Facility for the Characterization of Planar Multilayer Thin Film Superconductors

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Abstract. The maximum accelerating gradient of SRF cavities can be increased by raising the field of full flux penetration, $H_{vp}$. One method which can potentially increase $H_{vp}$ is to use structures consisting of alternating layers of superconductors and insulators (SIS). Magnetometry is commercially available but consists of limitations, such as SQUID measurements which apply a field over both superconducting layers, so $H_{vp}$ cannot be measured. If $H_{vp}$ is to be measured for SIS coatings, a parallel, local magnetic field must be applied from one plane of the sample, with no field on the opposing plane. A field penetration experiment has been developed at Daresbury laboratory allowing $H_{vp}$ to be measured using a local, parallel DC magnetic field. Using a field much smaller than the sample allows limitations such as edge effects to be significantly reduced. By increasing the field, $H_{vp}$ can be found by using 2 hall probes, one either side of the sample. The experiment was designed to use a variable temperature insert (VTI) to run in a cryogen free environment, but has been running in a LHe bath for thermal stability.

1. Introduction

The maximum accelerating gradient $E_{acc}$ for SRF cavities is limited due to the superconducting properties of bulk Nb. One method to increase the maximum accelerating gradient which was theorized by Gurevich\textsuperscript{[3]}\textsuperscript{[4]} is to use multilayer S-I-S coatings. The use of S-I-S coatings cause the field to be screened by the first superconducting layer, reducing the field applied to the second superconducting layer. Hence, the bulk superconducting layer will reach $H_{c1}$ at an increased magnetic field.

There are various commercial magnetometry applications which can be used to study the magnetic properties of superconductors, such as SQUID magnetometry. A small sample is placed into a magnetic field which is produced over the whole sample. As the magnetic field is increased, the sample responds through the Meissner effect, as the sample opposes the field. The magnetization of the sample is measured, allowing the DC fields of the sample to be obtained. Although this method works for studying the superconducting effects of planar single layer structures, it cannot be used to study the effects of multilayer S-I-S structures easily. For multilayer S-I-S structures to be studied in a SQUID magnetometer, the sample must be an
ellipsoid structure, with each superconducting layer deposited having a consistent thickness over the entire sample, which is a difficult task to achieve.

Substrates for sample deposition are commonly planar. However, planar multilayer S-I-S structures cannot be tested using SQUID magnetometry due to the applied parallel field \(H_a\) penetrating through the insulating layer as shown in Fig 1. When the field penetrates through the insulating layer, the screening effect expected to be observed with S-I-S structures cannot be observed. To observe the the screening effect created by multilayer structures the field must be applied from one side of the sample with no field on the opposing side to allow the field to decay as it passes through the structure, as shown in Fig 2.

Figure 1: A simplified sketch of how \(H_a\) applied by a SQUID magnetometer penetrates a multilayer structure.

Figure 2: A simplified sketch of how \(H_a\) applied from one side of a multilayer penetrates a multilayer structure.

One method to study the screening effect produced by multilayer structures, suggested by A. Gurevich, was to use a small coil to produce a parallel field, and place a long sample tube through the center \([2]\). A facility has already been designed and tested at Daresbury laboratory which has tested this method which is further discussed in \([2]\), which consisted of using two hall probes. One hall probe was placed outside the sample tube, whilst another hall probe was placed inside the tube. As the field produced by the solenoid was ramped up, the outer hall probe measured a field whilst the hall probe inside the tube read zero field due to being shielded.
by the sample. The field of full flux penetration was determined when the internal Hall probe started to read a field. When both Hall probes read the same value/increased linearly, the applied field was greater than $H_{c2}$.

However, the deposition technique of tubes does not resemble the deposition of a cavity, and is not standard practice. Standard practice of deposition at Daresbury Laboratory is on planar Cu gaskets. A facility was then designed to recreate a magnetic field penetration idea for planar samples rather than tubular samples.

2. Method
It was determined that a local parallel magnetic field should be created on the sample surface. By applying a field much smaller than the sample size, the field should not penetrate through the sample early due to edge effects. The required field can be created by using a ferrite C-shaped dipole magnet with a superconducting solenoid. Increasing the current applied to the solenoid increases the field linearly until the yoke saturates. Two Hall probes are used, one placed in between the dipole to read the applied field (HP1), and one placed on the opposing side of the sample (HP2) as shown in Figure 3. As with the tubular samples, HP1 will increase as the field is ramped up whilst HP2 will read zero field due to being screened by the sample. When HP2 begins reading a non-zero field, $H_{vp}$ is measured. By further increasing the field $H_{c2}$ can be found when the field measured from HP2 becomes linear.

![Figure 3: An image of the magnet showing where the Hall probes will be placed with respect to the magnet. A Hall probe is placed in between the dipoles to determine the field on the surface of the magnet, HP1. A second Hall probe is placed on the opposing side of the sample to determine when the field breaks through, HP2. The gap between the dipoles is 2mm, the total length of the magnet is 40 mm.](image-url)

3. Experimental
A variable temperature insert (VTI) has been designed at Daresbury Laboratory which contains a magnetic field penetration experiment. A parallel field is applied by the use of a ferrite C-shaped dipole magnet with a low temperature superconducting (LTS) solenoid shown in Figure 3. The C-shaped dipole magnet was chosen to guide the flux through the yoke to produce a parallel field between the poles, as shown in Figure 4. Increasing the current increases the field produced by the magnet. When the field is increased above $H_{vp}$, the field will penetrate through the superconducting sample as shown in Figure 5. The gap between the dipole is 2mm, which
Figure 4: An illustrative simulation of the magnet applying a parallel field below the field of full flux penetration.

Figure 5: An illustrative simulation showing the applied field once the field has been increased above the field of full flux penetration.

reduces the amount of stray flux produced from the parallel field. The full insert is shown in Figure 7, and is further discussed in [1].

4. LHe testing
The VTI did not reach the required temperature as discussed in [1], therefore a new approach has been built to ensure the facility works. A flange has been designed for an existing Dewar to
Figure 6: The normal to superconducting joins made at Rutherford Appleton Laboratory. Diodes are placed facing either way to short the superconducting leads in the case of quenching. The total length is 343.5 mm.

accommodate the insert, allowing no changes to be made to the insert. The Dewar is an open cycle system, with no LHe recovery. The insert is slowly lowered into the Dewar allowing the VTI to be vapour cooled, with the possibility of LN$_2$ pre-cooling to reduce the amount of LHe consumed. The use of LHe allows the sample and LTS magnet to remain at a stable temperature (4.2 K).

4.1. Results
Initially, a Cu gasket was placed in the sample area. The magnet was then tested to determine that both Hall probes were working, and to make sure both were in proximity of the applied field due to the thickness of the sample will move HP2 further away from the magnet source, in turn causing the field to fall off. In addition, by using a Cu gasket it enabled the field to be determined to the applied current.

It was found that the magnet saturated at a field of 137 mT, read by HP1 at a current of 7 A, which is much lower than expected. It was found that the field read by HP2 is $\approx \frac{1}{3}$ of HP1, shown in Figure 8.

The first test was to determine how reliable the equipment is, therefore it was decided to use a sample of bulk Nb. The current was ramped up from 0 A to 15 A, and stepped back down to 0 before reversing the polarity and repeating, allowing the maximum field produced by the magnet to be determined as well as determining at what field $H_{vp}$ was measured.

Initially the current was ran with a negative polarity, producing a negative field for HP1 as shown in Figure 9, corresponding to a maximum field of (-) 153 mT. However it was expected that HP2 should read zero field before $H_{vp}$, followed by a sharp increase as the field penetrates through the superconductor.

After the initial current was passed through the magnet, the polarity was immediately switched to positive and the field was ran up to 15 A, and then again in a negative polarity. It was observed that the field produced from the dipole magnet is asymmetric. It was initially thought that the C-shaped dipole had been magnetised, so the magnet was de-gaussed by ramping up the current and decreasing the current by 10 % each cycle, whilst alternating the polarity of the applied current. As the measurements were repeated, it was determined that running the magnet in a set polarity led to some magnetization/polarization around the sample, therefore any results taken after the initial field are unreliable, shown by the data in Figure 10. In addition, it can be seen that the after the initial test shown in Figure 9, there was a remanence field present within the dipoles as the field, up to 6.2 mT.

The raw data was taken from the initial run to acquire $H_{vp}$ shown in Figure 11 by removing
Figure 7: The variable temperature insert, VTI, total length of 950 mm.

the flux leakage. There is no field read by HP2 as the field produced from the magnet increases. The field read from HP2 then increased sharply at 117 mT, and continued increasing in a linear trend, hence $H_{vp}$ had been found.

5. CONCLUSION
A VTI has been designed and constructed for the purpose of testing planar multilayer thin film superconductors in a cryogen free environment. Due to the thermal conductivity of the system neither the sample or the magnet could be reduced to a temperature to be tested effectively. An open cycle liquid He system was built to test the insert without modifying the VTI. A Cu gasket was tested first to determine what field was produced at corresponding currents, which saturated at 153 mT. The low field is expected to have been produced due to an increased amount of flux leakage due to the permeability of the yoke reducing at cryogenic temperatures. In addition, there is a possibility of increasing the field by the use of superconducting magnet training.
Figure 8: The field as a function of applied current for both HP1 and HP2.

Figure 9: A hysteresis curve for bulk Nb.
Figure 10: A hysteresis curve for bulk Nb post de-gaussing.

Figure 11: First field post de gaussing, showing $H_{vp}$ through the bulk Nb sample.
Following the Cu gasket, a bulk Nb sample was tested, with the field of first full penetration measured to be 117 mT. The next step is to test more samples, and build a second generation of the facility to allow samples to be tested in a cryogen free environment.

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References
[1] D. Turner et al. Characterization of Flat Multilayer Thin Film Superconductors - 19th International Conf. on Superconducting Radio Frequency. 2019.
[2] O. B. Malyshev et al. A Facility for Magnetic Field Penetration Measurements on Multilayer S-I-S Structures - 17th International Conf. on Superconducting Radio Frequency. 2015.
[3] A. Gurevich. Enhancement of rf breakdown field of superconductors by multilayer coating. 2006. DOI: https://doi.org/10.1063/1.2162264.
[4] A. Gurevich. Maximum screening fields of superconducting multilayer structures. 2015. DOI: https://doi.org/10.1063/1.4905711.