ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP050

MEASUREMENT OF THE MAGNETIC FIELD PENETRATION INTO SUPERCONDUCTING THIN FILMS*

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Abstract

The magnetic field at which first flux penetrates is a fundamental parameter characterizing superconducting materials for SRF cavities. Therefore, an accurate technique is needed to measure the penetration of the magnetic field directly. The conventional magnetometers are inconvenient for thin superconducting film measurements because these measurements are strongly influenced by orientation, edge and shape effects. In order to measure the onset of field penetration in bulk, thin films and multi-layered superconductors, we have designed, built and calibrated a system combining a small superconducting solenoid capable of generating surface magnetic field higher than 500 mT and Hall probe to detect the first entry of vortices. This setup can be used to study various promising alternative materials to Nb, especially SIS multilayer coatings on Nb that have been recently proposed to delay the vortex penetration in Nb surface. In this paper, the system will be described, and calibration will be presented.

INTRODUCTION

A superconductor can stay in the Meissner phase if no nucleation sites for vortices are presented. The maximum field above which this metastability disappears is called the superheating critical field (H_{sh}). In another words, the superheating field determines the field at which vortices start to penetrate into the superconductor with no topographic defects on the surface. For type I superconductor, H_{sh} is higher than thermodynamic critical field (H_c), which defines the condensation energy of the superconducting state. H_{sh} of type II superconductor is above the lower critical field (H_{c1}). The actual superconducting surface involves a tremendous number of topographic defects which cause local penetration of vortices at the field $H_{c1}< H< H_{sh}$ or even at $H<H_{c1}$ [1].

The investigation of magnetic field penetration into materials that are used to fabricate SRF cavities is important because the field at which the first onset penetration determines the onset of increased power dissipation. The high-power dissipation limits the maximum possible accelerating gradient (E_{acc}) of the cavity. With the development of the Nb SRF cavity technology, E_{acc} of 40-50 MV/m is now achievable [2]. A large H_{sh} is attractive for future high energy accelerators, as cavities reaching peak magnetic field close to H_{sh} would greatly decreases the overall length and cost.

In order to investigate magnetic field penetration into SRF materials, an accurate experimental method is needed. Different experimental methods are explained in Refs. [3-5]. This paper will discuss the design and calibration of an experimental setup which allows us to capture magnetic field penetration into a superconducting sample. This experimental set up can be used to study potential alternative superconducting materials to Nb for SRF applications.

METHODOLOGY

The experimental setup was designed and built to measure onset penetration directly through bulk, thin film and multilayer superconducting samples. The samples prepared for the measurements are bulk superconductors and superconducting thin films fabricated on a dielectric or metallic substrate. As shown in Figure 1, a superconducting solenoid magnet made using NbTi thin wire is placed in the middle of the sample to generate a magnetic field parallel to the sample. Since the size of the magnet is small compared to the sample, magnetic field becomes negligible few diameters away from the center of the magnetic coil, with no edge and demagnetizing effect.

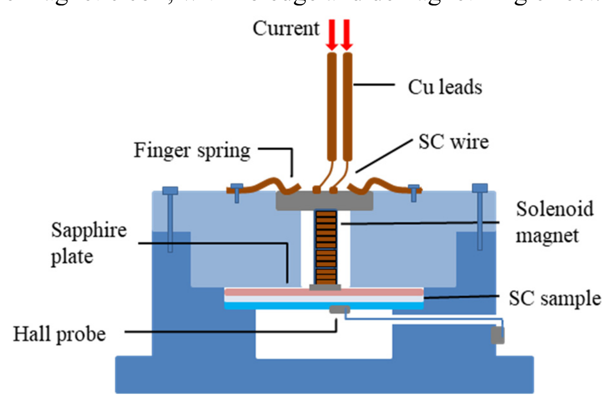

Figure 1: Schematic cross section of experimental setup.

In the Meissner state the sample acts as a magnetic mirror which cancels out vertical component of the magnetic field. The field felt by the sample is equal to twice the radial component of the magnetic field that would be generated by the solenoid in free space. Since the radial magnetic field is parallel only to one side of the sample, this field configuration closely resembles the SRF cavities.

Another sapphire plate with thickness 0.5 mm is placed on the top of the sample to maintain a fixed distance between the sample and the magnet. This also helps to keep

*Work supported by NSF Grants PHY-1734075 and PHY-1416051, and DOE Award DE-SC0010081
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ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-THP050

the sample intact during the experiment. In order to measure onset penetration of the magnetic field, the magnetic field sensor (Hall probe) is placed underneath the sample. The Hall probe chosen to measure the magnetic field is the cryogenic probe HHP-NP from Arepoc, which measures the magnetic field normal to the probe and it has an active area of 500 µm x100 µm. Figure 2 shows a picture of nonmagnetic container which is used to assemble the sample, solenoid magnet, and Hall probe symmetrically.

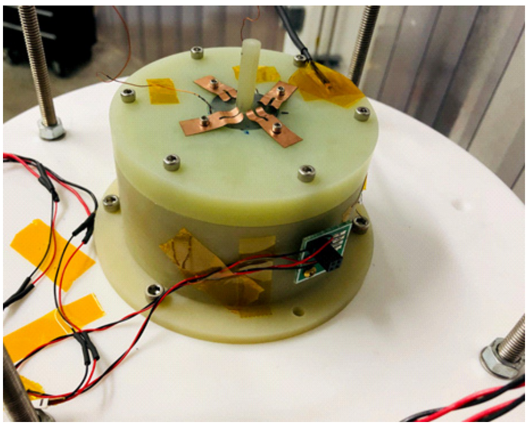

Figure 2: External view of nonmagnetic container which supports the sample, solenoid magnet, and Hall probe symmetrically.

This system is placed in a liquid He dewar at Jefferson lab to perform the experiment at both 2 K and 4 K. Figure 3 represents the schematic diagram of the complete experimental setup which is placed in liquid He dewar. The penetration of the magnetic field can be identified when the Hall probe reads the magnetic field for the first time while gradually increasing the external magnetic field provided by the superconducting solenoid magnet.

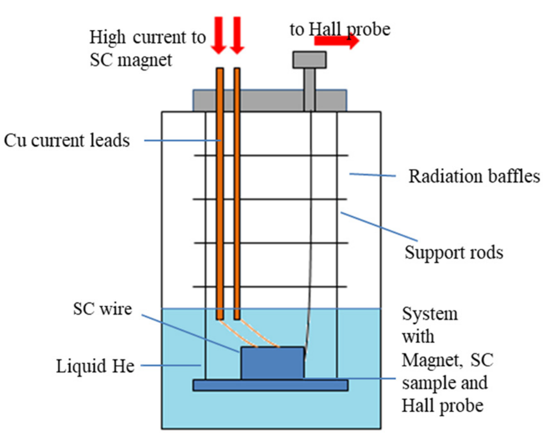

Figure 3: The details of the cryogenic insert at Jefferson Lab.

MAGNET

Superconducting NbTi wire with thickness 0.317 mm, which can hold a maximum current of 100 A was used to fabricate the superconducting magnet. Superconducting wire can generate intense magnetic field compared to Cu coil using low electrical power input. This magnetic coil was fabricated by winding NbTi thin wire carefully on dielectric spool using strategies followed in magnet fabrication. An epoxy was used after winding to obtain a good insulation and a monolithic structure which cannot allow any movement of the conductor inside the coil (Figure 4).

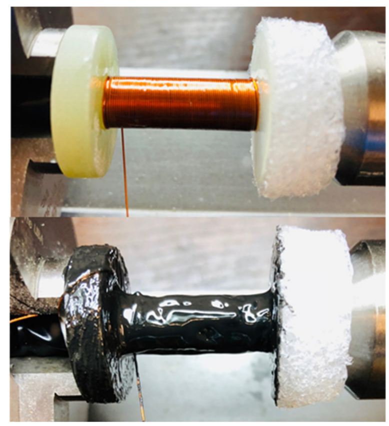

Figure 4: Superconducting solenoid magnet before (top) and after (bottom) applying an epoxy.

The computer code Poisson [6] was used to simulate the expected field generated by the coil, when it is placed above the superconducting sample. This gives the idea of the dimensions of the magnet with required number of turns and maximum current for a given distance between the sample and the magnet.

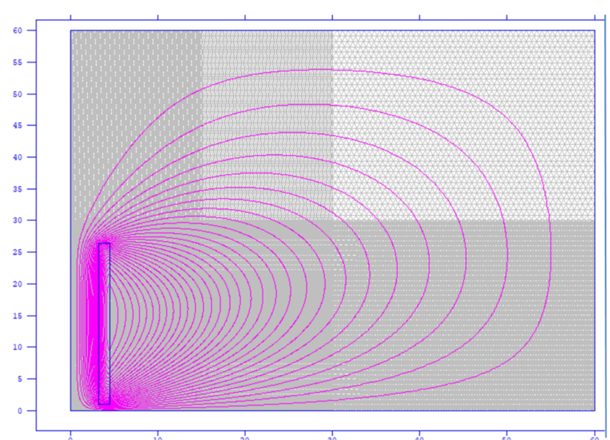

Figure 5: Field lines from the right half of solenoid magnet placed at 1 mm above the superconducting sample.

The fabricated magnet consists of 4 layers of 80 turns to produce field on the sample higher than 500 mT. It is 25.36 mm in length and 9.04 mm in diameter with core diameter

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6.5 mm. The magnetic field configuration of solenoid magnet placed 1 mm above the superconducting sample is depicted in Figure 5.

The maximum field felt by the sample is at the edge of the coil and decreases with the radius of the sample. Figure 6 represents the radial magnetic field felt by the sample along the sample radius, when the magnet current is 100 A. In addition, this solenoid magnet must have quench protection. This can be achieved by powering up the magnet using a power supply with a quench protection or by adding resistance or diode in parallel to the output of the magnet.

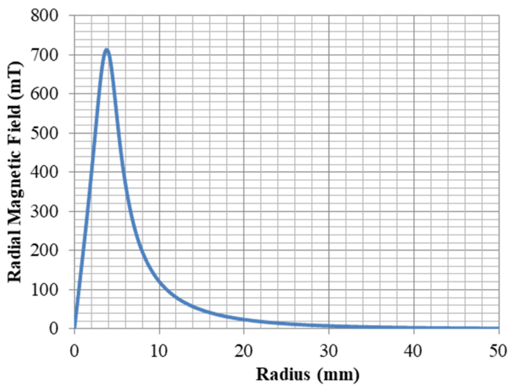

Figure 6: The radial magnetic field felt by sample when magnet is powering up by 100 A (using Poisson simulation [2]).

CALIBRATION

The calibration of our measurement system was performed in three steps. For the first, the high linearity HHP-NP Hall sensor was calibrated in order to determine its sensitivity. This calibration was performed using a superconducting solenoid magnet which gives a maximum field 1 T. Measurements were performed in the increasing and the decreasing directions in order to examine the linearity of the characteristic. The sensitivity of the sensor was calculated from the slope of the obtained characteristic curve of Hall voltage plotted against magnetic field (V_H=f(H)) and it gave us the sensitivity value equals to 157.7 mV/T ± 0.2% at 4.35 K.

Then the calibration of the fabricated solenoid magnet was done using the calibrated Hall sensor. At this step, dependence of the magnetic flux density generated by the solenoid magnet on its electrical current is examined. A final result of the calibration is the magnetic field as a function of the applied current (B= g (I)). The sensor was placed in the middle of the solenoid, so that the sensor surface is perpendicular to its longitudinal axis and the magnetic field. Measurements were performed under forward and reverse electrical current in order to examine the linearity of the characteristic. According to the linear fit of measured results, the slope of the B=g(I) characteristic of the solenoid magnet is 2.4 mT/A ± 0.2% at 4.35 K. Since the NbTi wire can hold the current up to 100 A, we can power up the magnet with the current below 100 A without quenching the magnet.

In the third step, calibration was performed on the complete system using both calibrated Hall probe and solenoid magnet. 99.99% pure bulk superconducting Lead (Pb), Tantalum (Ta) samples from Advent Research Materials Ltd and Niobium (Nb) sample from Stanford Advanced Materials shown in Table 1 have been prepared for this step of calibration. Pb, Ta and Nb are well known superconductors and many investigations have been performed to characterize them. The critical field values from Refs. [7-9] can be used to calibrate our system. All samples are 50 mm in diameter and 0.1 mm in thickness.

Table 1: Details of Reference Samples Used in Calibration of the Experimental Setup

Reference Sample	Critical Temperature (K)	Temperature at measurements (K)
Pb	7.20	4.35
Ta	4.50	2.00
Nb	9.26	4.35

The curves in Figure 7 represent the Hall probe response against Pb, Ta and Nb samples while powering up the magnet with gradually increasing current. These curves indicate the first penetration of magnetic flux for each three sample clearly, which confirms that this technique is successful to determine the surface fields at which first flux penetrates through the various superconducting samples.

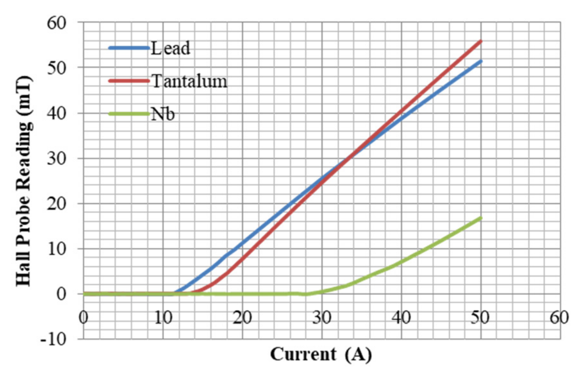

Figure 7: Field Penetration measurements with 99.99% pure Lead, Tantalum and Niobium samples.

Figure 8 shows the calibration curve of the experimental system which is a linear representation of the critical magnetic field against current at which first penetration detected using Hall sensor of each three material.

This experiment was repeated with samples having different thicknesses, between 0.1 mm and 0.5 mm. Table 2 shows the comparison of current at the critical field values corresponding to samples with different thicknesses. When the sample thickness increases, the current at which the magnetic field is detected at the opposite side of the sample increases.

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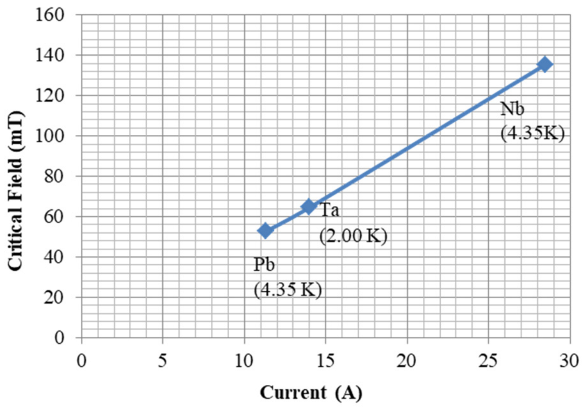

Figure 8: The calibration curve of the experimental setup.

This is possibly because the identification of first flux penetration through the Hall probe is delayed while magnetic flux is passing through the sample thickness. We estimate that this effect would negligible with 0.1 mm sample thickness. This will be explained properly in experimental and theoretical work planned for near future.

Table 2: The Dependence of the Current at First Penetration on the Sample Thickness

Sample	Thickness (mm)	Current at first penetration (A)
Pb	0.1	11.3
	0.5	15.0
Ta	0.1	14.0
	0.5	17.0

We used this calibrated system to determine the field penetration of a thin film. Figure 9 shows our first penetration measurement done using Nb thin film coated on a-plane sapphire (Al_2O_3 (110-2)) produced by electron cyclotron resonance post-ionization (ECR) at continuous ion energy of 94 eV. The bake-out and coating temperatures were 500 C°. The resulting film is about 1 µm thick Nb (110) with a Tc of 9.34 ± 0.07 K and RRR value of about 50. Our calibration indicates that the first field penetration of this Nb thin film occurred at 94 mT.

The field penetration of a thin film heavily depends on the surface quality, which is closely related to the coating process. This experiment is going to be continued to study field penetration on different coating parameters which contribute to the film quality.

Furthermore, we were able to observe the magnetic response of the superconducting samples under forward and reverse current. In Figure 10, the curves obtained for Tantalum sample with thickness 0.1 mm at 2.0 K describes the hysteretic behaviour of superconducting sample.

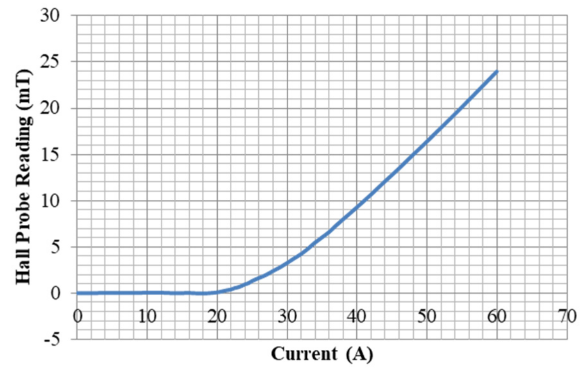

Figure 9: The Hall Probe response against Nb thin film.

Once the external field exceeds the value H_c (H_{c1} for type II superconductor) and field penetrates the sample, the magnetization is no longer reversible. The reverse path falls above the initial magnetization curve and leads to a positive value in zero external field. This is due to formation of trapped vortices inside the superconductor. Repeating curve follows the same shape as first time, but begins with positive value mentioned above.

The experimental results are very sensitive to the accuracy of the position and orientation of each and every part in this assembly. Misalignment of the magnet can affect the results. To minimize experimental errors, all experiments were carried out with the same orientation of the solenoid magnet and the same position of Hall probe.

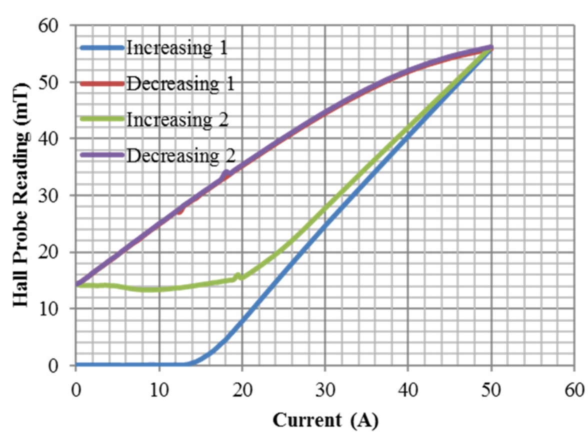

Figure 10: The Hall probe responses observed for Tantalum sample having 0.1 mm thickness while increasing and decreasing current two times.

CONCLUSIONS

The new experimental setup for magnetic field penetration measurements of superconducting samples was designed and built successfully at Jefferson Lab. 99.99 % pure Lead, Tantalum and Niobium bulk samples were used to calibrate the system accurately and calibration follows linear relationship. This experimental system is appropriate for bulk samples as well as thin films. The linearity of calibration curve confirms that the system is

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ready for the future measurements to study possible alternatives to Nb and multilayer system.

ACKNOWLEDGEMENT

We would like to thank Anne-Marie Valente-Feliciano for providing thin films. We also thank for the technical support by the SRF staff and the machine shop staff at Jefferson Lab.

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