MAGNETIC FIELD PENETRATION TECHNIQUE TO STUDY FIELD SHIELDING OF MULTILAYERED SUPERCONDUCTORS*

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Abstract

The SIS structure which consists of alternative thin layers of superconductors and insulators on a bulk niobium has been proposed to shield niobium cavity surface from high magnetic field and hence increase the accelerating gradient. The study of the behavior of multilayer superconductors in an external magnetic field is essential to optimize their SRF performance. In this work we report the development of a simple and efficient technique to measure penetration of magnetic field into bulk, thin film and multilayer superconductors. Experimental setup contains a small superconducting solenoid which can produce a parallel surface magnetic field up to 0.5 T and Hall probes to detect penetrated magnetic field across the superconducting sample. This system was calibrated and used to study the effect of niobium sample thickness on the field of full magnetic flux penetration. We determined the optimum thickness of the niobium substrate to fabricate the multilayer structure for the measurements in our setup. This technique was used to measure penetration fields of Nb_3Sn thin films and Nb_3Sn/Al_2O_3 multilayers deposited on Al_2O_3 wafers. The system was optimized to mitigate thermomagnetic flux jumps at low temperatures.

INTRODUCTION

For decades, bulk Nb has been the material of choice for SRF accelerator cavities due to its machinability and desirable superconducting properties. With continues progress in SRF technology, the performance of Nb cavities has steadily improved and approach theoretical limits. Best Nb cavity can reach breakdown field up to the thermodynamic critical field, B_c~200 mT which corresponds to accelerating gradient ~40-50 MVm^{-1}[1-4]. Further significant increase of accelerating gradients in the SRF cavities requires superconductors with superheating fields and critical temperatures higher than those for Nb to provide lower surface resistance R_s (high quality factor) and higher breakdown fields (high accelerating gradient) in the Meissner state [5,6]. Since clean Nb has the highest lower critical field $B_{c1} \simeq 180$ mT among type-II superconductors, all other alternative materials have B_{c1} lower than B_{c1}^{Nb}. To address this problem S-I-S multilayer structures with thin superconductors (S) with $B_c > B_c^{Nb}$ separated by dielectric (I) layers deposited on bulk Nb (Fig. 1) have been proposed to enhance the peak surface magnetic field by increasing the field onset of penetration of vortices [7,8]. Surface materials and topographic defects can cause premature local penetration of vortices resulting in hot spots on the cavity surface [9]. The insulating layers block propagation of vortices to the bulk of Nb cavity and increases the breakdown field of the cavity. By developing the S-I-S coating technology, we would be able to achieve high thermal stability to operate cavity at 4.2 K to reduce the operating costs.

The study of SIS multilayers is important to optimize their SRF performance. Many such investigations are going on to study technological issues and SRF characteristics of SIS multilayers [10-17]. This work is based on investigation of the behavior of S-I-S multilayer structures in an external dc magnetic field. Since, maximum accelerating gradient is determined by the peak surface magnetic field at the inner cavity surface, the field onset of magnetic flux penetration is a key characteristic of the breakdown field and the high-field performance of SRF cavities. To measure the field of flux penetration in SRF materials, we developed a simple and efficient technique.

This measurement system was used to investigate bulk Nb, Nb_3Sn thin films and multilayer structure which consists of Nb_3Sn thin films. Nb_3Sn is an attractive choice for the next generation coating materials which could nearly double the maximum accelerating gradient as compared to the best Nb cavities [5].

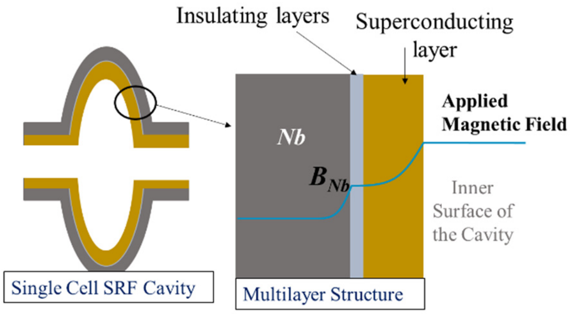

Figure 1: SIS multilayers fabricated on niobium cavity enhances peak surface magnetic field at inner cavity surface.

MEASUREMENT TECHNIQUE

This technique is designed to efficiently measure full flux penetration across the superconducting sample using a simple methodology. To mimic the field configuration in SRF cavities, the magnetic field from the magnet should be applied to the one side of the sample so that the field lines are parallel to the surface, as shown in Fig. 2. Here a NbTi superconducting magnet is placed above the flat sample to produce parallel magnetic field on the surface of the sample up to 500 mT. The magnet is small enough compared to the sample diameter to prevent penetration of magnetic

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flux from the edges (Fig. 3 (b)). Two copper leads are used to pass high current to the magnet as shown in Fig. 3 (a).

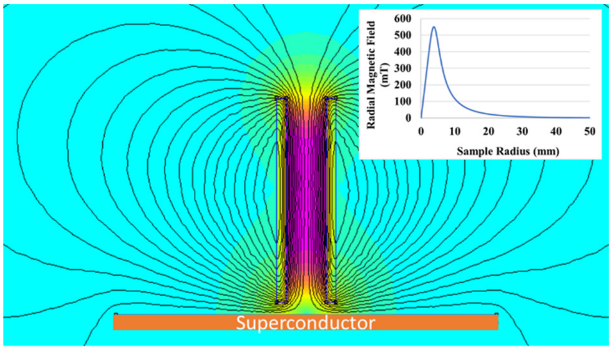

Figure 2: Magnetic field distribution when magnetic field is fully excluded from the superconductor in Meissner state. Right corner: magnetic field on the sample surface decays along the sample radius avoiding edge effect.

Sample holder is designed for 50 mm diameter discs (Fig. 3 (b)). Three high linearity cryogenic Hall probes shown in Fig 3(d) are mounted at three different locations under the sample to measure magnetic fields at the centre, at 4 mm and 10 mm from the centre. A separator plate is inserted between the sample and the magnet to maintain a fixed distance between them. Detailed experimental setup is described in [16].

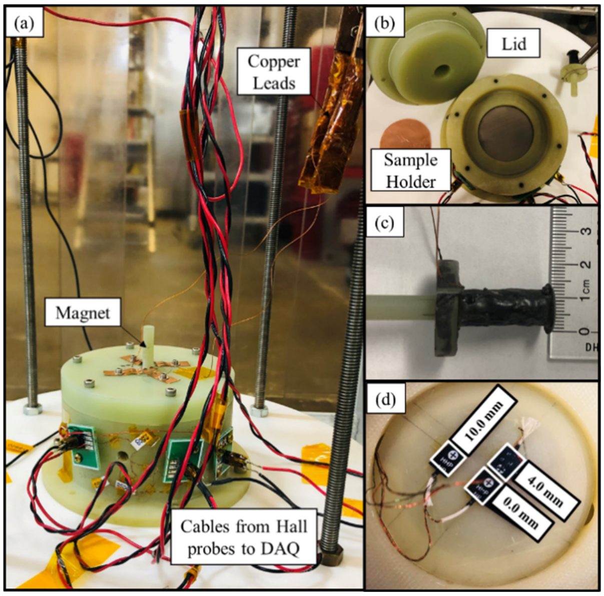

Figure 3: The setup assembly of the experimental system (a) Outer (b) Inner view of the non magnetic container (c) Superconducting magnet coated with epoxy layer (d) Three Hall probes mounted at different locations.

For the first, sample is cooled to a particular temperature (4.35 K or 1.97 K) using liquid helium with a zero magnetic field. Then the magnet current is increased gradually, at a certain magnet current, superconductor shows mixed state transition and at the full flux penetration across the sample, Hall probes can detect penetrated field.

Calibration of the setup is done in few steps and found that maximum magnetic field on the sample is 5.5 mT/A [17]. This simple and efficient technique is dedicated to measure bulk Nb and candidate thin film superconductors to multilayer system, eventually to study shielding effect of multilayer structure to Nb cavities.

BULK NIOBIUM

We measured four Nb samples with different thicknesses. According to Fig 4, magnet current at first flux detection is linear with the sample thickness. Since the superconducting magnet can hold current less than 100 A, sample should be thin enough to be measured in our system. Apparently, 250 µm thick Nb substrate is convenient to deposit SIS multilayers and test them with this experimental setup since it leaves more room to demonstrate enhanced breakdown field.

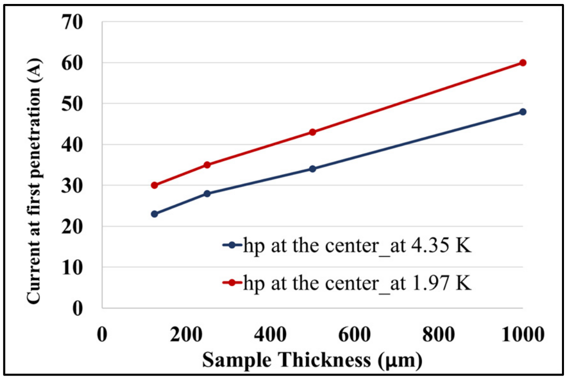

Figure 4: The current at first flux penetration with respect to the sample thickness of niobium with RRR= 356.

Figures 5 and 6 depict the flux penetration through 250 µm bulk Nb at 4.35 K and 1.97 K. Three Hall probes read first flux penetration at the same time. Center probe detected strongest penetrated magnetic field which decreased along the sample radius. The opposite field polarity at 10 mm from the center was observed due to the dipole-like magnetic field line configuration of the magnet.

NIOBIUM-TIN THIN FILMS

As Nb_3Sn has higher T_c=18 K and B_c=530 mT compared to those of Nb [18], it is an attractive candidate for SIS multilayers.

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° by Nizam Sayeed at Jefferson Lab.

First the sample was loaded with sapphire plate as a separator. Since the sample is sandwiched between week thermal conducting plates, sudden change in the internal magnetic flux due to vortex avalanching causes flux jumps as shown by blue curve in Fig. 7. Materials defects in a superconductor act as pinning centers, which impede the vortex motion. Penetration of vortices causes local heating and depinning of neighboring vortices from their pinning sites, which can develop in a thermo-magnetic avalanche or partial flux jumps [19]. This process is controlled by thermal conductivity across the sample which can be improved by replacing the sapphire plate with a copper plate to supress

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the flux jumps. As shown by the red curve in Fig. 7, the flux jumps disappeared, but the first full penetration field remained the same at 137.5 ±2.8 mT.

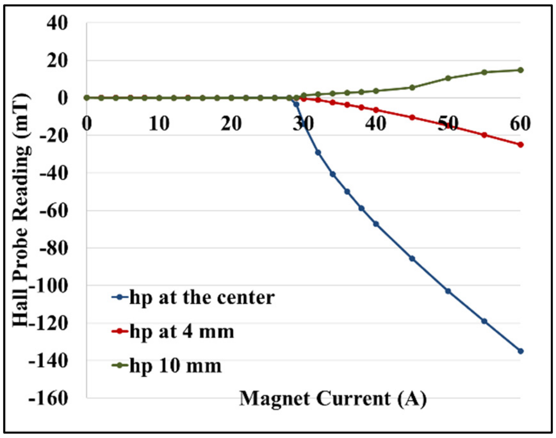

Figure 5: Three Hall probe responses against 250 µm thick niobium substrate at 4.35 K. First penetrated flux is detected at 154.0 ± 2.8 mT.

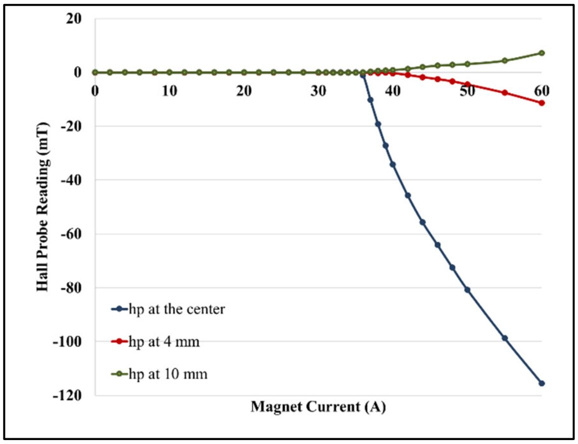

Figure 6: Three Hall probe responses against 250 µm thick niobium substrate at 1.97 K. First penetrated flux is detected at 192.5 ± 2.8 mT.

the flux jumps. As shown by the red curve in Fig. 7, the flux jumps disappeared, but the first full penetration field remained the same at 137.5 ±2.8 mT.

We found that reducing the current ramp rate from 0.5 A/s to 0.1 A/s doubles the current at full flux penetration, as indicated by the green curve. At higher current ramp rates and small heat capacity and thermal conductivity at low temperatures, dissipative motion of vortices causes significant local overheating and premature flux penetration. This process can be mitigated by slower ramping of the applied magnetic field which reduces the overheating effects [19].

We also investigated Nb_3Sn/Al_2O_3 multilayers deposited on R-plane of 300 µm thick sapphire wafers by Chris Sundahl at University of Wisconsin-Madison [20]. This multilayer sample consists of four 125 nm Nb_3Sn layers separated by 6 nm Al_2O_3 interlayers. A 200 nm thick Nb film was deposited on the back side of the wafers to prevent leakage of RF field during cavity measurements. With the increase of the effective thermal conductivity by the Cu plate, the penetration field of 115.5 ± 2.8 mT measured at 4.35 K exceeds H_{c1} of Nb_3Sn as shown in Fig. 8.

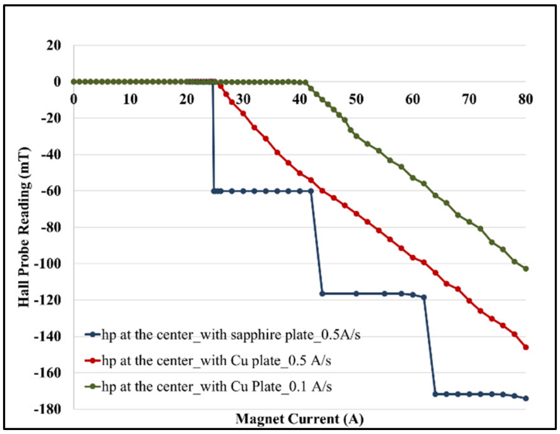

Figure 7: Increase of field at first flux penetration by increasing of thermal conductivity across the sample.

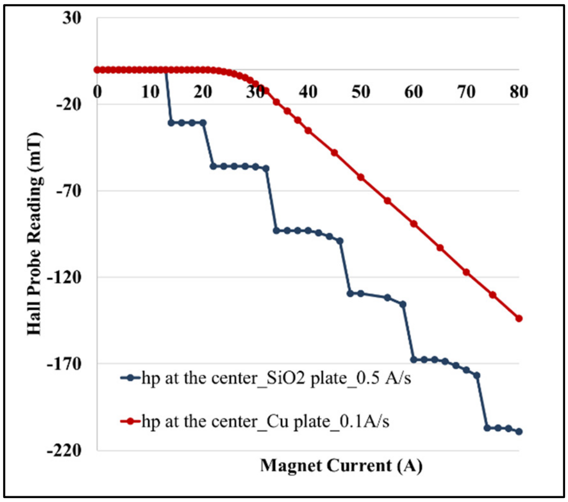

Figure 8: The measurement of Nb_3Sn/Al_2O_3 multilayers on Al_2O_3 wafer grown at University of Wisconsin [20].

CONCLUSION

Magnetic field penetration technique is developed to investigate breakdown fields in bulk, thin film and multilayered superconductors for SRF applications. Thin films show flux jumps due to thermo-magnetic instability, which is mitigated by increasing thermal conductivity across the sample. The penetration field is increased by slowing down the current ramp rate. First measurement on S-I-S multilayers shows that our technique is appropriate for study the shielding effect of SIS structures.

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