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REVIEW OF MUON SPIN ROTATION STUDIES OF SRF MATERIALS

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Abstract

Muons spin rotate in magnetic fields and emit a positron preferentially in spin direction after decay. These properties enable muon spin rotation (μSR) as a precise probe for local magnetism. μSR has been used to characterize SRF materials since 2010. At TRIUMF a so called surface beam implants muons at a material dependent depth of about 150 µm in the bulk. A dedicated spectrometer was developed for field of first vortex penetration and pinning strength measurements of SRF materials in parallel magnetic fields of up to 300 mT. A low energy beam available at PSI implants muons at variable depth in the London layer allowing for direct measurements of the London penetration depth from which the lower critical field and the superheating field can be calculated. This facility is limited to parallel magnetic fields of up to 30 mT. Here, surface and low energy μSR results on SRF materials are reviewed and cross-correlated to each other and to further results from additional experiments. Finally, we present the status of a new facility based on the similar beta-NMR technique enabling measurements in the London layer of SRF materials exposed to parallel magnetic fields above 200 mT.

INTRODUCTION

μSR (muon spin rotation) [1, 2] is a powerful condensed matter technique to understand superconductors in terms of their magnetic-phase diagram and penetration depth, as well as characterize impurities based on muon diffusion. In the early 1970's new high-intensity, intermediate-energy accelerators were built at PSI, TRIUMF and LAMPF. These new "meson factories" produced pions (and therefore muons) several orders of magnitude more than previous sources - and in doing so, ushered in a new era in the techniques and applications of μSR. Since 2010 the SRF group at TRIUMF has been using the μSR technique to characterize materials and processing techniques typical for the SRF community using the TRIUMF surface muon beam [3]. This type of muon beam is refered to as a surface beam as the muons are produced from pion decay at the surface of the production target.

In case of niobium the implantation depth is about 150 μm and large compared to the London penetration depth of a few tens of nanometers. In order to probe magnetic fields in the London layer the energy of surface muons has to be reduced from about 4 MeV to a few tens of keV using large band-gap solid moderators. This process requires a high surface muon current as the efficiency for low energy muon production is only about $10^{-4} - 10^{-5}$ [4]. This process has first been explored at TRIUMF and is now implemented in a user facility at PSI [5]. Note that the extraction scheme from the cyclotron at TRIUMF is not suited to produce a large enough muon current for a LE-μSR user facility. LE-μSR has first been used to study niobium in 2005 by Suter et al. [6] to proof non-local effects in superconductors. The first application of LE-μSR to SRF materials has been reported by Romanenko et al. [7]. A strong change in Meissner screening with depth has been reported for samples treated by low temperature baking. LE-μSR at PSI is available for magneitc fields parallel to the sample surface up to 30 mT, which is small compared to fields relevant for SRF application. When designing a spectrometer for this field configuration one has to take into account that the magnetic field seen by the muon before implantation will not only cause spin rotation but also bend the beam trajectory. This effect becomes more pronounced for lower energy. betaNMR is a technique similar to μSR but uses heavier 8Li ions instead of muons as the magnetic probe. A spectrometer dedicated for SRF studies and therefore called betaSRF is currently under construction at TRIUMF [8, 9].

This paper gives a brief overview of μSR studies of SRF materials. For more detailed information the reader is refereed to previous publications

SURFACE μSR STUDIES

Initial studies have been performed on coin shaped samples with the sample surface orientated perpendicular to the magnetic field [3], see Fig.1. In this configuration samples can be tested in terms of their pinning strength. The field will first break in at the edges where it is enhanced. If the pinning strength of the material is large the movement of the flux to the sample center, where it is probed by the muons, is delayed, see Fig. 1. This is demonstrated in Fig. 2 for a coin which went through different treatments typically applied in cavity production i.e forming, etching and annealing.

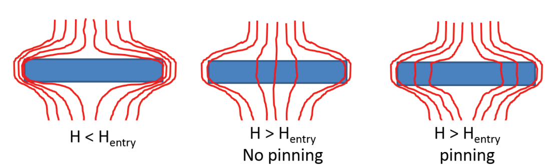

Figure 1: Left: Field breaks in at the edges first. At Hentry it will redistribute to the center for a pin free sample. Pinning resists redistribution requiring a higher field to reach the center.

In order to measure the field of first vortex penetration ellipsoidal samples have been produced for tests in the initial transverse field spectrometer. However, this configura-

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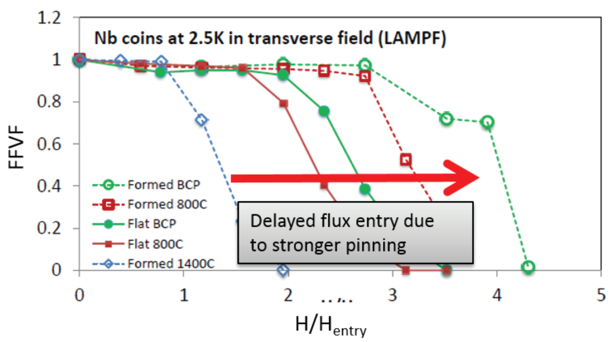

Figure 2: Field Free Volume fraction (FFVF) for a coin shaped sample with the magnetic field applied perpendicular to the sample surface.

tion was still found to be sensitive to pinning. Therefore, a dedicated parallel field spectrometer has been developed to test both ellipsoidal and coin shaped samples. In total four generic sample-field configurations can be used at TRIUMF depending on the property of interest, see Fig. 3 [10]. The coin in transverse field is best suited for pinning studies while the ellipsoid in parallel field is best suited for field of first vortex entry studies. The coin in parallel field is also well suited for these studies as it is only slightly more sensitive to pinning. For thin film studies coin shaped samples need to be coated on both sides and at least partly on the edges to prevent flux penetration from both sides of the coating.

Utilizing the parallel field spectrometer we have demonstrated that a layer of a higher Tc material on niobium can enhance the field of first vortex penetration by about 40% from a field consistent with the lower critical field Hc1 to a field consistent with the superheating field Hsh. This enhancement does not depend on material or thickness suggesting that the superconductor-superconductor (SS) boundary is providing effective shielding up to the superheating field of niobium. For details refer to [11].

LOW ENERGY μSR STUDIES

Le-μSR enables to probe the magnetic field in the London layer. It can therefore be used for a direct measurement of the London penetration depth. Several SRF materials have been tested. These include micrometer thick niobium films on copper substrate [12], NbTiN [13] and Nb3Sn [12, 14]. Comparing penetration depth values obtained with LE-μSR to RF frequency shift results there is a better agreement for the two methods for Nb3Sn compared to Nb. This might be related to the non-local properties of Nb.

When preparing thin film samples it is crucial to coat the whole sample surface area to avoid field penetration from both sides of the film. This is especially relevant for superconductor-insulator multilayer samples where fields can penetrate through the insulator. Fig. 4 shows results of two NbTiN on Nb samples. The NbTiN layer of the SS sample is about 160 nm thick and there is no interlayer. The SIS sample has a NbTiN thickness of about 80 nm and a

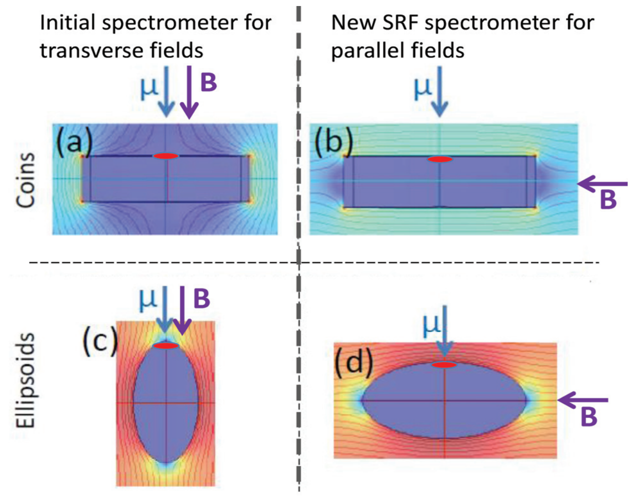

Figure 3: Four generic arrangements of sample, muon and field direction used for pinning and field of first vortex penetration studies [10].

20 nm AlN interlayer between the NbTiN film and the Nb substrate. Here the cosh shaped penetration profile signifies field penetration from both sides of the sample. The same behavior is observed for the SS sample above the critical temperature of Nb. Note that at 9 K Tc is already reached as it depends on applied field.

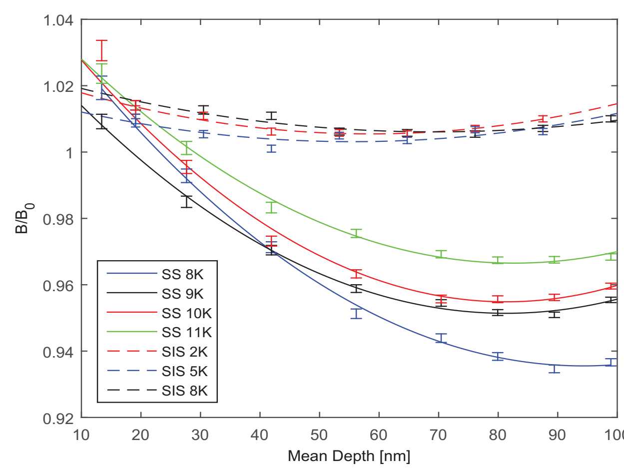

Figure 4: Field penetration in NbTiN on Nb samples with and without insulating interlayer.

In [12] LE-μSR and point contact tunneling are used to investigate paramegnetic impurities in Nb on Cu samples. A strong correlation between the two methods was found and it is suggested that magnetic impurities form along grain boundaries for Nb on Cu samples. Whether these are a dominant source for RF dissipation remains an open question.

COMBINED SURFACE AND LOW ENERGY μSR STUDIES

In a recent study surface and low energy μSR have been combined and correlated to RF critical field measurements

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performed with a Quadrupole Resonator. Critical field of Nb3Sn prepared for SRF application [14] have been investigated. The combined experimental results strongly confirm that Nb_3Sn SRF cavities can indeed be operated in a flux free Meissner state above H_{c1}. It is suggested that localized vortex penetration with little or negligible preheating prevents current Nb_3Sn SRF cavities to reach higher field values. This might be interpreted as a local suppression of the superheating field potentially at coating flaws as reported in [15].

DEVELOPMENT OF A BETANMR FACILITY FOR SRF STUDIES

Surface and low energy μSR have both shown to be useful tools to study SRF materials as outlined above. However, surface μSR implents muons deep in the bulk, while LE-μSR is only available for parallel magnetic fields up to 30 μT. Ideally one would like to have a facility enabling strong (above 200 mT) parallel magnetic fields and their localized detection in the London layer of SRF materials. For this purpose TRIUMF is currently constructing a facility based on the beta-NMR technique (Fig. 5) [8, 9]. Initial commissioning is scheduled for June 2020.

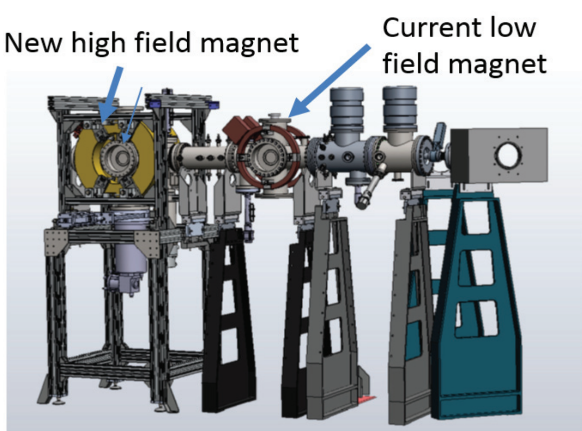

Figure 5: Extension of a beta-NMR beamline with the beta-SRF spctrometer. Note the larger size of the second Helmholtz coil enabling measurement in strong parallel magnetic fields.

OVERVIEW OF MEASUREMENT CAPABILITIES

Table 1 gives an overview of the three experimental techniques described in this contribution in terms of their capabilities for SRF material studies.

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Table 1: Measurement Capabilities Relevant to SRF Studies of Surface μSR, LE-μSR and betaNMR

Technique	Max parallel B field [mT]	Implantation depth in niobium	Measurement capabilities relevant to SRF
Surface μSR (TRIUMF)	300	about 130 μm (fixed)	Pinning strength [3, 10] Field of first vortex penetration [10, 11, 14]
LE-μSR (PSI)	30	about 10-100 nm (variable)	London penetration depth and magnetic screening profile in London layer [7, 12–14] Hydrogen diffusion and magnetic impurities [12]
Beta-NMR TRIUMF	200	about 10-200 nm (variable)	Vortex penetration in the London layer

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