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FIRST RESULTS OF MAGNETIC FIELD PENETRATION MEASUREMENTS ON MULTILAYER S-I-S STRUCTURES

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Abstract

The performance of superconducting RF cavities made of bulk Nb is limited by a breakdown field of $B_p \approx 200$ mT, close to the superheating field for Nb. A potentially promising solution to enhance the breakdown field of the SRF cavities beyond the intrinsic limits of Nb is a multilayer coating suggested in [1]. In the simplest case, such a multilayer may be a superconductor-insulator-superconductor (S-I-S) coating, for example, bulk niobium (S) coated with a thin film of insulator (I) followed by a thin layer of another superconductor (S) which could be e.g. dirty niobium [2]. Here we report the first results of our measurements of field penetration in Nb thin films and Nb-AlN-Nb multilayer samples at 4.2 K using the magnetic field penetration facility designed, built and tested in ASTeC.

INTRODUCTION

Recently a new facility for magnetic field penetration measurement was presented in Ref. [3]. The schematic layout of the experiment is shown in Fig. 1. A short superconducting magnetic coil, 30 mm long and 30 mm inner diameter, is placed over the middle of a relatively long sample tube with a large length to diameter ratio, made of or coated with superconducting material. Two magnetic field sensors (Hall Field Probes 1 and 2 in Fig. 1) are placed on the central plane of the magnet: one on the outside of the tube and one inside the tube. After cooling down a sample to 4.2 K in zero magnetic field, the magnetic field penetration measurements can be performed.

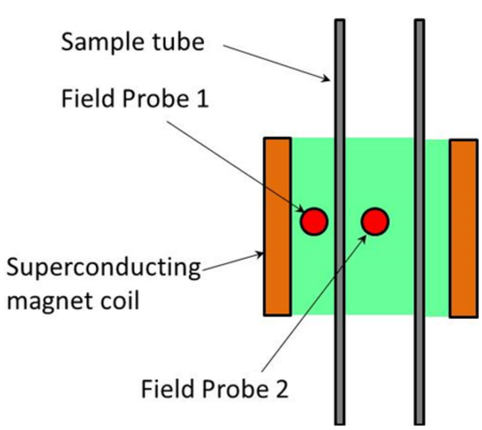

Figure 1: A schematic layout of magnetic measurements with tubular superconducting samples.

SAMPLES

Four samples were prepared for the measurements -
Sample 1: The tube was manufactured from cavity-grade niobium with RRR=384 by Niowave Inc. [4]. The tube was 230 mm long and had an outer diameter of 12 mm and an inner diameter of 7.5 mm. No chemical treatment was done after fabrication.

Three other samples were Nb films deposited on a polished copper tube which was 230 mm long and had an outer diameter of 12 mm and an inner diameter of 10 mm.
Sample 2 was an ~ 840 nm thick Nb film deposited with pulsed DC at 10^{-3} mbar of Kr. It has dense columnar structure.
Sample 3 was a ~56 nm thick Nb film, deposited with DC at 10^{-2} mbar of Kr. It has columnar structure.
Sample 4 was a S-I-S structure with: an ~840 nm thick Nb film deposited with the same parameters as Sample 2; followed by a ~3 nm thick AlN insulation layer deposited from an aluminium target in krypton and nitrogen gas in a 50/50 ratio, at a deposition pressure of 10^{-3} mbar; and finally, ~56 nm thick Nb film deposited with the same parameters as Sample 3. The high resolution FIB X-sectional view SEM images of samples 2-4 are shown in Fig. 2. The images were taken at 45°, hence the thickness has been scaled up by $\sqrt{2}$.

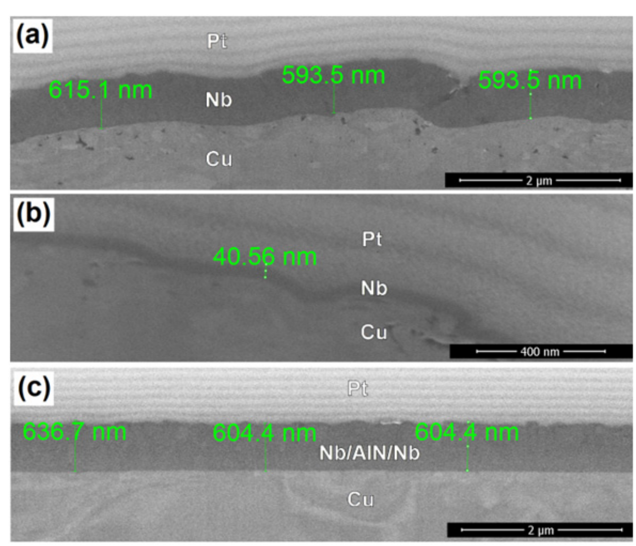

Figure 2: High resolution FIB X-section SEM images of deposited film: (a) Sample 2, (b) Sample 3, (c) Sample 4.

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Preliminary results of trial runs on these samples were first described in [3]. Here we report new results of more detailed field penetration measurements for all samples.

EXPERIMENTAL

Experimental Procedure

Initial conditions: A sample was cooled down from room temperature to 4.2 K with no magnetic field (i.e. zero magnet current). The magnet was held stationary in the middle of the sample tube.

Measurements: Magnet current was ramped up in variable steps to increase the magnetic field up to 1 T in steps of between 5×10^{-4} and 2×10^{-2} T. Magnetic field measurements *B1* and *B2* were performed with Field Probes 1 and 2 after the current had been stabilised after each step, which was checked with a routine written in LabVIEW™.

After initial magnetisation up to $B1 \approx 1$ T, measurements of a full hysteretic magnetisation loop were performed between $B1 \approx 1$ T and $B1 \approx -1$ T, i.e. the magnetic field was ramped down to -1 T followed by ramping up to $B1 \approx 1.7$ T. The magnet current was then turned off to measure the residual magnetisation of the sample.

Experimental Runs

The results of our measurements are shown in Fig.3. Measurements of the initial magnetization of the samples in a magnetic field $B1 = 0$ T showed that for all samples, except the thin film Sample 3, the magnetic field *B2* measured inside the sample tube was zero (within the sensitivity of the Hall probes $\pm10^{-4}$ T) up to a certain applied magnetic field $B1 = B_{FP}$. This is the so-called full penetration field defined in the Bean model as $B_{FP} = d\,J_c$, where J_c is the critical current density due to pinning of vortices and *d* is the wall thickness [5].

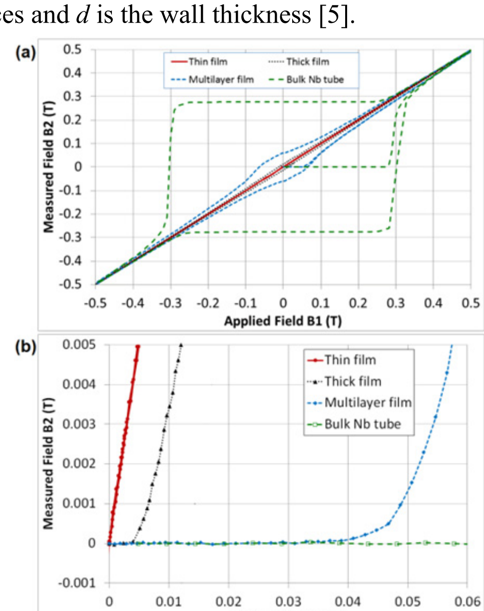

Figure 3: Results of measurements with Experimental procedure 1 for Samples 1-4 shown for (a) $-0.5 < B1 < 0.5$ T and (b) $0 < B1 < 0.06$ T.

The measured values of B_{FP} shown in Table 1 correspond to the mean of the last measurement of *B1* with $B2 = 0$ and the following measurement of *B1* with $B2 \neq 0$. For Sample 3, in the whole range of measurements, both Hall probes detected approximately the same field: $B1 \approx B2$. This suggests a very small full penetration field for this sample, $B_{FP3} < 3\times10^{-4}$ T.

Discussion

The results for full penetration magnetic field demonstrated that B_{FP} increases with the thickness of the niobium: from the below-sensitivity-level $B_{FP3} < 1\times10^{-4}$ T for the 56-nm thick film (Sample 3) to $B_{FP2} = 4\times10^{-3}$ T for the 840-nm thick film (Sample 2). This is much lower than the results for the 2.25-mm thick bulk Nb (Sample 1) which has a $B_{FP1} = 0.28$ T.

One might expect that the full penetration magnetic field of a thin film with a thickness of 840 nm would be close to the sum of those of Samples 2 and 3: $B_{FP2} + B_{FP3} = 4.1\times10^{-3}$ T. However, the S-I-S multilayer film (Sample 4), consisting of two Nb layers deposited at the same conditions as for Samples 2 and 3 and separated by a 3-nm thick AlN insulating layer, shows a much higher value of $B_{FP4} = 3.2\times10^{-2}$ T. Enhancement of the full penetration magnetic field with S-I-S structures has therefore been demonstrated.

Table 1: Full Penetration Magnetic Field and Residual Magnetic Field

Hall Probe	Sample 3: Thin film	Sample 2: Thick film	Sample 4: S-I-S film	Sample 1: Bulk Nb
	Full penetration magnetic field B_{FP} (T)			
B1	**1×10^{-4}** $\pm1\times10^{-4}$	**0.0040** ±0.0010	**0.032** ±0.002	**0.2793** ±0.0009
	Residual magnetic field B_R (T) after exposure to 1.7 T			
$B1_R$	8×10^{-4}	0.0011	-0.0005	-0.0002
$B2_R$	5×10^{-4}	0.0136	0.0588	0.2769
ΔB_R	**-3×10^{-4}**	**1.24×10^{-2}**	**5.93×10^{-2}**	**0.2771**

For SRF cavity applications it is important to know how well the superconducting films can screen the magnetic field. The magnetic field screening efficiency can be quantified either by the magnetic screening field

$$\Delta B = B1 - B2 \quad (1)$$

or by a dimensionless parameter, the screening efficiency *S*, defined as

$$S = 1 - B2 / B1 \quad (2)$$

The ΔB results for Samples 1, 2 and 4 are shown in Fig. 4. The results for Sample 3, where $\Delta B < 10^{-3}$ T over the whole range of measurement, are not shown. One can see that ΔB is equal to the applied magnetic field, *B1*, up to $B1 = B_{FP}$, then it increases more slowly than *B1* until reaching a maximum value, ΔB_{max}, at $B1(\Delta B_{max})$. ΔB then reduces to zero as *B1* continues to increase.

The results for the screening efficiency, S, for all samples are shown in Fig. 5. $S = 1$ corresponds to full screening up to $B1 = B_{FP}$, then it reduces with magnetic field $B1$. For example, if the magnetic field at the surface of a Nb cavity was 0.1 T then if the cavity was coated with a film like Sample 2 the bulk Nb would be exposed to ~0.09 T. If the same cavity was instead coated with a S-I-S film like Sample 4 the bulk Nb would be exposed to ~0.06 T. The magnetic field screening efficiency S for each sample at $B1$ = 0.1, 0.2, 0.3 and 0.4 T, as well as S_{max} and $B1(S_{max})$ are shown in Table 2.

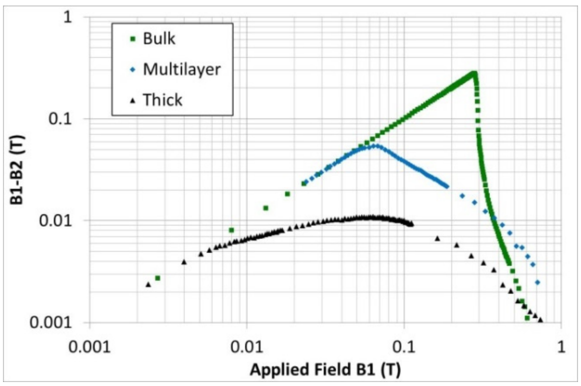

Figure 4: Magnetic screening field ΔB as a function of applied magnetic field.

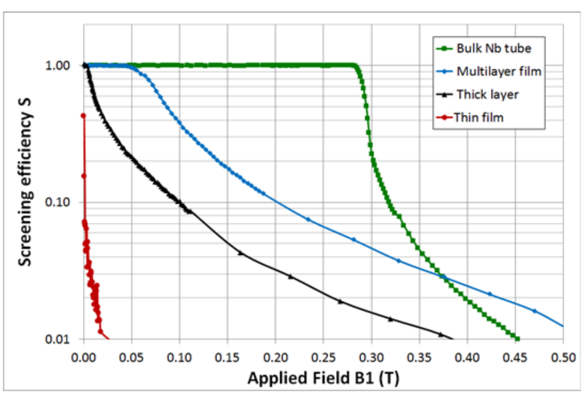

Figure 5: Magnetic field screening efficiency, S, as a function of applied magnetic field.

The residual magnetisation ΔB_R of the samples measured after exposure to 1.7 T is shown in Table 1. These values are higher than B_{FP} for the film samples (Samples 2-4).

Superconducting thin films which would be potentially interesting for SRF applications should provide screening in the range of $0.2 < S < 1$, corresponding to $\Delta B = 0.05$ T at $B1 = 0.25$ T.

Notice that the direct comparison of ΔB for thin films on Cu and the Nb tube is not appropriate as the penetration field $\Delta B = B_{FP} = \mu_0 J_c d$ for the Nb tube is proportional to its much larger wall thickness d = 2.5 mm. A more relevant for SRF applications would be to compare ΔB for the Nb tube before and after deposition of multilayers, which we plan to do soon. Yet the measurements reported here demonstrate a capacity of our magnetic field penetration method and facility for future research and for the thin film optimisation.

Table 2: Magnetic Field Screening Efficiency S and Magnetic Screening Field ΔB at 0.1, 0.2, 0.3 and 0.4 T, and ΔB_{max}

	Thick film		S-I-S film		Bulk Nb	
$B1$ (T)	ΔB (T)	S	ΔB (T)	S	ΔB (T)	S
0.1	0.010	0.1	0.038	0.4	0.1	1.0
0.2	0.0063	0.03	0.020	0.1	0.2	1.0
0.3	0.0038	0.015	0.014	0.045	0.05	0.22
0.4	1.8×10^{-3}	8×10^{-3}	0.010	0.025	0.007	0.02
ΔB_{max}	0.011		0.054		0.28	
$B1(\Delta B_{max})$	0.064		0.065		0.28	

CONCLUSIONS

The magnetic field penetration facility was designed, built and tested at ASTeC. It can accommodate tubular samples made of e.g. bulk superconductors, non-superconductors coated with superconducting films or S-I-S structures or bulk Nb coated with S-I-S structures. First tests demonstrated that the full penetration magnetic field B_{FP} increases with the thickness of the niobium films and that the results for a bulk Nb sample are as expected: B_{FP} = 0.28 T. They also demonstrated that the full penetration magnetic field for a S-I-S multilayer film, B_{FP} = 0.032 T, is higher than the sum of B_{FP} for the two single layer Nb films that comprise it. The S-I-S enhancement has therefore been demonstrated. Although the obtained results for the studied films are not as good as required for SRF applications, they demonstrate the capability of a magnetic field penetration measurement method and facility for future research.

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