LIMITING MAGNETIC FIELD MEASUREMENTS OF SUPERCONDUCTING MATERIALS FOR SRF CAVITIES*

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Abstract

Exploration of new recipes and novel materials for superconducting RF cavities is necessary to push to higher quality factors and accelerating gradients. The superheating field is the material property that sets the limit on the maximum accelerating gradient achievable for a superconducting cavity of a given geometry. The Cornell SuperHeating Radiofrequency Pulsed Power Probe (C-SHRP^3) is a sample host cavity designed to measure the superheating field of material samples. We present results on superconducting materials of interest to the SRF community that demonstrate the high-field potential of novel materials.

INTRODUCTION

Accelerating cavities are the heart of a particle accelerator, accelerating charged particles through a beamline like a heart pumps blood through the body. For superconducting RF (SRF) accelerating cavities, niobium is the preferred material, however alloys such as Nb3Sn, NbZr, and Nb_3Al are current subjects of research and development [1–4].

The most desirable traits of an accelerating cavity are high quality factor and high accelerating gradient. The quality factor, Q, is a figure of merit describing the cavity's efficiency – the higher the Q, the less energy the cavity dissipates. Niobium cavities are consistently able to achieve a Q on the order of 10^{10} [5]. The accelerating gradient, E_{acc}, is how much energy can be transferred to the charged particle beam per length of cavity. State of the art niobium cavities have reached accelerating gradients near the predicted limit well over 40 MV/m, however in application, the accelerating gradient used is much lower than that [6, 7].

Below the critical temperature (T_c), a superconductor in an applied magnetic field acts as a perfect diamagnet, expelling all magnetic flux. This is referred to as the Meissner state. In some superconductors (type-II), it becomes energetically favorable above a certain applied field magnitude (the first critical magnetic field, B_{c1}) for some magnetic flux to penetrate the material. The flux passes through normal conducting "cores" while the rest of the material remains superconducting. This state is called the vortex or mixed state. If the applied field becomes too strong (the second critical magnetic field, B_{c2}), the superconductor can no longer expel magnetic flux and it is forced normal conducting [8].

Superconducting RF cavities must operate in the Meissner state. Any penetrating flux causes significant dissipation and leads to heating [5, 7]. This heating can cause the cavity to "quench", or cease superconducting [7, 9]. The conventional transition between the Meissner and vortex states is at the first critical magnetic field, B_{c1}, however it is possible to maintain a metastable persistence of the Meissner state above B_{c1}. The upper bound of this metastable Meissner state is referred to as the superheating field, B_{SH} [8].

The superheating field sets the material limit on the accelerating gradient achievable by a cavity [7]. There are a number of theoretical predictions of B_{SH} for materials such as Nb and Nb_3Sn, however current models have significant limitations. For example, the Ginzburg-Landau model is only valid near T_c [10].

Previous attempts at measuring B_{SH} using elliptical SRF cavities have been made, but were deemed unsatisfactory due to limiting thermal effects [6, 7, 9, 11]. The time it takes for an elliptical cavity to "fill", or reach maximum fields, is long enough that heating due defects or other surface features is able to spread and cause a premature quench. In order to successfully measure B_{SH}, an alternative to the elliptical cavity must be explored. Here, we present the Cornell SuperHeating Radiofrequency Pulsed Power Probe (C-SHRP^3), a sample host cavity designed specifically for the measurement of B_{SH}.

DESIGN AND FABRICATION

C-SHRP^3 is a 1.3 GHz sample host cavity. The host structure, shown in Fig. 1 is made of copper, chosen for its high thermal conductivity. A superconducting sample is attached to the cavity top plate and extends into the high-field region of the host structure.

In order to successfully measure B_{SH}, the superconducting material must reach 10 s of mT before thermal effects from surface defects have time to spread. To achieve this, the sample geometry is designed to take advantage of field enhancement. This phenomenon occurs when a superconductor in the Meissner state, expelling all magnetic flux, results in locally higher fields at sharp features [8]. The C-SHRP^3 samples are designed such that on the sample's sharp edge, the magnetic fields are enhanced by a factor of $435\,\mathrm{mT}/\sqrt{J}$ as calculated by electromagnetic field simulations done with CST MicrowaveStudio [6]. The magnetic fields inside the cavity are shown in Fig. 2.

The forward power antenna is optimized for near-unity coupling ($\beta \simeq 1-3$). The rate of "filling", or rate at which

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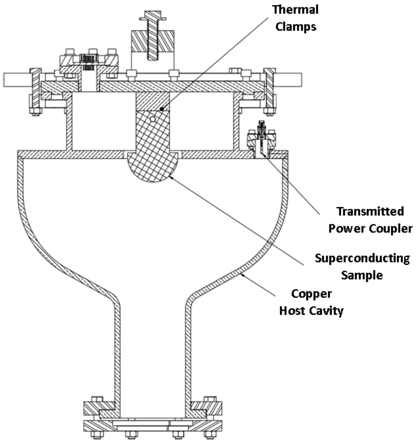

Figure 1: Diagram of C-SHRP^3. A superconducting material sample is attached to top plate of the copper host cavity with high thermal conductivity clamps. The fields inside of the host cavity are probed with a small transmitted power coupler.

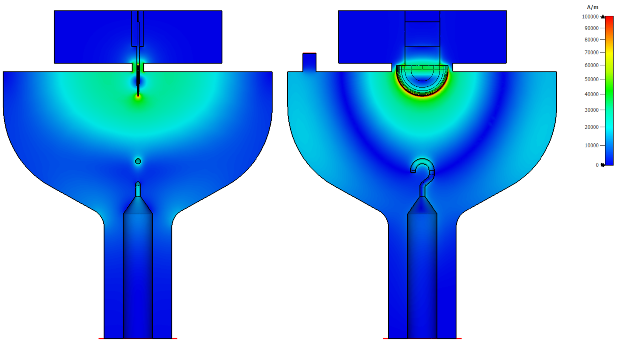

Figure 2: A cross section of the x-y plane (left) and z-y plane (right) of magnetic fields in the C-SHRP^3 cavity from a CST MicrowaveStudio simulation. While superconducting, the superconducting sample forces all magnetic fields out and around the sharp edge of the sample, creating a very high local field. This field enhancement phenomenon allows C-SHRP^3 to reach fields as high as 0.5 T in less than 4 µs.

fields in the cavity rise to their steady state value, is related to the coupling β:

$$B(t) = \left(\frac{B_{pk}}{\sqrt{U}}\right)_{const} \sqrt{\frac{4\beta P_f Q_0}{(1+\beta)^2\omega_0}} \left(1 - e^{-\frac{\omega_0}{2Q_L}t}\right), \quad (1)$$

where $B(t)$ is the peak magnetic field on the sample, $(B_{pk}/\sqrt{U})_{const}$ is the constant factor of field enhancement as calculated in CST MicrowaveStudio, β is the coupling, P_f is the forward power to the cavity, Q_0 is the intrinsic quality factor of the cavity, ω_0 is the angular resonant frequency, Q_L is the loaded quality factor, and t is time.

The cavity host structure components were turned from OFHC copper and electron beam welded under vacuum. The superconducting samples were machined from 3 mm nominally high RRR niobium sheet. They received a baseline preparation including a 40 µm chemical polish and a bake

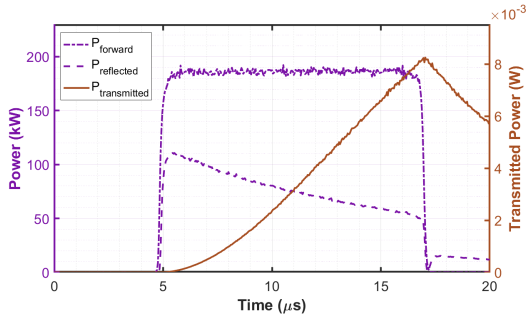

Figure 3: An example of raw RF data. The forward and reflected power are shown in purple corresponding with the left-hand y-axis. The transmitted power is shown in orange and corresponds with the right-hand y-axis. The magnetic field on the sample is proportional to the square root of the transmitted power [5]. This data is from a Nb sample taken at ~ 3.5 K.

in a UHV furnace at 800 C for 5 hours. Additional films and treatments can be applied after this point, for example, a Nb_3Sn sample was coated with a 3 µm Nb_3Sn film using a vapor deposition furnace [4, 11].

A prepared sample is assembled onto the host structure top plate in a class 100 cleanroom. The full top plate assembly is lowered onto the main cavity body, which is on a cryogenic dewar insert, and vacuum sealed.

The full insert is submerged in a cryogenic dewar and cooled with liquid and gaseous helium. Several Cernox cryogenic temperature sensors are used to monitor the helium bath temperature. We cannot directly measure the temperature of the superconducting sample inside of the cavity, however the sample is in good thermal contact with the top plate as confirmed by thermal simulations [6]. A Cernox temperature sensor is attached on the cavity top plate directly above the sample to monitor its temperature. A resistive heater is attached to the bottom of the insert and used to control the temperature of helium bath when above liquid helium temperatures (> 4.2 K). Forward power is carried to the cavity through a waveguide and a small antenna is used to probe the field inside of the cavity.

DATA COLLECTION AND ANALYSIS

We calibrate C-SHRP^3 in continuous wave (CW) operation at low power (~ 1 W) at 4.2 K to determine the constant relationship between the peak magnetic field on the sample and the transmitted power. This allows us to determine the magnetic field during pulsed operation directly from the transmitted power. During CW calibration, we also measure the coupling β and the loaded quality factor Q_L.

After calibration, high pulsed power measurements are taken. The cavity is driven by a 1.3 GHz klystron using pulses of 10 µs to 40 µs. The klystron has a maximum power output of 1 MW which allows us to reach 0.5 T in under 4 µs. We measure the forward power to the cavity (P_f), power reflected from the cavity (P_r), and the power transmitted through the cavity (P_t). An example RF pulse is shown

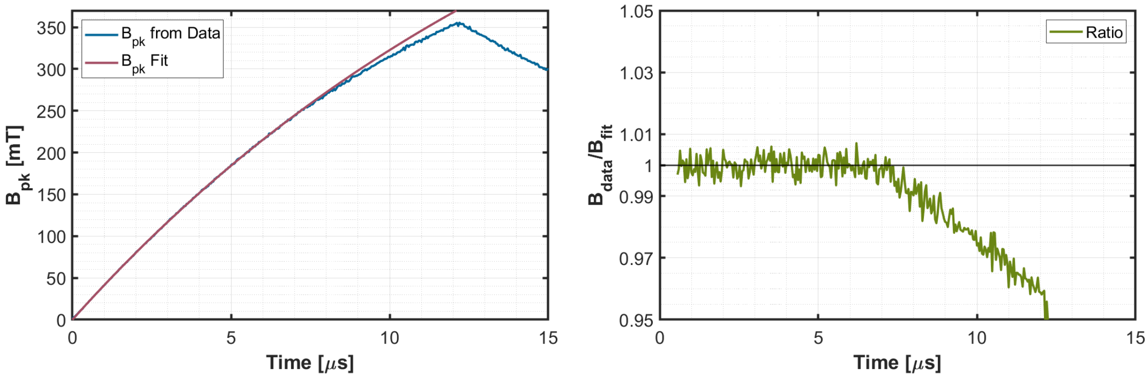

Figure 4: The peak magnetic field on the sample (blue) is calculated from the transmitted power. The beginning of the magnetic field fill is fit (pink) up to an upper bound safely below the material's quench field (left). The ratio between the magnetic field on the sample (green) is at unity while the sample is superconducting. When the sample quenches, the quality factor changes significantly and the ratio diverges from unity (right). This figure represents data from a Nb sample taken at ~ 3.5 K.

in Fig. 3. The forward power is increased incrementally between pulses until quench behavior is observed.

During quench, the quality factor of the sample decreases significantly. While the sample surface is small compared to the host structure, the fields on it are very high. Thus, when the sample quenches, there is a notable change in quality factor Q_0. The fill rate of the magnetic field is dependent upon Q_0 as shown in Eq. (1), meaning a sample quench is visible in $B(t)$.

To determine the time (and thus field) at which quench occurs, we perform a curve fit of the form of Eq. (1) from the beginning of the fill to safely below where quench occurs. We compare this fit, B_{fit}, to the $B(t)$ from the data by looking at the ratio between the two shown in Fig. 4. When this ratio diverges from unity, we know that quench has occurred.

SUMMARY

The superheating field B_{SH} describes the maximum magnetic field at which the metastable persistence of the flux-free Meissner state is possible for a given superconducting material. The absolute material limit on the accelerating gradient E_{acc} achievable by an SRF cavity is directly proportional to B_{SH}. It is difficult to measure B_{SH} due to the extreme thermal sensitivity and the very high fields that must be reached. C-SHRP^3 is a sample host cavity designed to measure B_{SH} of superconducting samples and can reach fields as high as 0.5 T in less than 4 µs. This timescale is short enough that any thermal effects that occur at surface defects do not have time to spread and affect the measurement.

We have performed measurements across a full temperature range from ~ 2 K to T_c of both clean Nb and Nb_3Sn. We are excited to announce that our results will be available in a preprint on arXiv later this year.

REFERENCES

[1] A. Grassl, N. Sitaraman, and M. Liepe, "Early exploration of zirconium doping SRF cavities with chemical vapor deposition", in *Proc. SRF'25*, Tokyo, Japan, Sep. 2025, pp. 70–73.

[2] G. Gaitan *et al.*, "Initial results for CVD based growth of Nb_3Sn", in *Proc. SRF'25*, Tokyo, Japan, Sep. 2025, pp. 98–101.

[3] N. Sitaraman, Z. Baraissov, T. Oseroff, D. Muller, and M. Liepe, "Improving quench fields of enhanced-Tc surfaces", in *Proc. SRF'25*, Tokyo, Japan, Sep. 2025, pp. 573–579.

[4] L. Shpani, M. U. Liepe, T. E. Oseroff, G. Eremeev, and S. Posen, "Mechanically Polishing Electroplated Nb3Sn for Higher Accelerating Gradients", in *Proc. SRF'25*, Tokyo, Japan, Sep. 2025, pp. 336–340.

[5] H. Padamsee, *RF Superconductivity for Accelerators*, J. Knobloch and T. Hays, Eds. Weinheim: Wiley-VCH, 2008.

[6] R. D. Porter, "Advancing the Maximum Accelerating Gradient of Niobium-3 Tin Superconducting Radiofrequency Accelerator Cavities: RF Measurements, Dynamic Temperature Mapping, and Material Growth", Ph.D. thesis, Cornell University, 2021. doi:10.7298/z9dj-y848

[7] S. Posen, N. Valles, and M. Liepe, "Radio Frequency Magnetic Field Limits of Nb and Nb_3Sn", *Phys. Rev. Lett.*, vol. 115, no. 4, p. 047001, Jul. 2015. doi:10.1103/physrevlett.115.047001

[8] M. Tinkham, *Introduction to superconductivity*. Mineola, NY: Dover Publ., 2015.

[9] N. Valles, "Pushing The Frontiers Of Superconducting Radio Frequency Science: From The Temperature Dependence Of The Superheating Field Of Niobium To Higher-Order Mode Damping In Very High Quality Factor Accelerating Structures", Ph.D. thesis, Cornell University, 2014. doi:1813/36143

[10] G. Catelani and J. P. Sethna, "Temperature dependence of the superheating field for superconductors in the high-κ london limit", *Phys. Rev. B*, vol. 78, no. 22, p. 224509, Dec. 2008. doi:10.1103/physrevb.78.224509

[11] S. Posen, "Understanding And Overcoming Limitation Mechanisms In Nb3Sn Superconducting Rf Cavities", Ph.D. thesis, Cornell University, 2014. doi:1813/39470