A facility for the characterisation of planar multilayer structures with preliminary niobium results

Daniel A Turner¹,², *, Oleg B Malyshev¹,³, Graeme Burt¹,², Tobias Junginger⁴,⁵,*, Reza Valizadeh³ and Lewis Gurran¹,²

¹ Cockcroft Institute, STFC Daresbury Laboratory, WA4 4AD Warrington, United Kingdom
² Lancaster University, Engineering, LA1 4YW Lancaster, United Kingdom
³ ASTeC, STFC Daresbury Laboratory, WA4 4AD Warrington, United Kingdom
⁴ Department of Physics, University of Victoria, Victoria, BC, V8P 5C2, Canada
⁵ TRIUMF, Accelerator Division, Vancouver, BC V6T 2A3, Canada

E-mail: daniel.turner@cockcroft.ac.uk

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Abstract
The maximum accelerating gradient of superconducting radio frequency cavities are currently reaching their theoretical limits, due to the magnetic field entering the superconductor in the form of vortices. To overcome these limits, thin film coated superconducting materials are required, however these need to be tested to optimise their properties. A system has been designed, built, and commissioned at Daresbury Laboratory that applies a local DC magnetic field parallel to the surface, from one side of a sample, similar to that in cavity operation. A magnetic flux density (up to 600 mT) is generated parallel to the sample surface in the 2 mm gap of a C-shaped ferrite yoke. Two Hall probe sensors are used to measure both the applied and penetrated magnetic field. The system operates in a cryogen free environment, with a minimum temperature of approximately 2.6 K. A Pb foil has been used to characterise the system, and determine how the sample size affects the results. Nb thin film samples have been tested for varying thickness to determine how the depth effects the field of full flux penetration, $B_{fp}$. The design, operation, methods of analysis and first results of this facility will be reported in this paper.

Keywords: superconductivity, magnetic field penetration, lead, niobium, type I, type II, superconducting radio frequency

(Some figures may appear in colour only in the online journal)

1. Introduction
Most particle accelerators use radio frequency (RF) power to accelerate bunches of particles in accelerating cavities. The RF wave has two components; an electric field that accelerates the particles, and a magnetic field which is generated perpendicular to the electric field as a consequence of Maxwell–Amperes law. The electromagnetic fields that are produced also act on the electrons inside the accelerating cavities walls inducing a current, and therefore Ohmic heating. The heating requires most normal conducting cavities to be run in a pulsed mode with a lower duty factor to ensure the cavity does not detune or warp due to thermal expansion. Therefore, some of the RF power is dissipated in the cavity walls, and hence not all the RF power is applied to accelerate the beam. For applications that
require a high duty cycle or to be run in continuous wave with high fields, superconducting RF (SRF) systems are preferred. Superconductors (SCs) have an intrinsic property that when cooled below their critical temperature ($T_c$), they expel any external applied magnetic field. This is known as the Meissner effect. In this state the DC resistance also approaches zero as the change is carried by Cooper pairs. As the charge carriers have a mass, they therefore have a momentum, and the change in direction due to the oscillation prevents perfect screening of the applied magnetic field. There is a small amount of heating produced by the RF in SRF cavities as the field penetrates a short distance into the surface (known as the London penetration depth, $\lambda$) causing a time varying electric field which can accelerate the normal electron charge carriers.

The maximum accelerating gradient ($E_{acc}$) of an SRF cavity is proportional to the ratio of the accelerating gradient to the maximum surface magnetic field for a given geometry. Cavities are a closed structure, and therefore the RF is only applied to the internal surface. The magnetic field for all cavity modes are applied parallel to the cavity surface, and will be expelled whilst in the Meissner state. If imperfections exist on the surface such as any dislocations or impurities, the magnetic field ($B$) can enter the cavity early in the form of vortices, which can be visualised as cone like normal conducting structures [9]. The vortices will oscillate as the RF is applied to the cavity, which can generate heating and can cause the cavity to quench due to either thermal runaway or the vortices becoming too dense.

The main material of choice for SRF cavities is bulk Nb due to having the largest $T_c$ of any single element, the largest lower critical field ($H_{c1}$) for any known SC and its suitability to be mechanically formed into cavity geometries [9]. However, niobium is reaching its theoretical limit due to the magnetic field on the cavity walls. By increasing the maximum applied magnetic field ($B_1$) in which an SC can remain in the Meissner state, the maximum $E_{acc}$ can also be increased. Novel SC materials are being investigated to replace or aid Nb, such as MgB$_2$ [23], Nb$_3$Sn [11] and N infused Nb [2, 6]. Other novel ways of increasing $B$ is to use multilayer superconductor–insulator–superconductor (SIS) or bi-layer structures [7, 8, 16] where thin films (thickness $< \lambda$) are deposited on the surface of a superconducting substrate. Thin films can remain in the Meissner state up to a much higher $B_1$, as $B$ is not reduced to 0 within the SC and can be described as magnetically transparent. In multilayer samples, the thin films cause a screening effect of $B_1$, allowing a larger field to be applied to the surface of the cavity, whilst the bulk substrate will see a lower magnitude of field than without the screening layer, which is shown in figure 1(a).

To develop superconducting films and SIS structures a number of techniques have been employed for testing their superconducting properties such as; DC resistance measurements to define the residual resistance ratio and $T_c$, DC magnetisation and AC magnetic susceptibility in $B$ (with $B$ parallel or perpendicular to the surface) such as vibrating sample magnetometry (VSM) to measure the field of first flux entry ($B_{vp}$) and the upper critical field $B_{c2}$. In general these methods are useful for studying SCs, however their results do not provide sufficient evidence to predict the behaviour of the SC under RF conditions. One of the main limitations is that the magnetic field in a cavity is applied only from one side of the superconducting film, while in some of the commercial methods mentioned above the magnetic field is applied to both sides. When a magnetic field is applied from both sides of a sample, the flux may not break in through the superconducting face that would be witness to the RF if the SC was present within a cavity, but the opposite face that may be not be adequately prepared for RF conditions. Additionally, for multilayer samples, the magnetic field would penetrate through the insulating layer such that the shielding expected to be produced by the thin films [8] would not be observed.

To bypass this problem a few methods have been developed with the main aim of producing a magnetic field in such a way that it is applied only to one side of the sample. Antoine et al have developed an AC magnetic susceptibility and third...
harmonic measurement system [1, 10, 13–15] to study flux dynamics. A joint team from Old Dominion University and Thomas Jefferson National Laboratory have built a DC penetration measurement set-up [22]. Both these methods produce magnetic field by using a coil placed on a sample with an axis perpendicular to the sample surface. Dhavale et al developed a facility at Jefferson Laboratory which tests hollow, cylindrical samples in a DC magnetic field which removes the demagnetisation factor [3].

Another method has been previously suggested by Gurevich and realised at Daresbury Laboratory utilising tubular samples. In this case, the penetration measurements are performed with a sample in a form of long superconducting tube placed inside a much shorter coil, such that \( B_1 \) is parallel to the surface of the tube. This method has been fabricated at Daresbury Laboratory [17, 18]. A short (3 cm in length) superconducting magnetic coil was placed in the middle of a relatively long (≈20 cm long and ≈12 mm diameter) sample tube made of, or coated with, a superconducting material. Two magnetic field strength sensors (e.g. Hall-effect sensor/probe) were placed on the central plane of the magnet: one inside of the tube and the other outside. It was demonstrated that this method allows measurements of field penetration where a parallel field is applied on only one side. The main disadvantage of this facility is that samples must be deposited on the outside wall, which required a dedicated deposition facility and deposition conditions and hence parameters were not directly translatable to the coating on an RF cavity.

Ideally, a magnetic field penetration facility should allow a parallel \( B_1 \) to be applied to a flat sample that could be easily deposited by conventional facilities, or onto a sample with a concave shape similar to that of the inside of an RF cavity. This paper will describe the development and testing a new magnetic field penetration facility meeting these specifications.

2. Design of the facility

2.1. Initial idea and a design of superconducting magnet

For the facility to be relevant to SRF and superconducting thin film applications the applied field had to meet specific requirements:

- The magnetic field must be applied from one side of the sample to the other, such that \( B_1 \) is only seen by one superconducting surface similar to that in an SRF cavity.
- The field must be parallel to the sample surface.
- The facility should allow small samples to be tested. A small gap between the poles of the magnet allows small samples to be tested.
- The field must be applied locally on the sample to ensure that there is no flux enhancement at the edges of the sample which can allow early flux entry.
- Samples of different geometries: curved or flat samples, with rectangular or circular shape.

A magnet was designed and built which met these requirements. The magnet uses a C-shaped yoke made out of high carbon steel (C1020) in order to maintain the largest possible \( B \) produced by the coil, and to ensure a greater field is produced at the dipoles while also reducing the maximum current applied and therefore heat produced. The yoke is modular, allowing the poles to be removed/attached to allow different field orientations to be made, or allow samples of different geometries. The yoke also directs the magnetic field to be parallel to the surface of the sample.

A low temperature superconducting (LTS) solenoid made out of NbTi (Supercon SC-VSF-678) is used to generate the applied magnetic field. The wire is 0.4 mm in diameter, containing 672 NbTi filaments embedded within a Cu matrix allowing the wire to also operate above \( T_c \) providing a low current is used. The coil was wound at STFC RAL with 234 turns over seven layers. Two identical magnets were produced, one has been previously used in a gaseous system on a variable temperature insert [25], the second magnet has been used for the new system described in this paper.

The C-shaped magnet has a pole cross section of \( 5 \times 10 \text{ mm}^2 \). A 2 mm gap between the poles was chosen to ensure \( B_1 \) remains localised. Without a sample present, a perpendicular component of \( B(B_y) \) is produced at the edges of the poles, as it diverges away from the poles. A smaller gap would result in the field being constrained within the gap. When a superconducting sample is placed across the magnet poles as shown in figure 2(a), \( B \) in the gap is forced parallel to the sample surface shown in figure 4, due to an SC in the Meissner state acting as a magnetic mirror. A 2 mm gap is large enough to place a Hall probe sensor to measure \( B_1 \) in the centre of the dipole. The poles were designed to generate a dense, uniform \( B \) whilst still allowing enough space for sensors.

2.2. Modelling the magnetic field of the superconducting magnet

The magnet was modelled using both Opera SIMULIA and CST Microwave studio to obtain the magnetic field pattern produced between the dipoles. The vector components of \( B \) are shown in relation to the axis to the magnet in figures 2(b) and 4 shows the strength of the vector components through the centre of the dipole if no sample is present within the system. Both \( B_x \) and \( B_y \) are the components parallel to a sample surface, where \( B_y \) is perpendicular to the pole faces and \( B_x \) is parallel to the pole faces. The perpendicular component to the sample surface is \( B_z \). The \( B_1 \) strength as a function of applied current is shown in figure 3.

The yoke was designed to produce a strong, localised field. The consequence of a localised field is that \( B_1 \) will reduce rapidly with distance moving away from the dipole. Figure 4 shows the magnetic field components \( B_x, B_y, B_z \) as a function of the \( Y \) co-ordinate for the coil current of 1 A. One can see that the largest \( B_1 \) is produced in the centre of the dipoles, shown at \( y = 0 \) in figure 4 as expected. The \( B_x \) magnetic field shows a plateau at a distance of approximately \( 1.5 \text{ mm} < y < 1.5 \text{ mm} \), as the distance from the centre of the dipoles increases, \( B_y \) begins to reduce with a \% comparison shown in table 1. Thus, the magnetic field \( B \) at the edge of the poles (i.e. on the sample surface if a sample is present) is 85.3% compared to \( B \) in the centre of
A study was performed to determine how the size of a sample in the Meissner state affects the amount of magnetic field which propagates around the sample and is measured by HP2, known throughout the paper as $K_2$. An SC in the Meissner state behaves as a perfect diamagnet, and therefore has a magnetic permeability $\mu = -1$. This cannot be easily simulated using the same software for simulating the magnet. It was decided the best way to simulate $K_2$ would be to reduce the magnetic permeability to a low value such that the $B$ is negligible inside the sample, simulating that an applied magnetic field ($B_1 = B_{\text{HP1}}$) is forced over the sample surface, and is therefore suitable for estimating the magnetic field leaking around the sample. It must be noted that some field still penetrates through the sample in the simulations, which is not the case with an SC in the Meissner state. These results are interesting to study the trends. The results of these simulations are reported here as parameter $K_2$ defined as:

$$K_2 = \frac{B_{\text{HP2}}}{B_{\text{HP1}}}, \text{ for a SC in the Meissner state.} \quad (2)$$

The results for $K_2$ as a function of sample area are shown in figure 6, together with experimental results presented later in this paper.

2.3. Cryogenic facility

The main purpose of a new facility was to provide magnetic field penetration measurements at a sufficiently low temperature (in the range from below 4.2 K up to $T_c$), the system should be simple and preferably LHe free considering the continuously rising cost of LHe and also allowing flexibility of use. In addition, cryogen-free systems provide safe operation. The cryogenic temperature is provided by a Sumitomo Heavy Industries RDK-408D2 cold head, which is a two stage Gifford-McMahon cryocooler which has a cooling power of 1 W at 4.2 K on stage 2 (S2), whilst stage 1 (S1) at 40 K has 43 W cooling power.

2.3.1. Cryogenic facility design and installation. The facility was designed by the authors using CAD software (Solid edge19) to determine the size available within the cryostat. Stage 2 of the cryocooler is used to cool the sample plate which is made of oxygen free high conductivity (OFHC) Cu. The sample plate was designed to accommodate the sample, the magnet, Hall probe sensors, heaters and thermometers. The sample plate also contained multiple heat exchange bobbins made out of OFHC Cu to thermalise all wiring connected to S1.

The sample is mounted between the sample plate and the magnet. The magnet is modular, allowing the poles to be changed, and is mounted to an OFHC Cu block to increase cooling and maintain thermal stability during testing. The Cu block has four holes as guide rails for the magnet, which four brass bolts are situated. The magnet is then placed onto the sample surface (or spacer if one is used) and hand tightened down to the sample plate using bolts to ensure the magnet does not move during testing. The sample temperature is controlled.

![Diagram of C-shaped dipole magnet](image)

Figure 2. The C-shaped dipole magnet: (a) shows the magnet and where the Hall probe sensors and sample are placed with respect to the magnet; (b) shows the simulated magnet and the co-ordinate system referenced throughout the paper. The axis centre (0, 0, 0) is the centre of the dipoles. $B_x$ and $B_y$ are parallel to where a sample would be situated, with $B_x$ being perpendicular to the poles, and $B_y$ is the vertical component compared to the sample.

The B measured by HP2 depends on the sample thickness. As the total thickness of the sample increases, so does the distance between the probes and therefore the $B$ field source, limiting the maximum B that HP2 can measure. Let us introduce a new parameter, $K_1$, defined as:

$$K_1 = \frac{B_{\text{HP2}}}{B_{\text{HP1}}}, \text{ for no SC present.} \quad (1)$$

Thus, $K_1 = 0.235$ if no sample is present, and $K_1 = 0.13$ in cases of normal conducting samples with a total thickness of 2 mm, see figure 5 and table 1. Note: these results are for no magnetic samples present. Magnetic field as a function of current is shown in figure 3, which shows that $B$ increases linearly with current up to 3 A which equates to $B = 432$ mT. Above 3 A the dependence is no longer linear, however a current of 5 A gives a $B = 617$ mT which is sufficient for the purpose of this work.
Figure 3. Simulation results for $B_1$ as a function of current applied to the coil. This is the magnetic field that is measured by HP1.

Figure 4. Simulation results for the magnetic field vectors through the centre of the gap between the poles in the $Y$ axis of figure 2, without a sample present and an applied current of 1 A to the coil.

by a temperature controller (Lakeshore 335) using a thermometer (Lakeshore Cernox CX-1050-CU-HT-1.4L), mounted on the surface of the sample, and two 10 $\Omega$ resistors in series mounted onto the sample plate to provide heating by passing through a small current. The thermometer uses the factory calibration curve with an error of $\pm 5$ mK. It should be noted that the magnet temperature (measured with a silicon diode) should be the same as the sample temperature due to additional heat links connecting the sample plate and the magnet. This ensures the temperature stability of the magnet whilst operating at a high current (usually at temperatures below $T_c$). Other sensors are mounted on S1 and S2 plates and radiation shields are
Figure 5. Simulation results for the parameter $K_1$ as a function of distance away from the dipoles.

Table 1. Simulated values for $K_1$ as a percentage with $B_1(1\,\text{A}) = 145\,\text{mT}$, for varying distances and the reason for the distance between HP1 and HP2.

| Position                                | Distance (mm) | % compared to $B_1$ |
|-----------------------------------------|---------------|---------------------|
| Dipole centre ($B_1$)                   | 0             | 100                 |
| Dipole edge                             | 2.5           | 85.3                |
| Sample surface with one brass spacer    | 2.8           | 74.3                |
| HP2 position with no sample             | 5             | 23.5                |
| HP2 position with two brass spacers     | 5.6           | 19.0                |
| HP2 position for Nb on 2 mm Cu sample   | 7             | 13.0                |

silicon diodes with a larger error of ±0.25 K from the standard silicon diode curve. Silicon diodes are used as accuracy is not required when measuring the temperature of the plates, and they are much cheaper than calibrated Cernox thermometers.

Two thermal radiation shields have been designed and made out of OFHC Cu, and wrapped in multi-layer insulation (MLI). MLI is typically made out of Al or Ag, layered and separated by Mylar or some other non-conductive insulator. The multiple layers of Al reflects thermal radiation and the Mylar inter layers ensure that the Al sheets are not connected such that heat can only pass as radiation. The thermal radiation shield mounted on S1 is to reduce the heat load due to thermal radiation from the steel vacuum can, and to reduce the heat load to the S2 plate by reducing the temperature gradient. The thermal radiation shield on S2 is to ensure that no higher energy photons strike the sample during testing, which would increase the temperature of the sample and cause the testing to become unreliable. The added mass from the thermal radiation shields also increase the thermal stability whilst testing the samples.

The OFHC Cu plate on S1 is a heat sink to reduce the total heat load to S2 by thermalising all wiring into the system, and to cool the thermal radiation shield around sample plate. Special attention had to be taken when considering the heat load produced by the magnet power supply. A high current requires a large cross section of Cu to reduce joule heating, but this increases the conductive heat load between S1 and S2. Instead, a 40 cm long high-temperature superconducting (HTS) ribbon has been used to connect the stages to minimise the heat load. The 10 cm long joins of HTS and LTS wires are attached using indium brazing to reduce the contact resistance between the SCs. The joins are thermalised using Cu bars mounted to the sample plate and electrically isolated using Kapton tape. The bolts are isolated by using ceramic and electrical heat shrink tubing to ensure there were no electrical shorts. On the S1 plate the HTS to normal conducting Cu connection is by mechanical mounting of the Cu wires (from the external feed-through) to two Cu bars.

The vacuum chamber is connected to the cold head using an adapter chamber. The adapter has two ports, one is used for vacuum, and the other port is used as an electrical feed-through for sensors and the magnet power supply. Another adapter, attached to the adapter chamber, which can be seen in figure 7,
Figure 6. The leakage parameter $K_2$ as a function of sample size for both simulation values obtained with a low permeability sample using Opera SIMULIA (in black) and experimental measurements in the Meissner state (in red).

Figure 7. The layout of the field penetration system: (a) shows the system open, (b) shows the stage 2 shield attached, (c) shows the stage 1 shield attached to the system and (d) shows the facility fully closed by the stainless steel vacuum can.

allows a larger S1 plate and connects to the outer steel vacuum chamber, shown in figure 7(d). The vacuum system consists of a scroll pump (Edwards nXDS10i) for initial pumping and for roughing the turbo-molecular pump (TMP) (Agilent TwisTorr 84 FS). The TMP is used to reduce the vacuum to the required pressure to cool the facility to the desired temperature. The pressure of the system is measured by two full range Agilent gauges (FRG-700), one gauge is connected to the main chamber to determine the pressure of the facility during testing, and the other gauge connected to the backing line to the TMP to ensure adequate backing pressure.

The magnet power supply is a ‘Cryogenic limited’ SMS120C. The power supply is designed for superconducting coils due having a maximum current supply of 120 A and maximum voltage of 5 V. If the resistance increases due to a quench in the superconducting coil, the power supply will trip to ensure the superconducting coil is not damaged. The stability of the applied current is ±20 mA.
2.3.2. Cryogenic facility testing. The facility design is optimised for a fast sample turn around. It takes 1 h to open the system from vacuum, change the sample and put the system back under vacuum. It takes \( \approx 5 \) h to pump down to around \( 10^{-5} \) mbar before the compressor (Sumitomo cryogenics F-50) is started in order to cool the system. The cooling process from room temperature to the minimum temperature of \( \approx 2.5 \) K on the sample is approximately 5 h. The stage 1 final temperature is \( \approx 25 \) K. The sample temperature can be varied in the range \( 2 \) K \( \leq T \leq 30 \) K which is sufficiently wide for studying both Nb and A15 superconducting materials while being wider than the operating range of the LTS magnet. The temperature accuracy is defined by the type of thermometer which is \( \pm 5 \) mK for Cernox and \( \pm 0.25 \) K for silicon diodes. The refrigeration cycle of the compressor causes small temperature fluctuation whilst at set temperatures. The temperature is controlled using a proportional–integral–differential control loop at set temperature points, using the resistors for heating other than for the minimum temperature where the heaters are turned off. The standard deviation of the temperature fluctuation during measurements is taken in order to quantify the error in the sample temperature during fixed temperature measurements, which was found to not exceed 15 mK.

Both the applied and penetrated field (\( B_1 \) and \( B_2 \) respectively) are measured by Arepoc Hall probe sensors, which are HHP-NP and HHP-NA for Hall probe 1 and 2 shown in figure 2, and the error in these Hall probes is \( \pm 0.27 \) mT and \( \pm 0.70 \) mT respectively. The SC magnet testing produced \( B_{\text{app}} \approx 144 \) mT at 1 A, with a maximum \( B_1 \) achieved in testing with a current of 8 A \( \approx 612 \) mT at 2.5 K. The perpendicular component of \( B \) had a maximum of 46 mT under one of the poles. Therefore \( \approx 63\% \) of the \( B \) can be described as parallel to a normal conducting sample surface.

At temperatures higher than \( T_c (\approx 7 \) K for the LTS solenoid) the maximum applied current is reduced due to heat loss in the wire/magnet. For safe operation when \( T > T_c \), the current should not be increased above 2 A. Here it should also be noted that Hall probe sensors are only sensitive in a specific direction, in this case both Hall probe sensors are aligned to be parallel to \( B_1 \) and will therefore not be sensitive to any other vector component of \( B \).

2.3.3. Automation. The facility is fully automated with LabVIEW, allowing the compressor to be turned on/off remotely and the facility to run automatically with a pre-defined procedure allowing control in the maximum current to apply to the magnet for a corresponding \( B_1 \), at set fixed temperatures, and whether the magnet should be demagnetised between each run. Depending on the amount of set temperature measurements and the maximum field required, it can take from a few hours to a day to perform a full temperature sweep. The Hall probe sensors are recorded by a USBD AQ from Arepoc, which records the voltage of the Hall probe sensors. A data sheet was provided with the sensors which give the sensitivity of the Hall probes at 297, 77 and 4.2 K, with the sensitivity used for each run being the 4.2 K sensitivity. The data sheet also contained an offset voltage for each Hall probe, but was determined again after the Hall probes had been integrated with the system.

3. Experimental

3.1. Sample preparation

The facility was designed to accommodate a sample size up to \( 50 \times 50 \) mm\(^2\). The ideal sample thickness is as thin as possible (usually 1–3 mm) to increase \( B_2 \) for more accurate measurements, however thicker samples up to 15 mm can be accommodated.

The purpose of the first series of measurements were to demonstrate the capability and limitations of the facility. For this, two types of sample have been prepared: type I SC (Pb), and type II SC (Nb).

A type I SC was preferable for initial testing as all the flux enters the sample at once and hence the results can be interpreted easier, limiting the number of factors that can affect the results. A 10 \( \mu \)m thick Pb (purity of 99.99\%) sample with a cross section of \( 50 \times 50 \) mm\(^2\) was bought from Goodfellow to be tested in the field penetration facility. The advantage of Pb is that it is a type I SC allowing easier interpretation of the field of full flux penetration. A foil was chosen as the thin sample can be easily cut down to determine how both sample size and geometry affect the results of the measurements (or prove that the measurements are insensitive to the sample geometry). Due to the Pb foil being soft it could be easily damaged (squeezed) by the magnet poles and the sample plate. To avoid this, two 0.3 mm thick brass spacers were made: one had a cross section of \( 50 \times 50 \) mm\(^2\) (maximum size of the sample) and another \( 40 \times 10 \) mm\(^2\) (total cross section of the magnet poles in contact with a sample).

Three type II Nb samples were deposited at Daresbury Laboratory using DC magnetron sputtering. The deposition facility consists of two chambers: deposition and load lock chambers. Up to seven samples can be inserted into the cartridge inside the load lock vacuum chamber. Prior to deposition, the entire deposition facility was baked to 150 \( ^\circ \)C for four days. A base pressure of \( 5 \times 10^{-10} \) mbar was reached after cooling back to room temperature. Inserting multiple sample substrates into the load lock vacuum chamber allows baking of all the samples at once without the need to vent and bake the system in between depositions. After all samples are deposited, new substrates are inserted and only the load lock vacuum chamber has to be baked again. The process gas is injected into the deposition chamber by separate MKS 1179A12CS1BVB mass flow controllers, calibrated for krypton. The mass flow controllers have a flow range up to 100 sccm and are controlled by MKS Type 250B and MKS Model 247 C control units. Pressure during deposition is typically \( 10^{-3} \) mbar and is set by adjusting the flow rate through the mass flow controller, with a constant pumping speed, until the desired pressure is read from the Baratron. The deposition chamber has four 3 inch concentric magnetrons which can be configured both in balance and unbalanced conditions. The vacuum in both
3.2. Procedure

The sample is mounted at room temperature, then pumped down to below $10^{-4}$ mbar before the compressor is started to cool the system. Once the system has reached the minimum temperature ($T \approx 2.5$ K) the operator can start a predefined sequence. After ensuring the system is at an equilibrium temperature the testing sequence can be initiated. Each test sequence is written prior to the test using LabVIEW, where the fixed temperature points ($T$) are chosen, along with the current step and the current set points for each test. The current starts from 0 A and is increased in steps chosen by the operator. It must be ensured by the operator that the current is increased such that the maximum $B_1$ is increased above the field of full flux penetration, $B_{fp}$. Once the maximum set current is reached, the current is reduced back to 0 A, and the magnet is demagnetised.

To demagnetise the magnet, the current is ramped up to the maximum stated value of the previous test but in the opposite polarity. The current is then reduced by 10% of the previous current and the polarity is switched. This repeats until the smallest step that the power supply can produce, which is 1.8 mA. Once the demagnetisation process has completed, the sample temperature is increased above the $T_c$ of the sample which is defined by the operator, and held for 20 min to ensure that all possible trapped flux has been expelled from the sample. The sample is then cooled to the next set $T$, and held within a 0.05 K range for 20 min to ensure the sample has fully thermalised before the next temperature run begins. If the $T$ falls out of range of 0.05 K, the timer resets and starts again when the sample temperature is back within range. The following temperature runs increase by 0.5 or 1 K to ensure a full sweep of the sample is performed. Once each temperature run has been completed, the compressor is turned off, the sample temperature is set to 280 K and the system is left to warm up under vacuum.

### 3.3. How to define the field of full flux penetration?

#### 3.3.1. Raw data.

Typical results of measurements (the results of one of the first measured samples: Pb, 99.99% purity, $50 \times 50$ mm$^2$ area and $10 \mu$m thick) are shown in figure 8. One can see that all results lie between two straight lines: $B_1K_1$ and $B_1K_2$ where $K_1$ and $K_2$ have been previously defined in equations (1) and (2). In all graphs, at low $B_1$, the field on the opposing side of the sample $B_2 = B_1K_2$; i.e. HP2 is measuring the $B$ which has propagated around the sample. At higher $B_1$, there is a sharp increase in $B_2$ measured by HP2 when the field breaks all the way through the sample, known as the field of full flux penetration, $B_{fp}$. At much higher $B_1$, $B_2$ tends towards $B_1K_1$; i.e. the magnetic field distribution without an SC present.

Whilst $B_{fp}$ can easily be determined where a sharp transition occurs in $B_2$, e.g. for $T < 5$ K in figure 8, however, this is not always the case. In this section, two different methods to determine $B_{fp}$ from the raw data are discussed.

#### 3.3.2. Method 1 — normalisation of the curve.

For a given position of the magnet with respect to the sample plate, the magnetic field $B_2$ measured with HP2 without a superconducting sample is defined by the parameter $K_1 = B_2/B_1$. The same is also true for a superconducting sample in a magnetic field greater than the upper critical field, $B_{c2}$. The superconducting state of an infinitely large sample can be described with a superconducting ratio, $R$:

$$ R_{\infty} = 1 - \frac{B_1}{B_1K_1}, $$

When $B_2$ is screened by a large sample, $R$ will remain 1 until $B_{fp}$, where $R$ will reduce. However, as one can see in figure 8, some magnetic field leaks around a finite sample with

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Substrate heated                 | 650 °C for 12 h        |
| Base pressure at 650 °C on a substrate | $<10 \times 10^{-8}$ mbar |
| Deposition temperature           | 650 °C                 |
| Power supply                     | DC MS                  |
| Current density                  | 1.11, 1.12, 1.26 A     |
| Voltage                          | 358, 354, 317 V        |
| Target power                     | 400 W                  |
| Discharge gas                    | Kr                     |
| Discharge gas pressure           | $1.5 \times 10^{-3}$ mbar |
| Target-substrate distance        | 10 cm                  |
| Substrate rotation               | 4 rpm                  |
| Deposition time                  | 2, 6, and 10 h         |
| Deposition rate                  | 11.2, 9.9 and 8.4 nm min$^{-1}$ |
| Nb film thickness                | 1.3, 3.6 and 5.1 μm    |
Figure 8. The raw data produced by the full magnetic field penetration facility with a 0.01 mm thick Pb sample with a 50 mm × 50 mm surface area. Here $B_1$ is measured by HP1 and $B_2$ is measured by HP2.

a leakage rate described with $B_{\text{leak}} = B_1 K_2$, which must then be accounted for, such that equation (3) becomes:

$$R = 1 - \frac{B_2 - B_1 K_2}{B_1 K_1}$$

which is simplified to:

$$R = 1 + \frac{K_2}{K_1} - \frac{B_2}{B_1 K_1}.$$  \hspace{1cm} (4)

The results shown in figure 8 have been analysed with equation (5) and are shown in figure 9. Theoretically, equation (5) should produce $R = 1$ for any sample in the Meissner state. However, it can be seen experimentally that at low $B_1$ the normalisation curve does not always produce $R = 1$ due to the large relative error in HP2 compared to the measured $B_2$. The error in $B_2$ due to HP2 must be accounted for during this process, as this can vary for each run. There are two possible causes for this:

- a small residual magnetisation of the magnet which can be different after each run, with a maximum residual magnetisation after degaussing being $B_1 \approx \pm 5$ mT.
- sensitivity of HP2 gives an error $\delta B_2 = 0.7$ mT.

However, for larger $B_1$ the plateau for $R = 1$ is clearly present, followed by a sharp transition. The points before the sharp transition are used to normalise the curve.

Using this method, $B_{fp}$ is defined as the $B_1$ where $R$ is reduced to $R = 0.99$. The error in $B_{fp}$ is $\leq \pm 2$ mT for $B_1 = 10$ mT depending on the step size of the applied current.

3.3.3. Method 2—second derivative. Another method has been developed to define $B_{fp}$ in cases where $B_{fp}$ transition is not as sharp, and therefore not as clear. This method should also allow robust numerical algorithm that can be employed for automated data analysis.

The curves can be analysed using the second derivative of $B_2(B_1)$. The second derivative of $B_2$ is 0 for both the Meissner state and the normal conducting state, i.e. $K_2$ and $K_1$ respectively. The $B_{fp}$ corresponds to the largest increase in $d^2B_2/dB_1^2$.

The numerical definition of the second derivative for three unevenly spaced points is defined as:

$$\frac{d^2y}{dx^2} = \frac{\left(\frac{y_{n+1} - y_n}{x_{n+1} - x_n} - \frac{y_{n} - y_{n-1}}{x_{n} - x_{n-1}}\right)}{\frac{x_{n+1} - x_n}{2}}.$$  \hspace{1cm} (6)

Equation (6) is performed using the ‘gradient’ function twice in MATLAB [20], and are referred to as $d^2(B_2)/d(B_1)^2$ in both the figures and text throughout this paper. The results shown in figure 8 have been analysed with equation (6) and are shown in figure 10. For each temperature the dependence of the second derivative as function of $B_1$ can be described as the following: initially $d^2(B_2)/d(B_1)^2$ is close to 0 (in theory it should be exactly 0), followed by a series of peaks. The first peak corresponds to the sharp transition in $B_2$ shown in figure 8, therefore $B_{fp}$ lies between the largest point of the first peak and the previous measurements (measured at a lower $B_1$). The practical complexity of this method is that the data is noisy, so it is sometimes difficult to define the first peak. To solve this problem an additional procedure can be applied to the raw data. A linear regression procedure is performed on
Figure 9. The data for 10 \( \mu \)m thick Pb once the Meissner state has been normalised to have a superconducting ratio of 1 using equation (5).

Figure 10. The rate of change of \( B_2 \) as a function of \( B_1 \) for the 10 \( \mu \)m thick Pb (50 \times 50 \text{mm}^2) sample.

\( B_2 \) to remove noise from the experimental data. The residuals are calculated using \( r = \text{data} - \text{fit} = y - \hat{y} \), where \( \hat{y} \) is found using a ‘window’ of points set by the user. The robust weights are then calculated given by the bisquare function below:

\[
    w_i = \begin{cases} 
    (1 - (r_i/6\text{MAD})^2)^2, & |r_i| < 6\text{MAD} \\
    0, & |r_i| \geq 6\text{MAD} 
    \end{cases} 
\]

(7)

where \( r_i \) is the residual of the \( i \)th data point produced by the smoothing procedure, \( w_i \) are the robust weights and MAD is the median absolute deviation is a measure of how spread out the residuals are, given by \( \text{MAD} = \text{median}(|r|) \). If \( r_i \geq 6\text{MAD} \), the associated data is excluded from the smoothing calculation. The data is smoothed again using the robust weights, and the final smoothed value is calculated using the local regression and robust weight. This process is repeated for
a total of five times. This procedure is done in MATLAB using the ‘rlowess’ function described in [19]. The ‘rlowess’ function was chosen due to being more resistant against outlying points, and therefore eliminating the noise that can be present within the data. The second derivative method with an additional step of smoothing (equation (7)) is required for the data with a high level of noise where the first peak is difficult to separate, and therefore difficult to determine \(B_{fp}\). Both equations (6) and (7) are included in the data analysis procedure wrote in MATLAB. If the window parameter is equal to 1 corresponds to not using the smoothing function described above, in all other cases where the window > 1, it does.

The error in this method is found by taking an average between \(B_1\) the point before \(B_{fp}\) after \(B_{upper}\) \(B_{fp}\), followed by including the error in the Hall probe sensor HP1, shown in equation (8). The step increase in \(B_1\) is always a similar value to that in the error in HP1, such that the error is \(\Delta B_{fp} \approx 0.26 \text{mT}\). If larger steps are used, for example 1 mT steps, the error would then be dominated by the step size such that the error would be \(\approx 1 \text{mT}\).

\[
\Delta B_{fp} = \sqrt{\left(\frac{B_{fp} - B_{lower}}{2}\right) + \left(\frac{B_{upper} - B_{fp}}{2}\right)^2 + 0.26^2},
\]  

(8)

4. Results

As described in section 3.1, two types of samples have been characterised to test the facility and the method of defining \(B_{fp}\): a type I SC (Pb), and a type II SC (Nb). In addition, the initial tests also allowed to determine whether the products of \(B_{fp}\) as a function \(T\) (such as \(B_{fp}(0\text{K})\) and \(T_c\)) are accurate and reproducible. In a greater sense, we would like to demonstrate what type of scientific information can be extracted from SC thin films using this facility.

4.1. Measurements of Pb foil

The aim of these tests were to determine whether the magnetic field leaking around the sample can cause flux enhancement, which could produce a lower \(B_{fp}\) as the field would enter the sample earlier. This was done by comparing \(B_{fp}\) for samples of varying size.

The original sample was a Pb foil (10 \(\mu\text{m}\) thick with a cross section of \(50 \times 50 \text{mm}^2\)) to be tested in the field penetration facility. After each test following the procedure described in section 3.2, the sample size was reduced to the dimensions shown in table 3. After each test some Pb was removed or the sample was rotated, shown in figure 11, which corresponds to table 3. The value of \(K_2\) has also been compared between samples of varying size.

4.1.1. Effect of sample temperature. Figure 8 shows \(B_2(B_1)\) for a sample of size \(50 \times 50 \text{mm}^2\) measured at temperatures pre-defined by the facility operator. As described in section 3.3.1, initially \(B_2 = B_1K_2 > 0\), signifying that some magnetic field is leaking around the sample. The majority of

\(B\) is screened by the SC (due to comparing \(B_2 = B_1K_1\)). As evidenced by a low \(B_1K_2\) value, followed by a sharp increase in \(B_2\) indicating \(B_{fp}\). The sharp breakthrough is intrinsic of a type I SC due to having no intermediate state; the sample is either in the Meissner state or the normal conducting state. Once the field has broke through the sample, the \(B_2/B_1\) ratio increases with a linear trend and matches the same gradient as the tests performed above \(T_c\), which shows that the Pb sample is now normal conducting. It can be seen in figure 8 that \(B_2\) does not immediately jump from the \(B_1K_2\) to \(B_1K_1\), and there is a short but gradual change. As the applied field is localised, we can expect an island of normal conducting volume to expand from the centre of the sample, hence this is expected to be the superconducting volume of the sample decreasing as \(B_1\) is increased, until all the field has penetrated through the sample. In addition, the higher the temperature, the less pronounced transition for \(B_{fp}\).

4.1.2. Effect of sample size/geometry. As Pb is a soft material and the sample was thin, the sample size was reduced to study the effect of sample size on the \(B_{fp}\). The raw data of \(B_2\) as a function of \(B_1\) were compared for various sample sizes and geometry measured at the same temperature. For examples, figure 12 shows this comparison for measurements at \(T = 3.5 \text{mK}\). Each sample size has been normalised due to a change in offset voltage within the error of HP2.

For all samples with a total length of 50 mm there is a sudden, sharp transition where \(B\) penetrates through the sample, however reducing the sample size causes the \(B_{fp}\) transition to become much harder to extract from the raw data due to the increase in \(B_1K_2\). Using the second derivative method to determine \(B_{fp}\). The affect of \(B_{fp}\) due to sample size can be portrayed, shown in figure 13. For samples 30 mm \(\times\) 30 mm and below \(B_{fp}\) can still be found, however produces a smaller \(B_{fp}\) as a function of temperature than found for larger samples. The smaller the sample becomes the greater \(B_1K_2\) becomes, indicating more magnetic field leaking around the sample shown in figure 12 by the initial slope for each sample size.
Figure 12. The field of full flux penetration for each 10 µm thick Pb sample size at 3.5 K, where sample size is given by length $\times$ width. The length corresponds to $B_x$ and the width corresponds to $B_z$. Here the $B_z$ values have been normalised due to the error in HP2.

Figure 13. The field of full flux penetration defined by second derivative method as a function of temperature squared for varying sample size of Pb samples, assuming a linear fitting. Sample size is denoted as length $\times$ width.

The $B_1K_2$ value is $\approx$ half of the normal conducting gradient ($B_1K_1 \approx 0.0945$) for the $20 \times 20$ mm$^2$ sample. The transition for $B_{fp}$ is less pronounced not only for the higher temperatures as mentioned above but for smaller sample sizes as well. Therefore for data analysis, the window for smoothing is increased up to 12 for small samples.
Table 3. The data from the field of full flux penetration for the Pb samples size, geometry, $B_{fp}(0 \text{ K})$ and $T_c$. Both $B_{fp}(0 \text{ K})$ and $T_c$ are extracted using the linear $B_{fp}$ as a function of $T^2$.

| Run          | Length (x axis) (mm) | Width (z axis) (mm) | $K_2 (10^{-3})$ | $B_{fp}(0 \text{ K})$ (mT) | $T_c$ (K) | $B_{fp}(0 \text{ K})$ (mT) | $T_c$ (K) |
|--------------|----------------------|---------------------|-----------------|-----------------------------|-----------|-----------------------------|-----------|
| Original     | 50                   | 50                  | 7.6 ± 0.9       | 96.0 ± 0.3                  | 7.10 ± 0.01| 96.7 ± 0.3                  | 7.16 ± 0.01|
| 1st cut      | 50                   | 45                  | 8.3 ± 1.4       | 94.9 ± 0.3                  | 7.15 ± 0.01| 96.0 ± 0.3                  | 7.19 ± 0.01|
| 2nd cut      | 50                   | 40                  | 7.5 ± 0.8       | 95.7 ± 0.3                  | 7.21 ± 0.01| 96.6 ± 0.3                  | 7.23 ± 0.01|
| Rotation     | 40                   | 50                  | 11.0 ± 1.0      | 98.9 ± 0.4                  | 7.14 ± 0.02| 101.8 ± 0.6                 | 7.12 ± 0.04|
| 3rd cut      | 40                   | 50                  | 11.0 ± 2.0      | 95.4 ± 0.3                  | 7.15 ± 0.01| 96.3 ± 0.3                  | 7.17 ± 0.01|
| 4th cut      | 40                   | 30                  | 17.5 ± 1.3      | 89.3 ± 0.4                  | 7.12 ± 0.02| 89.9 ± 0.4                  | 7.16 ± 0.02|
| 5th cut      | 30                   | 30                  | 24.1 ± 1.2      | 76.9 ± 0.3                  | 7.08 ± 0.02| 84.4 ± 1.1                  | 7.08 ± 0.09|
| 6th cut      | 20                   | 20                  | 47.3 ± 4.0      | 60.8 ± 0.3                  | 6.98 ± 0.02| 57.5 ± 1.3                  | 7.28 ± 0.16|

Figure 14. $B_{fp}$ as a function of Pb sample length.

4.1.3. The field of full flux penetration for Pb. The obtained $B_{fp}$ for all Pb samples are shown in figure 13 as a function of sample temperature: $B_{fp}(T^2)$. One can see that the results are practically comparable for samples with a length greater than 40 mm. The width is slightly less critical than the length, i.e. 30 mm or greater.

The data shown for $B_{fp}(T^2)$ in figure 13 has been fitted using a linear expression. Using this fit, two additional characteristics can be determined: the field of full flux penetration at $T = 0 \text{ K}$, $B_{fp}(0 \text{ K})$, and the SC critical temperature $T_c$ of the sample, defined at $B_{fp} = 0 \text{ mT}$. The results for $B_{fp}(0 \text{ K})$ and $T_c$ for each sample size have been determined and are shown in table 3 and figure 14.

It can be seen in figure 14 that $B_{fp}(0 \text{ K})$ can vary for different sample sizes when using the second derivative method without comparing to larger samples, with $B_{fp}(0 \text{ K})$ shown in table 3, where both $B_{fp}(0 \text{ K})$ and $T_c$ are found by assuming a $T^2$ dependence and extrapolating. This is higher than the expected $B_c(0 \text{ K})$ for Pb, however it has also been shown that sample thickness plays a part in $B_{fp}$. It can be seen that when the Pb sample had a length of 50 mm, $B_{fp}$ is similar for different widths. Reducing the sample length produces some inconsistency in $B_{fp}$ such as reducing the sample length from 50 to 40 mm causes $B_{fp}$ to reduce from 96.7 mT to 89.9 mT (40 × 30 mm$^2$) using method 2, whereas using method 1 creates a range in $B_{fp}$ of 96.0–89.3 mT. Further decreasing the length reduces $B_{fp}$, shown in figure 14 and table 3.

The $B_1K_2$ which has been observed experimentally is compared to simulations in figure 6. Due to the simulations using a low magnetic permeability rather than an SC, $K_2$ produced in the simulations is greater than experimental results due to $B$ still being present within the sample in the simulation whereas $B$ is reduced to 0 inside an SC. Both simulation and
experimental results show the same pattern produced for the sample size.

To ensure a reliable $B_{fp}$, $B_{fp}(0\,K)$ and $T_c$, the samples should remain as large as possible.

4.2. Measurements of bulk Nb

The material of choice for SRF cavities is bulk Nb, which is a type II SC. Type II SCs can split into SC/normal conducting regions (vortices) making it difficult to determine $B_{fp}$, therefore bulk Nb was chosen to determine how type II SCs behave in the field penetration facility due to having already been extensively studied. It should be noted here that $B_{fp}$ is not the same as the lower critical field, $B_{c1}$, as vortices can enter and leave from the same side as the sample if the sample is thick enough.

Another aim in this test was to determine how the effect of thickness affects the measurements in the field penetration facility, specifically $B_{fp}$ and $K_2$. If a normal component of the magnetic field is present during testing, it will penetrate through the sample much earlier than samples with thinner SC, and $K_2$ would be different for samples of the same area.

4.2.1. Effect of sample temperature. Figure 15 shows $B_2(B_1)$ for a 3.6 $\mu$m Nb sample deposited onto a Cu disk with a 50 mm diameter and 2 mm thick using DC magnetron sputtering, measured at temperatures pre-defined by the operator. Initially $B_2 = B_1K_2$, since $K_2 > 0$ there is $B$ leaking around the sample shown in figure 15, and the $K_2$ produced by the Nb and Pb are comparable for the same sample size.

For higher $B_1$, the dependence $B_2(B_1)$ is no longer linear indicating that the magnetic field has penetrated through the sample. However, unlike the Pb sample there is no sharp increase in $B_2$ indicating $B_{fp}$, with the change in $B_2$ being more gradual making $B_{fp}$ much harder to determine. This is due to $B$ not all penetrating through the sample all at once, and penetrating through in the form of vortices.

As $B_1$ is further increased such that $B_1 \gg B_{fp}$ for each temperature run, $B_2(B_1)$ is approaching $B_1K_1$, but does not reach it within the range of applied $B_1$ as seen for the Pb sample. This can be explained that although $B$ has fully broken through the sample, the system is still in the Abriskov state, with NC/SC boundaries still present. Therefore, only some of the $B$ is fully penetrating through, and the remaining $B$ is still being screened. This is intrinsic of type II SCs.

Finally, an artefact can be observed in figure 15 for the 6 K run, where $B_1$ rapidly reduces and recovers. However, it can be seen that as the current continues to increase, the expected $B_2(B_1)$ matches up with the original curve. For complexity these results have been shown, but no explanation has been found thus far.

The results shown in figure 15 have been obtained with equation (5) described in section 3.3.2. The results are shown in figure 16. One can see that similar to Pb results shown in figure 9, $R \approx 1$ for low $B_1$, it then gradually reduces. $B_{fp}$ is defined as where $R$ is reduced to $R = 0.99$.

Figure 17 shows the results of figure 15 obtained by the second derivative method described in section 3.3.3. The results shown are for three temperature runs only. One can see the results are much noisier than for the Pb sample due to the increased sensitivity of method 2.
4.2.2. Effect of sample thickness. First and foremost, it should be mentioned that both the 1.3 and 3.6 µm run were performed using silicon diode thermometers using the standard factory calibration curve which increased the error in the temperature readings to ±0.25 K due to no CERNOX thermometer being available. There was some concern that the magnetic field may have a normal field component on the surface of the superconducting sample due to the fringing fields of the magnet increasing the $B_1 K_2$ and penetrating the sample earlier than expected. To determine if any normal component exists within the experimental set up, superconducting samples with varying thickness were used. To ensure the magnetic field was not leaking around the sample the cross sectional area was maintained for each sample. If a normal
4.2.3. The field of full flux penetration for Nb. The obtained \( B_{fp} \) for the three Nb samples are shown in figure 18 as a function of \( T^2 \), fit using a linear expression. One can see that the thinner the sample is, the more error is produced in \( B_{fp} \), whilst thicker samples not only have a larger \( B_{fp} \), but it is also easier to determine. Additionally, extrapolating the line of best fit allows \( B_{fp}(0 \text{ K}) \) to be found as well as \( T_c \) which is shown in table 4. The thicker samples have an increased \( B_{fp} \), which makes sense as there is more superconducting volume for the magnetic field to break through, where the \( B_{fp} \) ranges from 127.1 ± 5.69 to 157.8 ± 0.39 mT for the 1.3 \( \mu \text{m} \) and 5.1 \( \mu \text{m} \) respectively using method 2, and 52.6 ± 0.3 to 131.0 ± 0.3 using method 1. However, from extrapolating \( T_c \) it can be seen that it varies from 8.8 K to 9.1 K for method 2 and 8.92 to 9.9 K for method 1.

Due to the difficulty extracting \( B_{fp} \) from figure 15, there can be increased error in figure 18 for \( B_{fp} \) as a function of \( T^2 \), which can therefore increase the error of \( B_{fp}(0 \text{ K}) \) and the \( T_c \).

5. Discussion

A new novel facility has been developed at Daresbury Laboratory which applies a parallel \( B \) by using a ferrite C-shaped yoke and a superconducting solenoid. The \( B \) is applied from one side of a sample to the other. The ferrite yoke allows large magnetic fields to be produced using a low current, whereas other methods must use a large current to produce a similar \( B \). The superconducting solenoid reduces the heat load on the cryocooler, allowing a wide range of temperatures to be available, which is the limiting factor for third harmonic systems. Applying a local, parallel \( B \) to the sample surface reduces geometry effects that are present in commercial magnetometry, such as VSM. Additionally, the \( B \) is applied to the surface that is prepared for SRF cavities, unlike VSM where \( B \) is applied over the whole sample and can therefore penetrate the superconducting sample in contact with the substrate, or through the insulating layers in multilayer structures.
The results shown above demonstrate that both type I and type II SC thin films can be characterised by this facility. Multiple methods have been tested to determine \( B_{th} \) such as: a deviation of \( B_2 \) away from \( B_{th} \) by a set percentage, taking the square root of the standard deviation of \( B_2(B_{th}) \) as presented in [21], normalising \( B_{th} \) to 1, and \( \frac{d^2(B_2)}{d(B_{th})} \). The first three methods are all very similar as they rely on the \( B_{th} \) slope. The latter two methods are shown in this paper, and show an insignificant difference between the results obtained with both methods for type I SC’s, whilst for type II SCs method 1 underestimates \( B_{th}(0\,\text{K}) \), where as method 2 can produce more noise.

The present limitation for SRF cavities is defined by the physical properties of Nb, with \( B_{th}(0\,\text{K}) = 174\,\text{mT} \) [4, 12] and \( B_{th} \approx 240\,\text{mT} \). Hence the aim of this facility is to test materials that outperform Nb, and therefore the facility should be able to reach much higher magnetic fields to test these materials. Thus, this new facility can apply up to approximately \( B_{th} = 600\,\text{mT} \) before saturation becomes a limiting factor. This is sufficient to cover the range of interest. The large \( B_{th} \) can be produced with a coil current of 5 A, which is relatively simple for cryogenic systems and vacuum feed-through’s.

Future SRF cavities can benefit greatly by operating at higher temperatures (4.2 K). This facility allows measurements to be performed at a wide range of temperatures, \( 2.5 < T < 10\,\text{K} \), with the lower \( T \) being limited by the cold heads lowest temperature, whilst the higher \( T \) is defined by the transition temperature of the NbTi wire used in the magnet. However, the facility can operate at higher temperature \( T > 10\,\text{K} \) at a reduced current (\( \lesssim 2 \,\text{A} \)) through the NbTi wire operating in the normal conducting state, corresponding a magnetic field to up to \( 280\,\text{mT} \).

Many deposition facilities will have a maximum sample size that can be deposited, which are normally within the range of sample size which can be tested by the field penetration facility. The ideal sample for measurements is \( 50 \times 50\,\text{mm}^2 \), however it has also been shown samples with a size of \( 40 \times 30\,\text{mm}^2 \) underestimate \( B_{th} \) by up to 10% lower. For smaller samples the error increases further, however samples of the same size can still be compared relative to each other.

All facilities based on local magnetometry techniques realised in various accelerator centres provide great insight into the study of thin films for SRF applications. The field penetration facility at Daresbury Laboratory provides a few specific benefits, that makes it stand out from other systems:

- The magnetic field applied to a superconducting sample in the Meissner state is parallel to the sample surface, similar to \( B \) in an RF cavity.
  - The field penetration facility is easy to align to the sample surface to ensure a parallel field unlike in superconducting quantum interference device (SQUID)/VSM [24].
  - The poles can be modified to allow the measurements of curved surfaces, for example tube or cavity cut outs.
- The magnetic field is measured directly using a Hall probe sensor.
- No modelling or calibration is required to define the applied \( B \).
- The data analysis is relatively simple.
- It easy to reduce the effect of flux enhancements by using a large sample.
- Can test at a large range of set temperatures.
- The field penetration facility can test three to four samples a week.
- Defined by the number of set temperatures for the test, the maximum applied current and the steps in current/magnetic field. A similar time is required to change sample, pump down, cool down and warm up the system.
- Although this is much slower than a SQUID magnetometer or VSM which can perform this number of measurements per day.
- The use of a cryogen free system allows the field penetration facility to be operational full-time due to not relying on a supply of LHe.

There is also an advantage compared to the earlier system using tubular samples [17] and a coil: this system is suitable to test planar samples, which are easier to deposit and do not require a dedicated facility for depositing long tubular samples.

In addition, in comparison to the previous gas-cooled facility, the new field penetration facility has advantages [25]. Being built directly onto a cold head allows a lower sample \( T \) to be reached (2.5 K compared to previous 7.4 K). The facility can be operated remotely and is fully automated, allowing a greater number of points to be taken for each sample.

However, the magnetic field penetration facility also contains some disadvantages:

- The sample size is limited to a maximum of \( 50 \times 50\,\text{mm}^2 \). To accommodate larger samples, the sample plate must be redesigned.
- Leakage must be taken into account by applying sophisticated mathematical procedure.
- Use of ferrite requires demagnetisation and result to some but tolerable residual magnetisation \( \lesssim 5\,\text{mT} \).
- Temperature is not stable due to the nature of the compressor, causing a fluctuation in temperature (\( \pm 20\,\text{mK} \)) with a frequency of 0.2 Hz.

A future aim is to compare results produced by the DC magnetic field penetration facility to other local magnetometer techniques such as the field penetration measurement at Old Dominion University [22] and the 3rd harmonic system [1]. Finally, the field penetration system should be compared to RF characterisation techniques such as a quadrupole resonator or the RF choke cavity at STFC Daresbury Laboratory [5] to determine if there is any correlation between devices or if the field is DC or RF. If any correlation is present, small, flat samples could be quickly tested in the DC field penetration facility, due to a fast sample turn around, to find samples which produce optimal characteristics for SRF applications.
6. Conclusions

A magnetic field penetration facility for studying superconducting thin films for SRF applications has been designed, built and commissioned at the STFC Daresbury Laboratory. The facility has demonstrated that $B_{fp}$ can be measured for various samples in the temperature range $2.5 \, \text{K} \leq T \leq 30 \, \text{K}$. The testing has been successfully demonstrated with both type I and II SCs to determine the limitations of the facility. Multiple analysis methods have been tested and developed to determine $B_{fp}$ for different types of SC, and different size and thickness of samples.

Using a 10 $\mu$m thick Pb sample starting at $50 \times 50 \, \text{mm}^2$ cross section and slowly reducing the size, $B_1K_2$ was determined and then compared. It was determined that the sample length is the most critical whilst testing for $B_{fp}$. Samples with a length smaller than 50 mm induces a greater $B_1K_2$ which can obscure a reliable $B_{fp}$ measurement. The width is less critical to $B_{fp}$, however to ensure reliable measurements it should also be kept as large as possible.

Three Nb samples of the same area and geometry were deposited at Daresbury Laboratory with varying thickness. It was found that the variation of film thickness does have an effect on $B_{fp}$, and for further investigations such as new materials or multilayer samples, a baseline thickness of the bulk SC should be tested prior to deposition of a thin film on the surface, to allow comparison. Finally, $B_1K_2$ has also been investigated for the samples of varying thickness to determine if any normal component of $B$ was produced on the surface of the superconducting sample which could cause early $B_{fp}$. Whilst it has been proven that a small normal conducting component of $B$ is present without a sample present, it has been concluded that it is negligible compared to the parallel component whilst a sample is in the superconducting state.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

Daniel A Turner  https://orcid.org/0000-0002-9487-8767
Tobias Junginger  https://orcid.org/0000-0002-2228-2809

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