2021

Measurements of Magnetic Field Penetration in Superconducting Materials for SRF Cavities

Iresha Harshani Senevirathne
Old Dominion University, isene001@odu.edu

Alex Gurevich
Old Dominion University, agurevic@odu.edu

Jean R. Delayen
Old Dominion University, jdelayen@odu.edu

A.-M. Valente-Feliciano

Lin Liu (Ed.)

See next page for additional authors

Original Publication Citation

Senevirathne, I., Delayen, J., Gurevich, A., & Valente-Feliciano, A.-M. (2021) Measurements of magnetic field penetration in superconducting materials for SRF cavities. In L. Liu, J. Byrd, R. Neuenschwander, R. Picoreti, V.R.W. Schaa (Eds.), *Proceedings of the 12th International Particle Accelerator Conference* (pp. 1208-1211) Joint Accelerator Conferences Website. https://doi.org/10.18429/JACoW-IPAC2021-MOPAB396

Authors

Iresha Harshani Senevirathne, Alex Gurevich, Jean R. Delayen, A.-M. Valente-Feliciano, Lin Liu (Ed.), John Byrd (Ed.), Regis Neuenschwander (Ed.), Renan Picoreti (Ed.), and Volker R.W. Schaa (Ed.)

MEASUREMENT OF MAGNETIC FIELD PENETRATION IN SUPERCONDUCTING MATERIALS FOR SRF CAVITIES*

I. H. Senevirathne†, A. Gurevich, J. R. Delayen
Centre for Accelerator Science, Old Dominion University, Norfolk, VA, USA
A. -M. Valente-Feliciano
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

Abstract

Superconducting radiofrequency (SRF) cavities used in particle accelerators operate in the Meissner state. To achieve high accelerating gradients, the cavity material should stay in the Meissner state under high RF magnetic field without penetration of vortices through the cavity wall. The field onset of flux penetration into a superconductor is an important parameter of merit of alternative superconducting materials other than Nb which can enhance the performance of SRF cavities. There is a need for a simple and efficient technique to measure the onset of field penetration into a superconductor directly. We have developed a Hall probe experimental setup for the measurement of the flux penetration field through a superconducting sample placed under a small superconducting solenoid magnet which can generate magnetic fields up to 500 mT. The system has been calibrated and used to measure different bulk and thin film superconducting materials. This system can also be used to study SIS multilayer coatings that have been proposed to enhance the vortex penetration field in Nb cavities.

INTRODUCTION

Bulk niobium SRF cavities for particle accelerators can provide accelerating gradients $E_{acc} \approx$ 40-50 MV/m [1, 2]. Further significant increase of accelerating gradient in Nb cavities is hardly possible as they already operate at the surface magnetic fields close to the superheating field H_{sh}. A lot of R&D research of alternative to Nb materials has been done to enhance the performance of SRF cavities [3]. However, the high field SRF performance is often limited by surface morphological defects which reduce H_{sh} and cause premature local flux penetration into the superconductor [4]. Multilayer structure containing alternative layers of insulators and superconductors, which can delay flux penetration, is a promising way to mitigate the effect of surface defects [5-7].

Measurement of the onset of magnetic field penetration is pivotal to study the behavior of bulk, thin film and multilayered superconductors for SRF accelerating cavities. This paper describes the design and calibration of a simple and efficient technique to measure the onset of magnetic field penetration into a superconducting sample. Using this system, we measured penetration of dc magnetic field in bulk Nb and Nb_3Sn thin film samples.

MESUREMENT SYSTEM

The technique was designed for the direct measurement of magnetic field penetration into flat superconducting samples 50 mm in diameter. Figure 1 (a) shows the main features of the experimental setup. Superconducting magnet fabricated using NbTi wire as a multi turn coil plays a major role in this setup to produce a magnetic field up to 500 mT on the sample surface. Here the field lines are parallel the sample surface, which mimics the magnetic field configuration of SRF cavity in the Meissner state as shown in Fig. 2. Since the size of sample is few times larger than the magnet bore, the surface magnetic field rapidly decreases along the sample surface with no significant edge and demagnetizing effect [8].

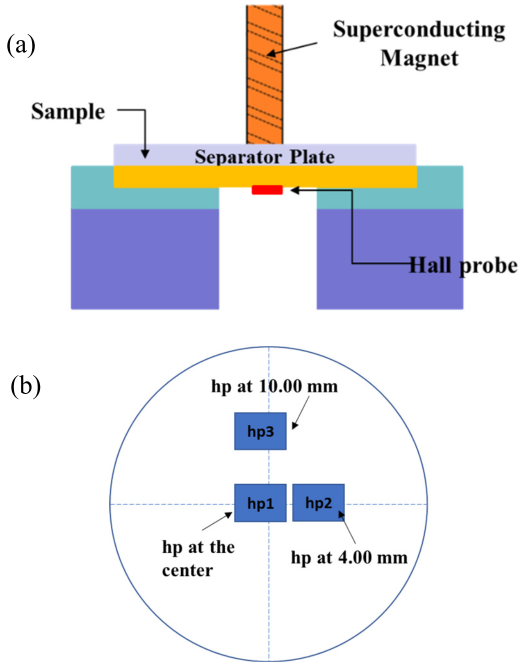

Figure 1: (a) Cross sectional view of the basic experimental setup (b) Configuration of three Hall probes mounted under the sample.

A separator plate between the sample and the magnet maintains a fixed distance to avoid the damage of the sample by direct contact with the magnet.

High linearity Hall probes from Arepoc s. r. o. calibrated at cryogenic temperatures were mounted under the sample to capture penetrated magnetic field through the sample. Three Hall probes are placed at the different locations at the bottom surface of the sample: at the center, at 4 mm

---

* Work supported by NSF Grants PHY-1734075 and PHY-1416051, and DOE Awards DE-SC0010081 and DE-SC0019399.
† isene001@odu.edu

and 10 mm from the center as shown in Fig. 1 (b) to determine the effect of probe location to our measurements. As the magnetic field is gradually increased above the onset of flux penetration, superconducting vortices start to penetrate the sample and the Hall probes detect the magnetic field at the full flux penetration through the superconducting sample.

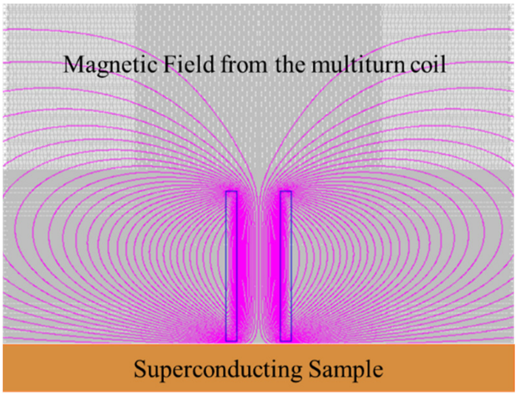

Figure 2: Magnetic field lines from the multiturn coil placed on the superconducting sample in Meissner state.

Nonmagnetic container was used to assemble the sample, the solenoid magnet, and the Hall probes symmetrically as shown in Fig. 3. The experiments were performed at 2 K and 4 K in a liquid He dewar at Jefferson Lab.

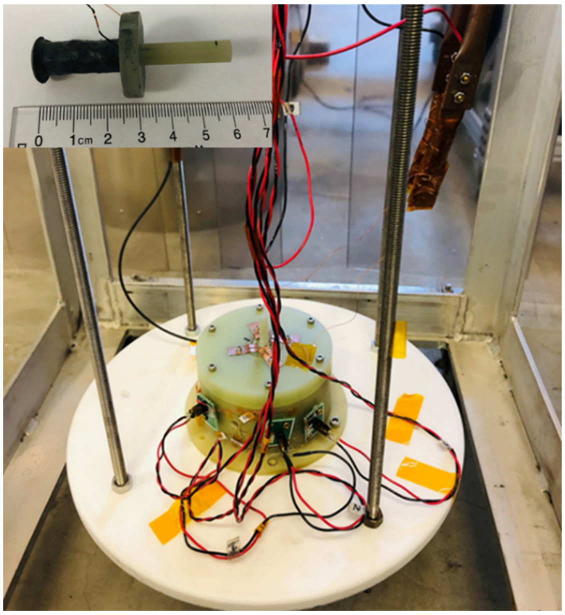

Figure 3: Setup assembly of the magnetic field penetration measurement system in a nonmagnetic container and the solenoid magnet coated epoxy layer (top left corner).

CALIBRATION

Setup calibration was performed in few steps to find the maximum surface magnetic field generated by the magnet at the sample surface. First, three Hall probes were placed just under the magnet with no sample between them. The separation between the magnet and the Hall probe sensor was 1.368 mm. Hall probe reading was recorded with respect to the gradually increasing current. The probe at the center showed the strongest magnetic field as expected (Fig. 4). The magnetic field of 445.3 mT at the center was measured at 100 A of magnet current.

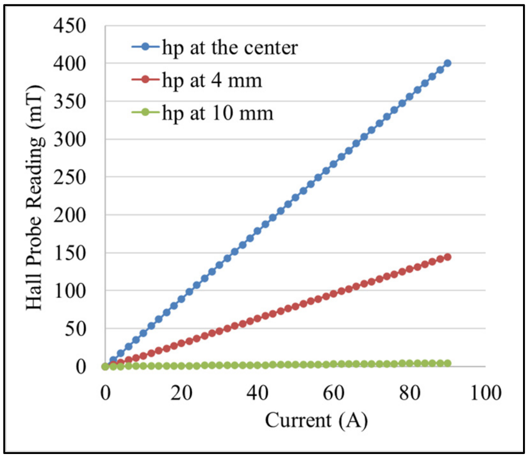

Figure 4: Hall probe responses against increasing magnet current with no sample.

The field distribution calculated by the Poisson computer code [9] gave 517.0 mT. The 13.9% difference between the experimental and simulation values of the centre magnetic field occurs because the separation between the magnet and the sensor is not known accurately. Then the simulation was run again to find the separation which matches the measured magnetic field in the centre. As a result, we obtained the corrected separation 1.815 mm, about 0.447 mm larger than it was assumed.

Finally, the maximum surface magnetic field on the sample surface was simulated with the sample being between the magnet and the sensor. The separation between the magnet and the sample 1.018 mm was corrected by adding 0.447 mm, as explained above. The maximum surface field produced by the magnet on the sample surface increases linearly with the current with the slope of 5.5 mT/A (Fig. 5).

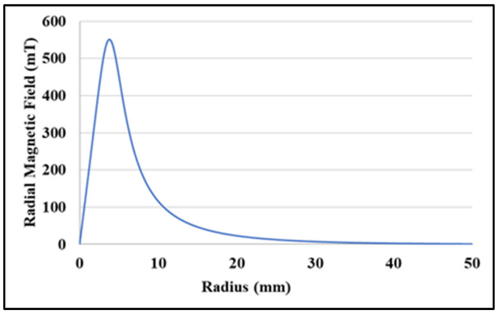

Figure 5: The radial magnetic field generated from magnet on the sample surface with the magnet current 100 A and the corrected separation between the magnet and the sample 1.465 mm.

MEASUREMENTS

The calibrated system was used to measure bulk and thin film superconducting samples.

Bulk Superconductors

Bulk Nb sample of thickness 88.9 µm was measured at 4.35 K. The centre Hall probe detected the full flux penetration at the applied magnetic field 134.7 ± 2.8 mT (Fig. 6). The penetrated field declined along the sample radius and the opposite polarity at the 10 mm was observed. Figure 7 illustrates the field penetration data at 4.35 K and 1.97 K.

However, the measured field of full flux penetration depends on the sample thickness as well, because the Hall sensors are mounted at the opposite side of the sample.

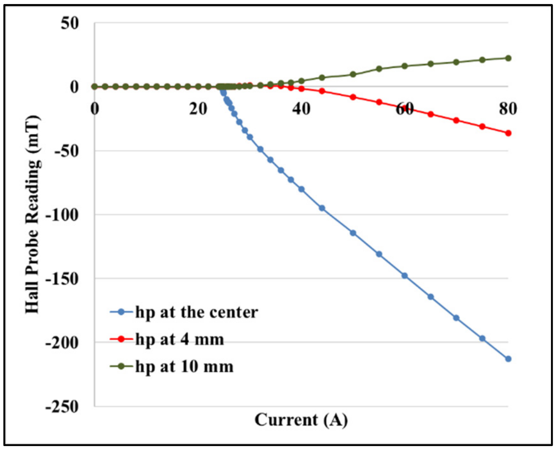

Figure 6: Magnetic field penetration measurements on bulk Nb with thickness 88.9 µm at 4.35 K.

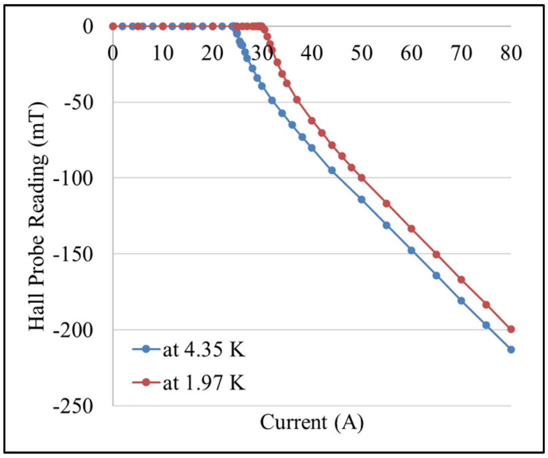

Figure 7: The centre Hall Probe response against bulk Nb at 4.35 K and 1.97 K.

Thin Film Superconductors

We measured a 1.5 µm thick Nb_3Sn thin film grown on sapphire (Al_2O_3) wafer by multilayer sequential sputtering at room temperature and annealed at 950 °C. Figure 8 shows the results of flux penetration measurement on this film. Unlike bulk superconductors, the Nb3Sn films exhibit clear flux jumps due to vortex avalanches associated with thermo-magnetic instabilities (blue curve). The first full penetration was detected at 137.5 ± 2.8 mT. It turned out that the flux jumps can be mitigated by improving heat transport across the sample. To show this, we replaced the sapphire separator plate by a copper plate in order to increase the thermal conductivity and suppress flux jumps. As shown by the red curve in Fig. 8, the flux jumps disappeared, but the first full penetration field remained the same. Then, we reduced the current ramp rate from 0.5 A/s to 0.1 A/s and found that the field of full flux penetration doubles, as indicated by the green curve.

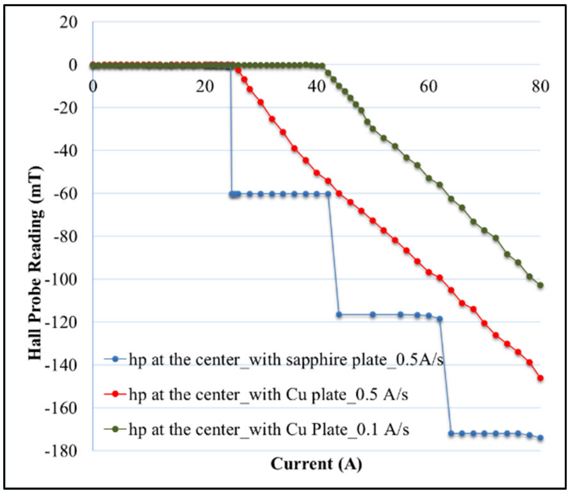

Figure 8: The centre Hall probe responses against forward current observed for Nb_3Sn thin film fabricated on sapphire substrate having 1.5 µm thickness.

CONCLUSION AND FUTURE WORK

The new experimental technique for magnetic field penetration measurement of superconducting samples was designed, built and calibrated at Jefferson Lab. This technique is appropriate for both bulk and thin films. Thin Nb_3Sn films show flux jumps due to thermo-magnetic instability, which is mitigated by increasing thermal conductivity across the sample. The penetration field limit is increased by slowing down the current ramp rate. This system is ready for the future measurements of SIS multilayer superconductors.

ACKNOWLEDGEMENT

We would like to thank Charlie Reece for useful discussion and comments, Gianluigi Ciovati for providing equipment for the measurement system with initial guidance and Nizam Zayeed for providing the Nb_3Sn thin film. We also thank SRF and the machine shop staff at the Jefferson Lab for the technical support.

REFERENCES

[1] H. Padamsee, J. Knobloch, and T. Hays, *RF Superconductivity for Accelerators, 2nd Edition*. Weinheim, Germany: Wiley-VCH, 2008.

[2] A. Gurevich, "Theory of RF superconductivity for resona cavities", *Supercond. Sci. Technol.*, vol. 30, p. 034004, 2017. `doi:10.1088/1361-6668/30/3/034004`

[3] A. -M. Valente-Feliciano, "Superconducting RF materials other than bulk Nb: a review", *Supercond. Sci. Technol.*, vol. 29, p. 113002, 2016. `doi:10.1088/0953-2048/29/11/113002`

[4] C. Z. Antoine *et al.*, "Optimization of tailored multilayer superconductors for RF application and protection against premature vortex penetration", *Supercond. Sci. Technol.*, vol. 32, p. 085005, 2019. `doi:10.1088/1361-6668/ab1bf1`

[5] A. Gurevich, "Enhancement of rf breakdown field of superconductors by multilayer coating", *Appl. Phys. Lett.*, vol. 88, p. 012511, 2006. `doi:10.1063/1.2162264`

[6] A. Gurevich, "Maximum screening fields of superconducting multilayer structures", *AIP Advances*, vol. 5, p. 017112, 2015. `doi:10.1063/1.4905711`

[7] T. Kubo, "Superheating fields of semi-infinite superconductors and layered superconductors in the diffusive limit: structural optimization based on the microscopic theory", *Supercond. Sci. Technol.*, vol. 34, p. 045006, 2021. `doi:10.1088/1361-6668/abdedd`

[8] I. H. Senevirathne, G. Ciovati, and J. R. Delayen, "Measurement of the Magnetic Field Penetration into Superconducting Thin Films", in *Proc. 19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, Jun.-Jul. 2019, pp. 978-982. `doi:10.18429/JACoW-SRF2019-THP050`

[9] Los Alamos National Laboratory, Los Alamos Accelerator Code Group, Download Area for Poisson Superfish, `https://laacg.lanl.gov/laacg/services/download_sf.phtml`