ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB024

HIGH PULSED POWER MEASUREMENTS OF SUPERHEATING FIELDS FOR SRF MATERIALS*

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Abstract

The Cornell High Pulsed Power Sample Host Cavity (CHPPSHC) is a new system designed to measure the superheating field of candidate superconducting RF (SRF) materials, giving insight into their operational limits. This system is designed to reach peak magnetic fields of up to 0.5 T in only a few microseconds, allowing us to achieve a purer magnetic field quench on the sample. We present an overview of the CHPPSHC system and proof of principle data from a niobium sample.

INTRODUCTION

Improving the accelerating gradient, E_{acc}, of superconducting radio-frequency (SRF) cavities is a desirable goal for the next generation of accelerators. The upper limit on E_{acc} for a given material is set by its superheating field, B_{SH}, and the cavity geometry. Niobium cavities are the current standard and has a B_{SH} of ~ 200 mT corresponding to a maximum E_{acc} of ~ 50 MV/m in an elliptical cavity [1]. The SRF community has been investigating other materials [2, 3] including Nb_3Sn, which is predicted to have a B_{SH} of ~ 400 mT [4, 5]. This corresponds to an upper limit on E_{acc} of ~ 100 MV/m.

To date, there has not been satisfying experimental measurements of Nb_3Sn's superheating field. Previous attempts have been made, however these experiments have been severely limited by thermal effects. The superheating field is an extremely temperature-dependent property, so even a small amount of heating can lower the quench field. Here, we explore the Cornell High Pulsed Power Sample Host Cavity (CHPPSHC), a sample host structure specifically designed to measure the limiting magnetic fields of candidate SRF material samples [6, 7].

THE CORNELL HIGH PULSED POWER SAMPLE HOST CAVITY

The CHPPSHC must be able to reach fields exceeding the predicted B_{SH} of Nb_3Sn fast enough that heating does not have a significant effect on the measurement. The CHPPSHC utilizes a 1 MW klystron with pulse lengths on the order of 10 µs. Past experiments at Cornell were done with 1.3 GHz elliptical cavities, but maximum fields were thermally limited due to pulse lengths of 50 - 100 µs [1]. The CHPPSHC's geometry is designed to charge quickly by exploiting field enhancement along the sharp edge of the sample. A simulation of the magnetic field in the cavity is shown in Fig. 1.

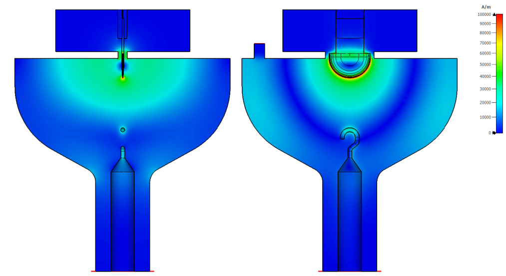

Figure 1: Simulation of peak magnetic fields along $x = 0$ (left) and $z = 0$ (right) planes of the CHPPSHC in CST Microwave Studio. The design exploits field enhancement to reach significantly higher peak fields on the sample edge. An upper bound of 1×10^5 A/m was set on the color scale for visibility purposes. The peak field on the sample is ~ 4×10^5 A/m corresponding to ~ 500 mT.

The peak field on the sample edge is enhanced by a factor of 500 due to this effect, which allows the system to reach a maximum field of ~ 500 mT in only ~10 µs [6].

The simulation also calculates the quality factors of various components of the system. While superconducting, the sample accounts for less than 0.001 % of losses. When the sample is normal conducting at 300 K, the losses on the sample reach ~ 70 % of losses. The resulting sharp drop in the system's Q_0 is large enough that it will be evident in RF power data when the sample has quenched.

PULSED RF DATA

Before investigating Nb_3Sn, baseline data for a niobium sample is necessary to ensure that quench information can be accurately extracted from our measurement results. A niobium sample was prepared using the same processes applied to a niobium cavity, receiving a bulk chemical polish, electropolishing, and a 5 hr 800 C bake. The sample was cleaned with DI water in a class 100 cleanroom before being assembled into the copper host structure.

The host cavity is tested in helium over a temperature range from 2 K to 9 K and driven by a 1 MW klystron. Before taking pulsed data, a system calibration is done in continuous wave (CW) operation to determine the loaded quality factor, Q_L, the coupling, β, and field calibration. In Fig. 2, an example pulsed operation data point is shown. B_{pk} is calculated from the RF data using the results of the CW calibration and the CST simulation.

Figure 2 shows a pulse that exhibits "overfilling" behavior where the cavity continues to fill despite the sample quenching. This makes it more difficult to accurately identify the quench field as the underlying mechanisms become more complex.

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ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB024

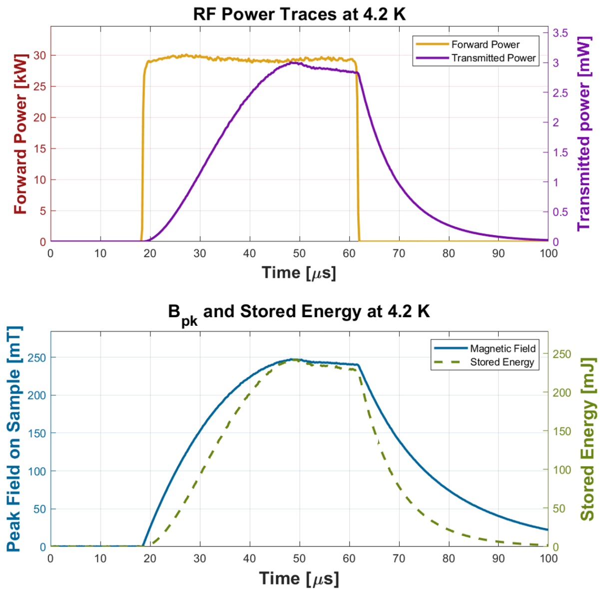

Figure 2: Example P_f and P_t data (top) from an RF test taken at 4.2 K and the corresponding B_pk and stored energy U profile.

RF Data Simulations

In order to ensure an understanding of the quench mechanisms at play, we used a numerical simulation to generate $B_{pk}(t)$ profiles. This simulation iteratively calculates the stored energy of the system considering factors such as the forward power, sample quality factor, and the quench field.

Prior to quench, the stored energy increments as [8]:

$$U_{n+1} = U_n + \left(\sqrt{\frac{8\pi f U_n P_{f,n}}{Q_{ext}}} - \frac{2\pi f U_n}{Q_0} - \frac{2\pi f U_n}{Q_{ext}}\right)dt \quad (1)$$

where U_i is the cavity stored energy for a given time step, f is resonant frequency, P_f is forward power of the pulse, Q_{ext} is the external quality factor, and Q_0 is the combined host structure and sample intrinsic quality factor when superconducting.

When the sample quenches (i.e., the peak magnetic field surpasses B_{SH}, which is another input), system's intrinsic quality factor drops due to the rise in surface resistance on the sample. The simulation assumes a smooth transition from the superconducting Q_0 to the normal conducting Q_0 over several µs.

Using this simulation, we were able to recreate B_{pk} profiles nearly identical to those observed in the data with realistic input values (Fig. 3).

QUENCH ANALYSIS

During a quench, the sample accounts for as much as 70 % of the losses in the system, making quench visible in the RF data. Extracting a quench field from B_{pk} profiles is not as simple as taking the maximum field. The cavity will

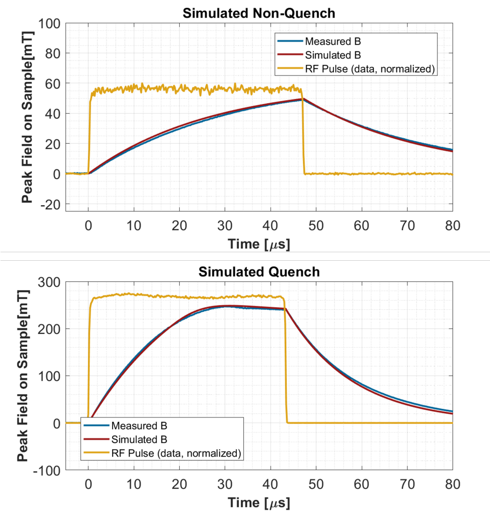

Figure 3: Simulations of B_{pk} during an non-quench (top) and quench (bottom) compared with actual RF data. The numerical simulation can recreate B_{pk} profiles from data with realistic inputs.

"overfill", where, despite a sample quench, the fields in the cavity will continue to rise.

The method used here for finding the quench field is simple but effective. When a cavity's stored energy ramps up, it should follow an exponential rise while the sample is superconducting [8]. To account for changes in the external quality factor between data points, the ramp up can be fit by varying the decay constant, τ_L defined as

$$\tau_L = \frac{Q_L}{\omega} \quad (2)$$

where the ramp up follows the form

$$B(t) = B_{lim}(1 - e^{\frac{-t}{2\tau_L}})^2 \quad (3)$$

where B_lim is the maximum value the exponential increase will level off as $t \rightarrow \inf$. This curve is fit to a section of the ramp up safely below the quench field. In the data point shown in Fig. 4, the fit range was 20 mT to 150 mT.

When the sample begins to quench, its quality factor will change causing the ramp up to deviate from the "ideal" exponential rise. By examining the ratio between the fit and the data, we can pinpoint quench by looking at where that ratio drops away from unity. A tolerance of 99.5 % (0.995) was chosen. For the example data point shown in Fig. 4, this method was used to find the quench field at 187 mT.

TIME TO QUENCH

The CHPPSHC was designed to avoid thermal effects, however it is impossible to fully eliminate them. There is a clear trend in quench field related to the length of time it took for the sample to quench, shown in Fig. 5. A lower forward power means a slower ramp up, which gives the sample more time to heat up.

The superheating field is no lower than the highest quench field measured for a given temperature, effectively setting

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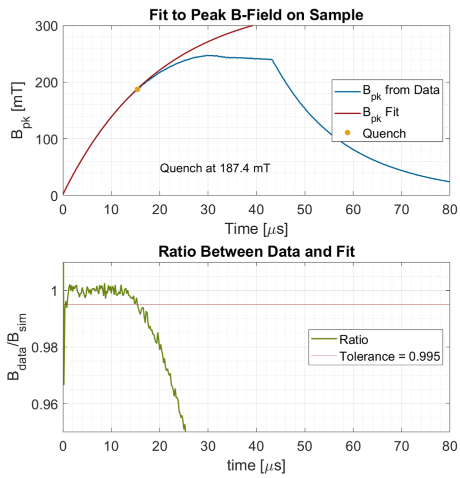

Figure 4: (Top) Low B-field section of ramp-up data is fit with an exponential field increase using parameters for a superconducting sample. (Bottom) Ratio between exponential fit and data. Deviation of the fit from the data indicates the sample has quenched. A ratio tolerance of 0.995, indicated by a horizontal red line, is used to determine when quench occurs. The above point quenches at 187 mT.

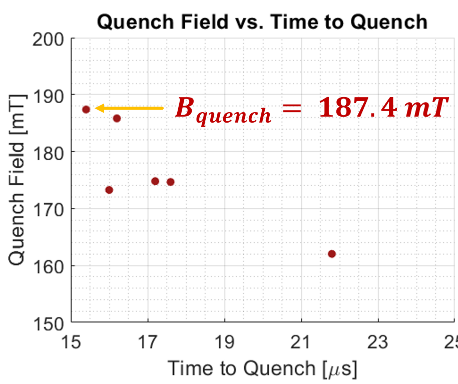

Figure 5: Quench B-field as a function of time to quench after beginning of pulse at 4.2 K. Longer times to quench correspond to lower quench fields, indicating some heating on the sample. The faster the quench occurs, the closer the quench field is to the value for the bath temperature.

a lower bound on the value. In the 4.2 K data shown, the highest quench field was at 187.4 mT which, when compared to theoretical predictions for niobium shown in Fig. 6, is well within the dark blue shaded region for the superheating field for clean (unbaked[1]) niobium.

SUMMARY

The Cornell High Pulsed Power Sample Host Cavity has been successfully commissioned for the purpose of measuring limiting magnetic fields of candidate SRF materials. Quench fields can be extracted by finding deviation from an

[1] Unbaked refers to a low temperature bake at 120 C and results in a "dirty" RF penetration layer with a small mean free path, which was the subject of the paper this figure is adapted from Ref. [1]

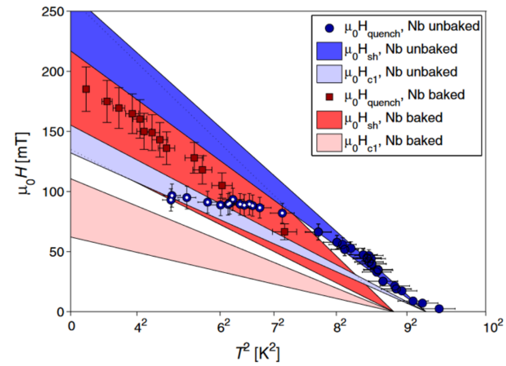

Figure 6: This plot shows in shades of blue predictions for B_{C1} and B_{SH} of clean niobium. The blue data points correspond to high pulsed power measurements of a niobium 1.3 GHz elliptical cavity. These measurements were severely limited by thermal effects at lower temperatures. The red regions and data are for a cavity that received a 120 C bake to eliminate high-field Q slope, resulting in a "dirty" surface layer. Figure adapted from Ref. [1]

"ideal" ramp up in the peak magnetic field on the superconducting sample. A small amount of heating on the sample is evident in the trend of lower quench fields for longer ramp up times. The lower limit of the superheating field is set by the highest quench field achieved at that temperature. Baseline tests with a niobium sample have given superheating field results that fall in the range predicted by theory.

ACKNOWLEDGEMENTS

This work would not have been possible without the support of the SRF technical staff, Holly Conklin, Terri Gruber-Hine, and Greg Kulina. The high precision machining was done by the Newman Machine Shop's talented machinists who adapted quickly and effectively to the unique engineering challenges presented to them.

REFERENCES

[1] S. Posen, N. Valles, and M. Liepe, "Radio frequency magnetic field limits of nb and nb3sn", *Phys. Rev. Lett.*, vol. 115, no. 4, p. 047 001, 2015. `doi:10.1103/physrevlett.115.047001`

[2] S. Seddon-Stettler, M. Liepe, T. Oseroff, N. Sitaraman, and Z. Sun, "Surface characterization studies of gold-plated niobium", in *Proc. 21th Int. Conf. RF Supercond. (SRF'23)*, Grand Rapids, MI, USA, Jun. 2023. `doi:10.18429/JACoW-SRF2023-MOPMB076`

[3] N. Sitaraman *et al.*, "Progress on zirconium-doped niobium surfaces", in *Proc. 21th Int. Conf. RF Supercond. (SRF'23)*, Grand Rapids, MI, USA, Jun. 2023. `doi:10.18429/JACOW-SRF2023-TUPTB004`

[4] G. Catelani and J. P. Sethna, "Temperature dependence of the superheating field for superconductors in the high-kappa london limit", *Phys. Rev. B*, vol. 78, no. 22, p. 224 509, 2008. `doi:10.1103/physrevb.78.224509`

ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB024

[5] S. Posen and D. L. Hall, "Nb3Sn superconducting radiofrequency cavities: fabrication, results, properties, and prospects", *Superconductor Science and Technology*, vol. 30, no. 3, p. 033 004, 2017. doi:10.1088/1361-6668/30/3/033004

[6] R. Porter, "RF Measurementns, Dynamic Temperature Mapping, and Material GrowthAdvancing the Maximum Accelerating Gradient of Niobium-3 Tin Superconducting RadioFrequency Accelerator Cavities", Ph.D. dissertation, Cornell University, Ithaca, NY, USA, 2021.

[7] N. Verboncoeur *et al.*, "Update on Cornell High Pulsed Power Sample Host Cavity", in *Proc. 21th Int. Conf. RF Supercond. (SRF'23)*, Grand Rapids, MI, USA, Jun. 2023, 2023, paper WEPWB108, pp. 841–846. doi:10.18429/JACoW-SRF2023-WEPWB108

[8] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators*. Wiley, 2008.