structures are the high induced magnetic field which causes 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 made or coated with HTS materials could be used as accelerating structures themselves, but their main use may be in high Q devices such as linearizers, deflector cells, and pulse compressors.

REBCO can be used as its critical temperature of ~90 K is above the 77K operating regime of these devices and can be easily formed into tapes and other coatings for accelerating structures.

* mitchs@slac.stanford.edu

REBCO DISCS FABRICATION PROCESS

Two distinct REBCO samples with different coating techniques and surface treatments were subjected to testing. The first coating technique, illustrated in Fig. 1a), utilised commercially available 2D coated conductors (CC) 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 [8]. This approach resulted in the REBCO being the topmost layer.

For the second sample, the REBCO was deposited via electron-beam physical vapour 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 Fig. 1b) [9].

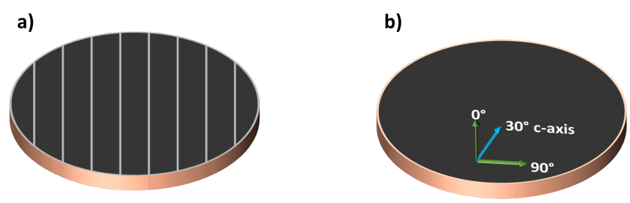

Figure 1: Sketch of the samples: a) soldered REBCO-CCs on copper and b) directly grown REBCO on MgO on copper.

SLAC TESTING FACILITY

Samples were tested at lowe power in a hemispherical cavity designed to have a TE_{23} mode so that the electric field on the sample surface is negligible while the magnetic field is maximized across the surface to be able to measure the quench field of the sample. The hemispherical cavity is coupled into a TE_{11} circular waveguide that can also be connected to a 50 MW X-band klystron (11.424 GHz) that can provide up to 2 µs pulse length. Due to the power constraints of the two-stage cryostat, a maximum of only 1 MW can be put into the cavity. 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 from the sample [4].

COLD TEST RESULTS

The Quality factor of the REBCO sample (Q_s) can be obtained form cold test measurements by obtaining the intrinsic quality factor (Q_0). which is a combination of Q_s and

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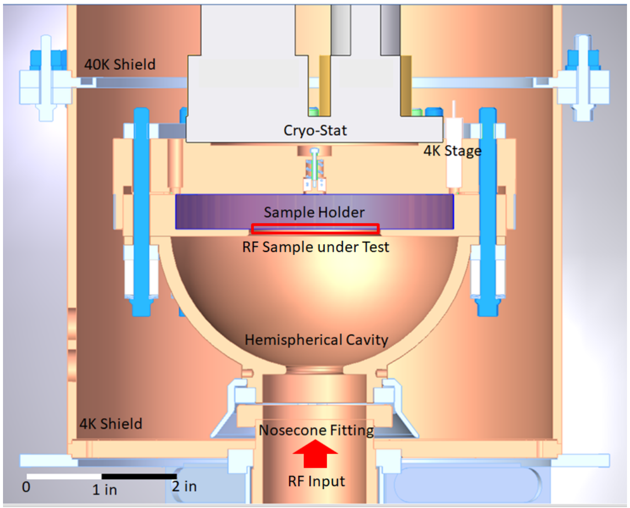

Figure 2: Schematic of Test Stand.

Q of the cavity (Q_{cav}) in Eq. (1). Q_0 is derived from a Q circle fit of the complex S_{11}) reflection coefficient.

$$\frac{1}{Q_0} = \frac{1}{Q_s} + \frac{1}{Q_{cav}} \tag{1}$$

Where Q_s can be used to derive the RF conductivity of the sample (σ_s) using a reference conductivity σ_{ref} then HFSS can be used to find a reference $Q_{s,ref}$. knowing that Q $\propto \sqrt{\sigma}$ then the σ_s is Eq. (2):

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

To determine the Q_{cav}, we tested a Nb and Cu sample. As the Nb is at 4K, we treat the Nb sample as a perfect conductor meaning that the $Q_0 \approx Q_{cav}$ due to $Q_{s,Nb} \gg Q_{cav}$ where the Q_{cav} at 4K is $1.9375{\times}10^5$. The Cu sample can to used to derive the functional form for Q_{cav}(Temp.) by fitting the Q_0(Temp.) as Q_{cav}(Temp.) = c$\times Q_0$(Temp.) where c is a constant. As the Bloch-Gruneisen law shows that the conductivity of the sample and the cavity are the same, the functional form is the same but scaled by a constant, see Fig. 3a. The Bloch-Gruneisen equation and the National Institute of Standards show that Q_0(Temp.) can be described by a modified logistics equation in Eq. (3) [5]:

$$Q_0(Temp.) = A + \frac{(K-A) * Temp^{\beta}}{(1 + C * Exp^{-B*Temp})^{\alpha}} \tag{3}$$

Where A represents the upper asymptotic limit, K represents the lower asymptotic limit and K, B, C, α, β are our fitting coefficients. A is a constrained parameter defined by Eq. (4) and y_0 is also a fitting parameter.

$$A = \frac{(1 + C)^{\alpha} * y_0 - K}{(1 + C)^{\alpha} - 1} \tag{4}$$

By fitting the Q_0(Temp.) for Cu (see Fig. 3b) with the corresponding difference between the measured and fitted data (see Fig. 3c) and combining with the Nb results allows

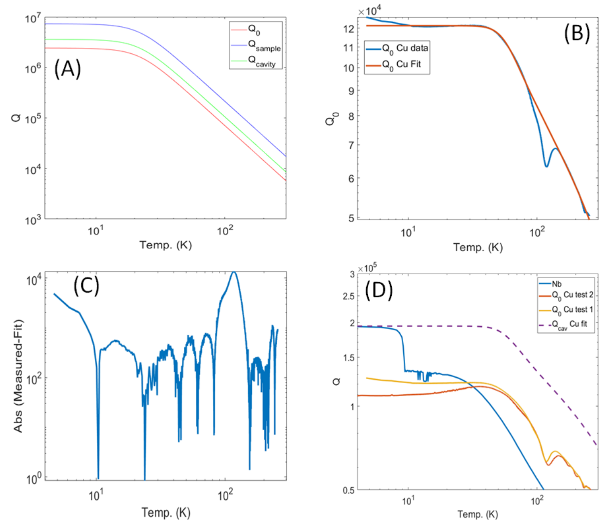

Figure 3: (A) Q_0, Q_{cav}, Q_s form HFSS simulation from using the conductivity at a given temperature derived from Bloch-Gruneisen. (B) Fitting Q_0(Temp.) from Eq.(3) and Eq.(4) for Cu data,(C) the difference between measured and fit v. Temp. (D) Q_0 (Temp.) for Cu and Nb use to find Q_{cav}(Temp.) for Cu cavity (dashed line).

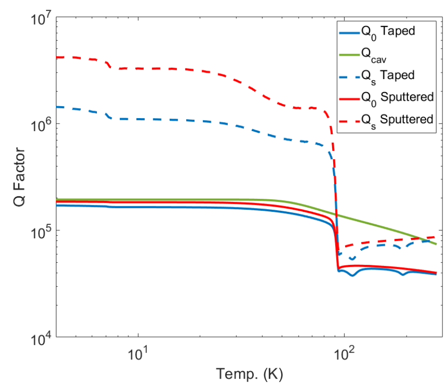

Figure 4: Quality factors of REBCO taped and deposited samples for their Q_0 ,Q_{cav}, Q_s for REBCO sample both had a critical temperature of 88K.

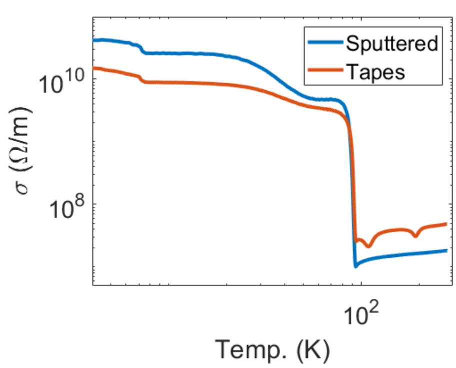

Figure 5: Conductivity (σ) for the deposited and taped REBCO sample use the reference conductivity of 43 GS/m.

us to obtain a Q_{cav}(Temp.)(see Fig. 3d). This was used to extract the Q of any sample. Note that the dip in the Q factor

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Table 1: Summary of cold test results for copper and REBCO taped and sputtered samples at 4 K and 80K show factor of 20 improvement over copper.

Sample	Q_0	Q_e	β	Q_s	σ_s
4K					
Cu	1.1*10^5	1.6*10^5	0.69	2.5*10^5	150 MS/m
REBCO Sputtered	1.9*10^5	1.3*10^5	1.4	4.2*10^6	42 GS/m
REBCO Taped	1.7*10^5	1.3*10^5	1.3	1.4*10^6	15 GS/m
80K					
Cu	9.2*10^4	1.5*10^5	0.63	2.3*10^5	134 MS/m
REBCO Sputtered	1.4*10^5	1.3*10^5	1.1	1.3*10^6	4 GS/m
REBCO Taped	1.2*10^5	1.3*10^5	0.90	6.0*10^5	2.6 GS/m

at 100 K is due to the cavity mode passing through and being superimposed upon a waveguide mode. The exact cause and a model to decouple these modes are still under development. Other waveguide modes can appear due to change in alignment metal to metal contacts waveguides from experiment to experiment

At low temperature Q_0 is dominated by the cavity as Q_{cav} « Q_s. The taped sample was about a factor of four less than the deposited sample (see Fig. 4) but was an order of magnitude greater than copper. Using the Q_s from Fig. 4 and Eq. 2 the RF conductivity can be found for both the deposited and taped REBCO samples see Fig. 5. The Reference conductivity for REBCO is 43 GS/m, from HFSS, the $Q_{s,ref}$ for the deposited sample is $4.2{\times}10^6$ and the taped geometry with copper between the tapes is 2.4×10^6. These are summarized for both 4 K and 80 K in Table 1.

DESIGN OF HTS CAVITY

Using the values in Table 1, we then set out to develop a single cell cavity whose cavity walls are REBCO. To do this, we cannot consider conventional clamshell design cavities as current limitations in the fabrication of REBCO prevent it from being deposited on highly complex curvilinear services without impeding the REBCO crystal structure needed for superconductivity. This is why we investigated the taped samples as REBCO tapes can now be easily and cost effectively be manufactured in meters in length. As the cavity walls must be flat, we developed a cavity geometry with an octagon cross-section. Each of the eight segments of the wall can be independently installed and disassembled to be coated with the tapes. This also allowed for us to use fillets in between each of the segments. These fillets can then be adjusted to add a small gap uniformly around the structure that can be used to tune the structure. The cavity and fillets were then encased in a copper vacuum canister, as seen in Fig. 6, almost resembling an orange like cross-section.

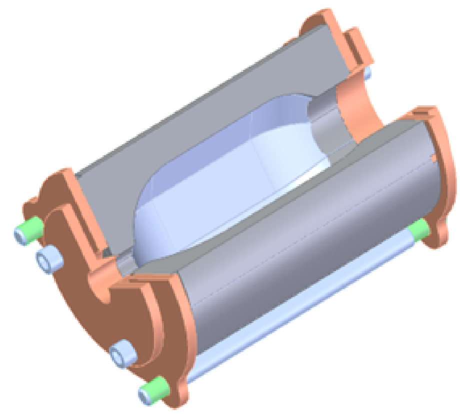

Figure 6: Mechanical drawing of pulse compressor.

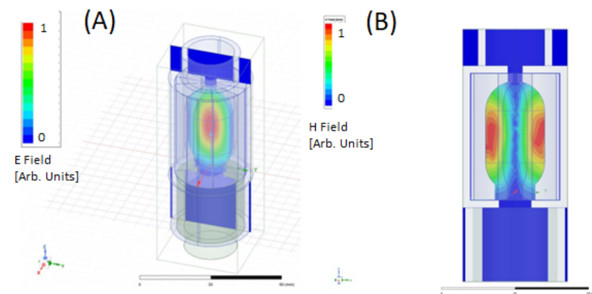

Figure 7: Pulse compressor 's (A) E field and (B) H field both in arbitrary units.

This cavity will be coupled into the TM01 circular waveguide from the klystron that powers the hemispherical cavity. The goal of this project is to develop a single cell structure with a high stored energy that also has a fill time that is compatible with the standard X-band klystron that can provide pulse length up to 1 µs.At the klystron frequency of 11.424 GHz this set the $Q_e \equiv 71,779$. This constraint of the beam aperture radius of 5.7 mm. This also led to an extremely overloaded cavity $\beta = 39.554$ due to the extremely high Q_0 of 201178 due to the high conductivity of the HTS and the low Q_e.

This pulse compressor should be able to compress the RF pulse length from 1 µs down to to ns scale while still having minimal pulse heating due to being in its superconducting state. The electric field and magnetic field are seen in Fig. 7 listed in arbitrary units. For Klystron power of 25 MW, the maximum electric field on the surface will be 618 MV/m, the maximum magnetic field will be 3.1216 MA/m and the electric field on axis will be 1.8 GV/m.

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REFERENCES

[1] D. Gonnella *et al.*, "Nitrogen-doped 9-cell cavity performance in a test cryomodule for LCLS-II," *J. Appl. Phys.*, vol. 117, p. 023908, 2015. doi:10.1063/1.4905681

[2] B. Aune *et al.*, "Superconducting TESLA cavities", *Phys. Rev. ST Accel. Beams*, vol. 3, p. 092001, 2000. doi:10.1103/PhysRevSTAB.3.092001

[3] A. Brachmann, M. Dunham, J. F. Schmerge, "LCLS-II - Status and Upgrades", in *Proc. FEL'19*, Hamburg, Germany, Aug. 2019, pp. 772–775. doi:10.18429/JACoW-FEL2019-FRA02

[4] P. B. Welander, M. Franzi, S. Tantawi,P. Krkotić, G. Telles,J. O'Callaghan, M. Pont, F. Perez, *et al.*, "Cryogenic RF Characterization of Superconducting Materials at SLAC With Hemispherical Cavities", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper TUPB065, pp. 735–738.

[5] N.J. Simon, E.S. Drexler, R.P. Reed,"Properties of Copper and Copper Alloys at Cryogenic Temperatures", *NIST Monograph*, 1992. p. 177.

[6] M. Schneider, V. Dolgashev, J. W. Lewellen, S.G. Tantawi, E.A. Nanni, M. Zuboraj, R. Fleming, D. Gorelov, M. Middendorf, E.I. Simakov, "High gradient off-axis coupled C-band Cu and CuAg accelerating structures", *Appl. Phys. Lett.*, vol. 121, p. 254101, 2022. doi:10.1063/5.0132706

[7] V. Dolgashev, S. G. Tantawi, Y. Higashi, B. Spataro,"Geometric dependence of radio-frequency breakdown in normal conducting accelerating structures", *Appl. Phys. Lett.*, vol. 97, p. 171501, 2010. doi:10.1063/1.3505339

[8] A. Romanov, P. Krkotić, G. Telles, J. O'Callaghan, M. Pont, F. Perez, *et al.*, "High frequency response of thick REBCO coated conductors in the framework of the FCC study", *Scientific Reports*, vol. 10(1), p. 12325, 2020. doi:10.1038/s41598-020-69004-z

[9] W. Prusseit, R. Nemetschek, C. Hoffmann, G. Sigl, A. Lümkemann, and H. Kinder, "ISD process development for coated conductors", *Physica C: Superconductivity and its applications*, vol. 426, pp. 866-871, 2005. doi:10.1016/j.physc.2005.01.054