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CHARACTERIZATION OF FLAT MULTILAYER THIN FILM SUPERCONDUCTORS*

D. Turner†[1,3], O. B. Malyshev[2,3], G. Burt[1,3], T. Junginger[1,3], L. Gurran[1,2,3], K. D. Dumbell[2,3], A. J. May[2,3], N. Pattalwar[2,3], S. M. Pattalwar[2,3]
[1]Lancaster University, LA1 4YW, Lancaster, UK
[2]ASTeC, STFC Daresbury Laboratory, WA4 4AD, Warrington, UK
[3]Cockcroft Institute, STFC Daresbury Laboratory, WA4 4AD, Warrington, UK

Abstract

The maximum accelerating gradient (E_{acc}) of SRF cavities can be increased by raising the field of initial flux penetration, H_{vp}. Thin alternating layers of superconductors and insulators (SIS coatings) can potentially increase H_{vp}, and hence E_{acc}. Magnetometry is commercially available but has limitations. For example, SQUID measurements apply a field over both superconducting layers, so H_{vp} through the sample cannot be measured. If SIS structures are to be investigated a magnetic field must be applied locally, from one plane of the sample, with no magnetic field on the opposing side to allow H_{vp} to be measured. A magnetic field penetration experiment has been developed at STFC Daresbury Laboratory, where a VTI has been created for a cryostat where H_{vp} of a sample can be measured. The VTI has been designed to allow flat samples to be measured to reduce limitations such as edge effects by creating a DC magnetic field smaller than the sample. A small, parallel magnetic field is produced on the sample by the use of a ferrite yoke. The field is increased to determine H_{vp} by using 2 Hall probes either side of the sample.

INTRODUCTION

The maximum SRF accelerating gradient E_{acc} of bulk Nb is defined by its superconducting properties. There are different methods suggested and studied on how to increase the maximum accelerating gradient, such as the use of multilayer S-I-S coatings which have been theorized by Gurevich[1, 2]. By using S-I-S coatings, the field is screened by the first superconducting layer, reducing the field applied to the second superconducting layer. Hence, the second superconducting layer will reach H_{c1} at a higher applied magnetic field.

To study the magnetic properties of thin films, one can use various magnetometer applications, such as SQUID magnetometry. In SQUID magnetometry, a small sample is placed into an applied magnetic field. By increasing the magnetic field, the magnetization of the sample is measured to allow H_{c1} and H_{c2} to be determined. However, to study multilayer structures, the sample should be deposited into an ellipsoid substrate, with consistent thickness of the layers all around the entire surface.

Samples are most commonly deposited on planar substrates. Using SQUID magnetometry is not ideal for the testing of multilayer structures on planar samples. This is due to SQUIDs applying a parallel magnetic field over the sample, on all sides of the sample, as shown in Fig 1. For a multilayer structure, the magnetic field will also penetrate the insulating layer between the two superconducting layers, causing the screening effect to be unable to be studied. To study planar multilayer structures one must apply a field from one side of a sample, allowing the field to decay as it penetrates through the multilayer, and allows the screening effect to be observed as shown in Fig. 2.

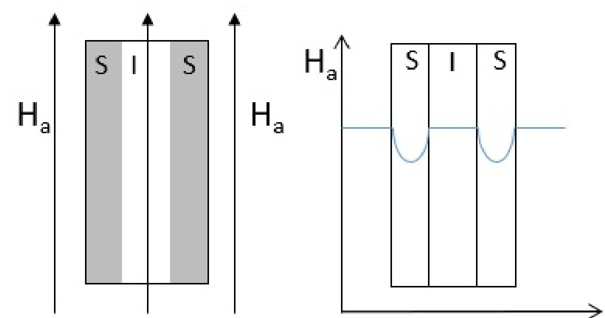

Figure 1: A simplified sketch of how a magnetic field (H_a) applied by a SQUID magnetometer penetrates a multilayer structure.

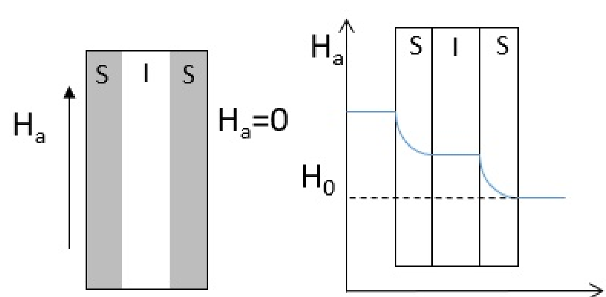

Figure 2: A simplified sketch of how a magnetic field (H_a) applied from one side of a multilayer penetrates a multilayer structure.

Gurevich proposed a method to study the effects of multilayer screening by applying a parallel field from a small coil and a long a tube placed in the center of the coil.

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† daniel.turner@cockcroft.ac.uk

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This idea was realised in previous work completed at Daresbury Laboratory [3]. The facility consisted of a superconducting solenoid, in which a sample tube made of bulk Nb or Cu, which can be coated with a thin film deposited on the outer wall. Hall probes were placed both inside and outside of the sample tube, half way through the solenoid such that the parallel field applied to the outer surface of the sample could be measured by one probe. By ramping up the magnetic field, the value of the Hall probe experiencing the magnetic field would increase, whilst the other would be shielded by the sample until the field reached H_{vp}, defined by when the second probe started measuring a field larger than zero.

When the magnetic field penetrated through the sample, the Hall probe inside the tube detected the magnetic field, the field of full vortex penetration, H_{vp}. When the applied field was greater than H_{c2}, both Hall probes would read the same value for the magnetic field.

The draw back testing tubular samples is due to the deposition on tubes not being standard practice, and the technique does not resemble the deposition of a cavity. The standard practice of deposition at Daresbury Laboratory is on flat copper gaskets. A facility should be designed such that planar samples can be tested, of which there is a backlog of samples at Daresbury Laboratory. The purpose of this work was to design, build and test a new facility for which would recreate a similar magnetic field penetration idea, but applied to planar samples.

METHOD

To provide localised penetration measurements, one should generate a strong magnetic field parallel to the sample surface at a small area of the sample and be negligible at the edges of the sample. This field can be created by the use of a ferrite C- shaped dipole, as shown in Fig 3 below.

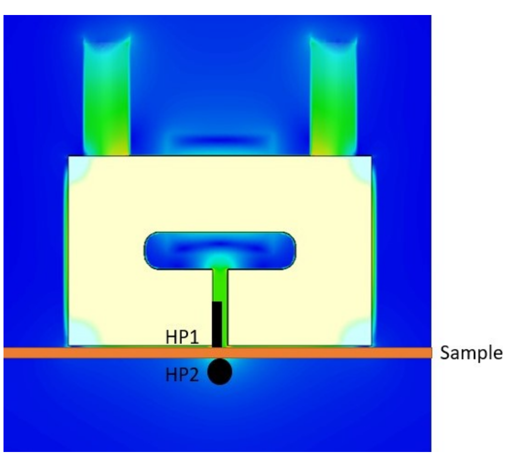

Figure 3: An illustrative simulation of the superconducting magnet showing the position of both HP1, HP2 and a sample.

By increasing the field produced by the dipole magnet, HP1 increases linearly with current whilst HP2 should not increase due to being shielded by a superconducting sample. At the point at which HP2 starts reading a field, H_{vp} is measured. Due to the samples consisting of thin films, the field should enter and leave from opposing sides of the sample, and hence H_{vp} can be measured accurately. By increasing the field further, the upper critical field can be found when HP2 readings become linear. The maximum field that can be produced in between the dipoles on the surface of the sample is approximately 0.5 T at 20 A, however this varies depending on the thickness of the sample/substrate as shown in Fig. 4. The two shaded areas shown on Fig 4 shows where the hall probes are situated compared to the maximum field. There is a possibility of further increasing the field if there is enough cooling capacity.

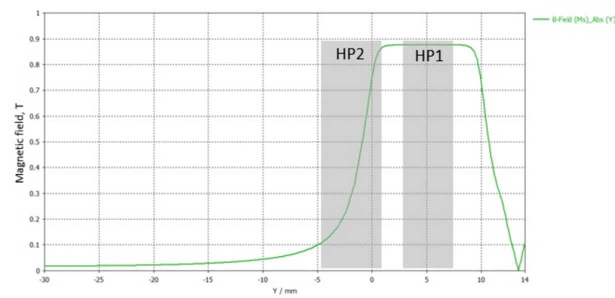

Figure 4: The magnetic field as a function of distance from the dipoles as determined from a simulation.

EXPERIMENTAL

A C-shaped dipole magnet has been designed with a low temperature superconductor (LTS) wire coiled around the magnet to produce a magnetic field. A C-shaped dipole magnet was chosen to guide the magnetic flux through the yoke to produce a parallel magnetic field in between the poles. As there is a 2 mm gap between the poles, so that the resultant field created is parallel to the sample with limited stray flux.

A variable temperature insert (VTI) has been designed and constructed to accommodate the magnetic field penetration experiment, see Fig 5. The cage which holds the magnet, sample, thermometers and Hall probes is placed at the bottom of the insert to be operated at the temperature range 4 - 7 K as shown in Fig 6. There are 2 Hall probes in the sample cage, one is placed in the gap of the dipole magnet with the sensitive area as close to the center of the field and the sample (HP1), whilst the other Hall probe (HP2) is placed on the alternate side of the sample shown by Fig. 3.

Construction and Operation of the VTI

The LTS leads were chosen to reduce the heat load to the magnet whilst in operation. The main challenges constructing the VTI were the limited volume in which the components and modifications could be applied due to the set volume of the chamber, and connecting the LTS magnet lead to a normal conducting power supply. This challenge was carried out by the team at Rutherford Appleton Labora-

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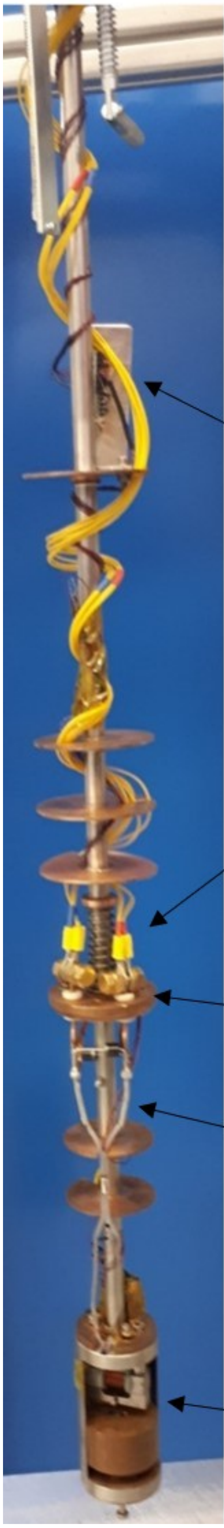

Figure 5: The constructed variable temperature insert, total length of 950 mm.

tory[1]. The LTS wire was connected to a high temperature superconductor (HTS) ribbon with a join as long as possible to reduce heating due to the join resistance, and joining the HTS ribbon to two copper rods that were fed through the baffle connected to the first stage. The superconducting joins are shown in Fig. 6.

The baffle is electrically isolated from the copper rods by the use of ceramic screw insulators, and is thermally anchored to the baffle by the use of copper braids. The copper rod are connected to by the use of electrical lugs. A brass bolt had a hole drilled through the center to enable the copper rod to be inserted through the center. The lugs are then compressed onto the copper rod by the use of the nuts, allowing a good electrical connection.

Cooling of the VTI

The pulse tube cold head is connected to the to two plates within the cryostat. The stage 1 (S1) and stage 2 (S2) cold head is connected to the corresponding plates (S1 and S2 respectively) by the use of thermal couplers. The S1 cold head is stated to reach 45 K, and the S2 cold head is stated to reach ≈ 3 K. The thermal couplers help remove heat from the plates whilst being flexible to allow the contraction of the plates due to the change in temperature. The S2 cold head is attached to the S2 plate in a similar fashion, as well as having another connection to the VTI chamber. For an in depth description on the cryostat, see [4].

The VTI is placed within a sealed volume within the cryostat, the chamber. The S1 plate enters this chamber forming a ring on which the baffle of the insert sits, allowing the insert to thermalise to the S1 plate. Thermalising on the S1 plate reduces the heat load on the second stage where there is a reduced cooling capacity of 1 W. The baffle connecting to the S1 plate is compressed by the use of a spring creating a good thermal contact.

The second stage of the insert (the cage) sits at about the same height of the S2 plate, however is not mechanically connected. The tube around the cage is directly connected the S2 cold head by the use of thermal strapping, as well as connected to the S2 plate and then the S2 cold head by further strapping. The VTI cage is then thermalised with the surrounding tube via the use of He gas which removes the heat from the insert. This is shown in Fig 7.

There are 2 Lakeshore Cernox thermometers attached to the cage. One is placed on the copper plate above the cage, and one is placed under the large copper holster. This allows a thermal gradient to be determined over the sample and the superconducting magnet to ensure that both will be in the superconducting state.

RESULTS

Under the current set up, the required temperature cannot be reached within the cryostat. When both the chamber and the cryostat are under vacuum, the cold head reaches 37.23 K and 3.25 K on the S1 and S2 cold head respectively, and the outside of the VTI chamber reaches 4.03 K. The determined heat loads on each stage can then be determined from the capacity map. The temperatures aforementioned determine

[1] Ben Green and Josef Boehm

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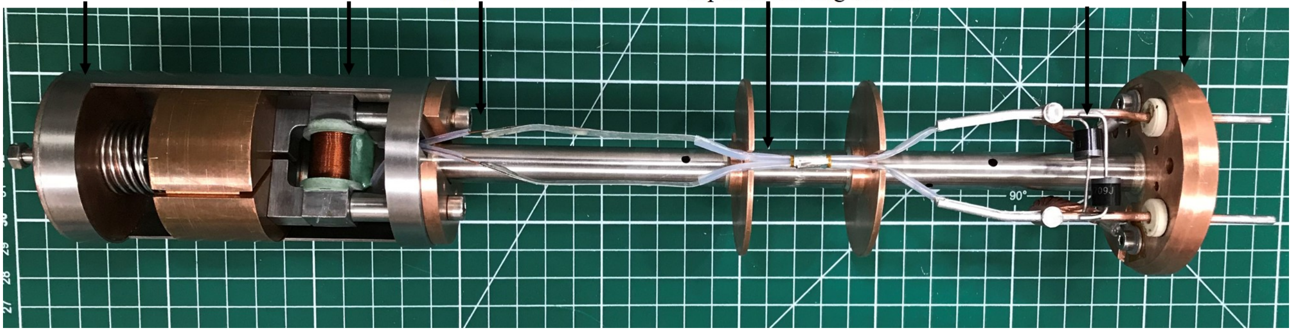

Figure 6: The superconducting joins made at Rutherford Appleton Laboratory by Ben Green and Josef Boehm. Diodes are placed facing either way to short the magnet in the case of resistance increasing, which protects the LTS leads, total length 343.5 mm.

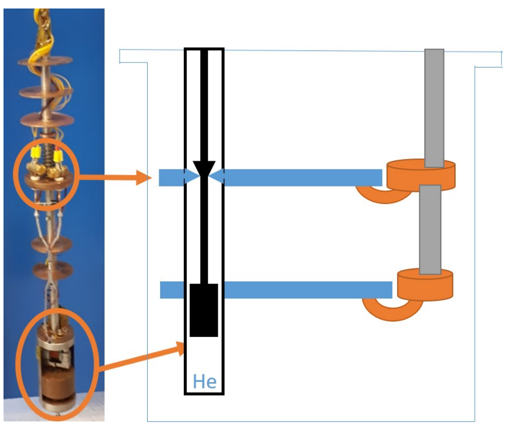

Figure 7: A schematic showing how the insert sits within the cryostat.

that the heat load on the S1 and S2 cold head are ≈ 20 W and less than 1 W respectively.

Inserting helium causes the temperature of the entire system to increase, with the minimum temperature recorded being 8.71 K and 7.41 K across the cage, at a He pressure of 2.1 mbar. Varying pressures have been tested to determine the most effective pressure to thermalise the system. The system remains at too high a temperature to enable current to be applied to the superconducting magnet. Low currents have been used to test the magnet, with the maximum current being 2 A which resulted in 51.8 mT. However, even a small current creates heating within the system causing the current to have to be turned off to make sure the superconducting magnet is not damaged.

As the heat loads for each wire had previously been calculated, the only apparent explanation for not reaching the temperature was due to the conducting heat load through the superconducting joins, mainly from the indium in the solder which was present all around the joins. The high temperature power leads were disconnected and moved away from the HTS ribbon to determine what the standard temperature was, followed by removing the thermal braids connected to the S1 baffle to determine if there was any difference. The resulting temperatures are shown in Table 1. The temperature difference for the thermometer above the cage is 0.13 K higher, whilst the temperature difference for the thermometer under the sample is 0.16 K.

Table 1: A table showing the recorded temperatures on the sample cage, where T_1 is above the sample, and T_2 is below the sample.

SC thermalised on S1 plate	T_1 (K)	T_2 (K)
Thermalised	8.44	8.14
Not thermalised	8.57	8.3

It was concluded that the temperature step between the sample and the cold head does not come from the superconducting joins, but due to poor thermal contact between the cage and the VTI chamber.

LHE TESTING

A new approach to cool the insert is ongoing, where the dry cryostat will be switched for a wet cryostat where the VTI will be immersed in LHe ensuring that the operational temperature is 4.2 K. The Lhe will act as a thermal reservoir as long as the vapour pressure is maintained. This allows the equipment to be used fully, with no concerns on the heat load of the equipment. The LHe facility requires no alterations for the VTI, as the LHe input and output are attached to the flange that the VTI will be connected too.

CONCLUSION

A VTI has been designed and constructed for the purpose of testing planar multilayer thin film superconductors. The VTI has been tested within a dry cryostat, where the facility has had a limited performance due to poor thermal conductivity between the insert and the S2 cold head. A new approach is to be undertaken in summer 2019, where the VTI will be placed in a wet Dewar, and cooled by the use of LHe.

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