

MUON SPIN ROTATION ON TREATED NB SAMPLES IN PARALLEL FIELD GEOMETRY

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Abstract

Muon Spin Rotation (μ SR) is a powerful tool to probe local magnetism in matter and hence can be used to diagnose the entry of magnetic flux in superconductors. First measurements on SRF samples were done with an external DC field applied perpendicular to the sample [1] (transverse geometry) with the muons applied to the sample face. Here, the results are strongly impacted by demagnetization, pinning strength and edge effects. A new spectrometer has been developed to allow sample testing with a field varying from 0 to 300 mT applied along the sample face (parallel geometry) analogous to RF fields in SRF resonators. The geometry is characterized by a small demagnetization factor reducing the impact of pinning and edge effects on field of first flux entry. The beamline installation and first results comparing transverse and parallel results will be presented.

MOTIVATION

Superconducting radio frequency (SRF) cavities face a limiting issue in which as the RF power input increases to achieve higher acceleration gradients, the surface resistance in the cavity walls increases causing the quality factor (Q) of the cavity to drop significantly (Figure 1).

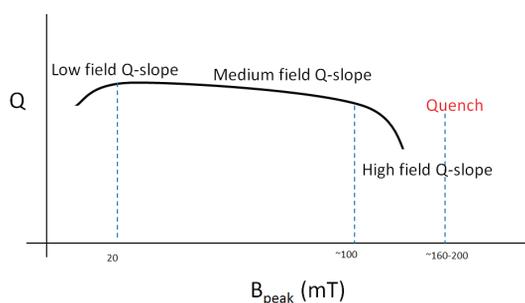


Figure 1: The quality factor of SRF cavities drops significantly peak magnetic fields are increased.

The reason for this shortcoming is not yet fully understood, however, it has been found that the performance of the cavity is heavily influenced by its surface preparations [2]. Common preparations include surface etching, bake-outs, and introducing impurities to the niobium. It is difficult and costly to test treatments on cavities so a technique such as μ SR, which allows for the testing of small samples mirroring potential cavity treatments with high sensitivity is important for making significant progress in the improvement of SRF cavities.

EXPERIMENTAL SETUP

Muon Spin Rotation

Muon Spin Rotation (μ SR) is a magnetic probe that can be used to detect the local magnetic properties of materials with extremely high sensitivity. μ SR takes advantage of the preferential emission of a positron along the polarization of the muon before its decay. By detecting the location of emitted positrons as a function of time with two detectors, in the case of parallel geometry “up” and “down”, the spin precession of the muons and therefore magnetic field properties can be inferred through an Asymmetry signal:

$$Asy(t) = \frac{N_U(t) - \alpha N_D(t)}{N_U(t) + \alpha N_D(t)} \quad (1)$$

Here, $N_U(t)$ is the number of counts in the “Up” detector and $N_D(t)$ is the number of counts in the “Down” detector. The parameter α is added to account for detector efficiencies and to remove any bias between telescopes caused by uneven solid angles; in the case where the detectors are identical in efficiency, α assumes a value of 1.

Previous μ SR experiments on superconducting Nb samples had used a geometry where the applied magnetic field is perpendicular to the sample face. It was concluded that the treatments affect the strength of pinning in the nb [1]. The experiment presented in this paper involves an applied magnetic field parallel to the sample face in order to achieve a more accurate model of field interactions inside the cavity, namely the boundary condition that, $B_{\perp} = 0$.

A spectrometer capable of providing fields up to 300 mT parallel to sample faces was built using TRIUMF’s M20 C-leg beamline. The spectrometer consists of a dipole magnet which provides the applied field, an internal and external muon counter used to specify muon location, and “up” and “down” detectors for detecting emitted positrons (Figure 2(a)). Due to the presence of the Lorentz Force in parallel geometry, a steering magnet is also employed to pre-steer the μ^+ beam such that by the time the beam enters the dipole’s field domain, the beam is steered back to the center of the sample (Figure 2(b)).

The beamline delivers muons with energy of 3.87 MeV \pm 6% and momentum of 28.9 MeV/c. The muons have an average stopping distance of $100\mu\text{m}$ in the nb, as simulated by TRIM [3] (Figure 3).

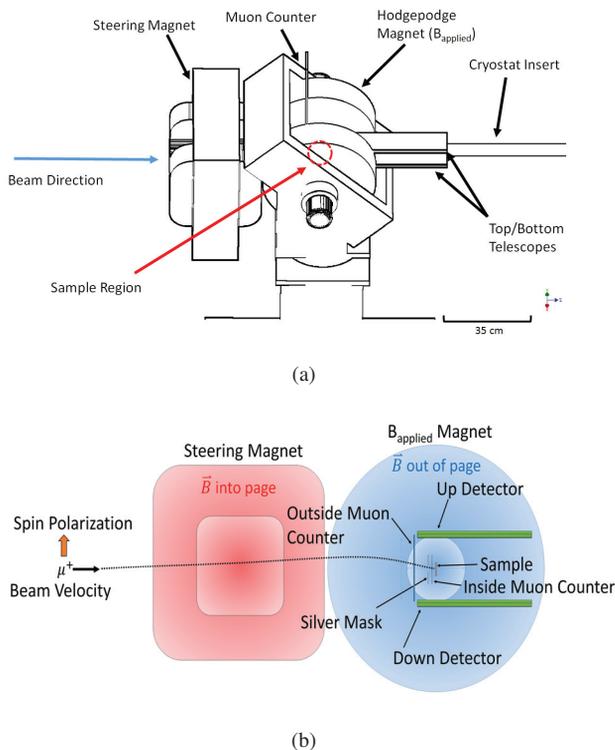


Figure 2: a) 3D render of the parallel μ SR spectrometer, b) Schematic displaying the components of the spectrometer and the beam trajectory.

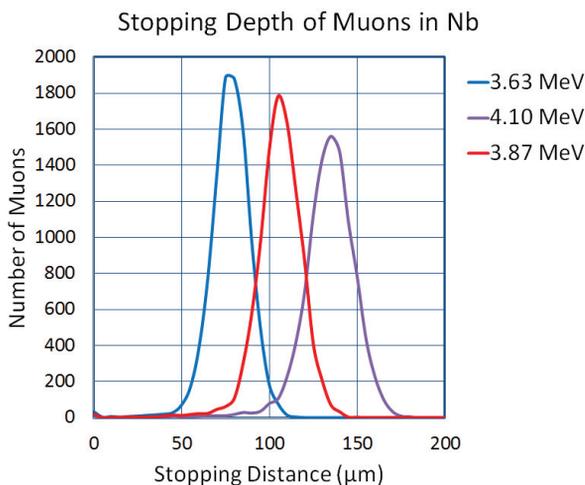


Figure 3: Muon stopping distance in Nb as simulated by TRIM. The simulation takes into account all obstacles the muons encounter in their path such as beamline windows and scintillators.

Samples

Four samples were prepared and studied for this experiment. All samples are disk shaped (20x3 mm) with the designated muon beam landing in the center of the samples. All samples except for a sample with a shell of Nb₃Sn formed around Nb (CF1) are composed of high purity ni-

bium (RRR=300). All samples include a base treatment of an ultra-sonic degrease. The base metal is then treated by etching, baking or a combination of both. Surface etching methods include Buffer Chemical Polishing (BCP) and Electrochemical Polishing (EP). Table 1 details the sample treatments used in the measurements.

Table 1: Sample Names and Their Treatments

Sample	Treatments
CF1	Nb ₃ Sn
TR9	Nitrogen Dope + EP
TR5	1400°C 5.5 hours, 120μm BCP
TR8	Pure

Surface etching smoothens and cleans the cavity surface. BCP and EP methods of etching each present distinct advantages and disadvantages. BCP involves a mixture of nitric acid, hydro uric acid and phosphoric acid with a 1:1:2 ratio, respectively. The etch rate for BCP is controlled mainly by turbulence, temperature and niobium concentration and the method provides an even etch but rougher surface compared to EP. Both methods clean the inside surface which eradicates impurities which can produce x-rays when passing large acceleration gradient voltages over the surface. EP involves a mixture of high concentration sulfuric acid and hydro fluoric acid. The etch rate for EP is lower than BCP (up to 40μm/h) for normal power since the EP etch rate is controlled by the amount of current and voltage supplied and the surface area of the metal being etched. Comparing the two methods further, BCP's main advantage is a faster process with higher efficiency while EP creates smoother surfaces.

THEORY

Asymmetry Signals

The asymmetry signal as a function of time, $A(t)$, retrieved from a superconductor in the Meissner State follows a Static Kubo-Toyabe function.

$$P_z(t) = \frac{1}{3} + \frac{2}{3}(1 - \Delta^2 t^2) \exp\left[-\frac{1}{2} \Delta^2 t^2\right] \quad (2)$$

where Δ is the width of the dipolar field distribution. The function is characterized by an initial Gaussian with a 1/3 tail recovery. The initial Gaussian portion of the polarization is explained by the Gaussian distributed nuclear magnetic dipolar fields from neighbouring Nb nuclear spins that influence the muon spins which then returns to 1/3 of the initial value; due to the component of local fields along initial direction of polarization, 1/3 of the muons are polarized along the axis of initial polarization [4]. The nuclear spin for ⁹³Nb is 9/2 with a magnetic moment of 6.1705 N.

The diffusion of muons between interstitial sites (hop-rate) in the lattice causes modulation in the tail of the signal,

which leads to a Dynamic Kubo-Toyabe:

$$A(t) = \frac{1}{2\pi i} \int_{\gamma-i\infty}^{\gamma+i\infty} \frac{f_G(s + \Gamma)}{1 - \Gamma f_G(s + \Gamma)} \exp(st) ds \quad (3)$$

where

$$f_G(s) \equiv \int_0^{\infty} G_{G,LF}(t) \exp(-st) dt \quad (4)$$

As the applied field is increased, flux begins to penetrate the sample. As a result of its influence on the precession frequency of the muons, the amplitude of the Gaussian portion of the Kubo-Toyabe decreases (Figure 4).

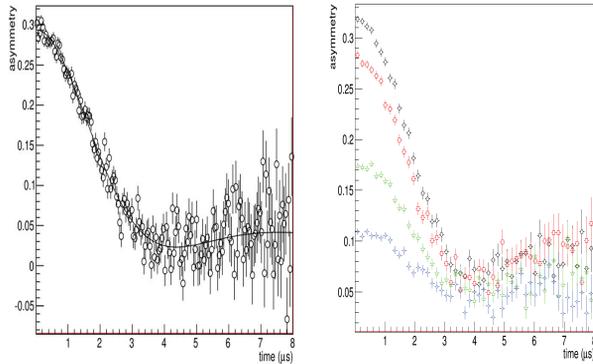


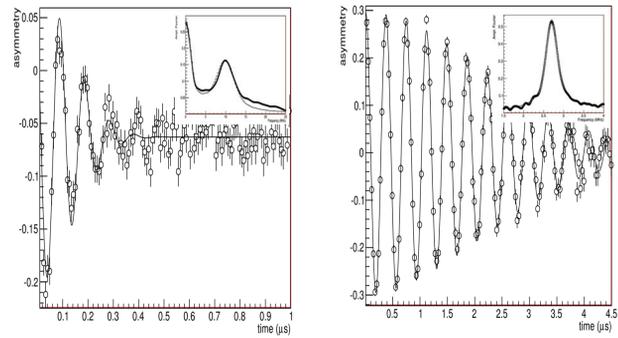
Figure 4: The Meissner State is characterized by a Kubo-Toyabe function (left). As $B_{applied}$ is increased the amplitude of the Kubo-Toyabe decreases (right). The spectra are retrieved from “musfit”, a fitting program used to analyse μ SR data [5].

Upon transitioning to the mixed state, the asymmetry signal assumes the form of a heavily damped oscillation (Figure 5(a)). The muons’ spin polarization will precess with varying frequencies that depend on their distance from the intruding vortices. The Fourier transform of the signal illustrates the varying spin precession frequencies.

As the field strength increases further, the damped oscillations transform into a much less damped oscillation which signifies the sample existing in the normal state (Figure 5(b)). In this state, the asymmetry implies that the muons are precessing largely with the same frequency since magnetic flux affects all sites almost uniformly. It is the existence of nuclear dipolar fields which adds slight damping to the signal. This can also be shown by a Fourier transform of the asymmetry. The existence of an outstanding peak among a distribution of smaller peaks shows that the muons’ spin polarizations precess largely with the same frequency, since the sample is fully penetrated by the applied field. One can then use the precession frequency and the gyromagnetic ratio of muons, 13.55KHz/G, to calculate the field strength present in the sample that would cause precession with the frequency produced by the Fourier transform.

Flux Entry and Pinning

For a superconducting sample with finite geometry, magnetic fields are enhanced at the edges by the demagnetization



(a) The mixed state is characterized by a heavily damped signal. Muons precess with different frequencies that depend on their distance from vortices (inset).

(b) A slightly damped oscillation signifies the normal state. Muons’ spin precession is mostly influenced by the applied field which penetrates the sample uniformly. The Fourier transform of the signal illustrates the outstanding precession frequency (inset).

Figure 5: Asymmetry signals corresponding to the mixed and normal state.

factor, N . This causes the level at which the applied field enters the sample, which we call H_{en} , to be lower than the theoretical H_{c1} value, such that:

$$0 < H_{en} < H_{c1} \quad (5)$$

When the field strength reaches H_{en} , it is energetically favourable for the flux lines to go through the superconductor. The intruding flux lines can then be pinned at their location with some strength that depends on the bulk properties of the metal. Increasing the field strength further causes the density of the vortices to increase until H_{c2} is reached at which point the superconductor undergoes its final phase transition to its normal state (Figure 6).

RESULTS AND DISCUSSION

The performance of the samples is illustrated by normalized “Asy(0) vs. Applied Field” plots (Figure 7). The treated disks share measured H_{c1} values close to their theoretical value of 170 mT. This is likely due to the small demagnetization factors based on the parallel geometry. Larger demagnetization factors in similar transverse field measurements caused measured H_{c1} values to be much lower [1]. The behaviour of the samples is also characterized by sudden transitions from the Meissner State to the Mixed State, indicated by steep slopes on the plot. This is also a geometrical effect; since the signal is retrieved from muons stopping in the center of the sample, flux vortices will immediately affect the spin precession of the muons and thus a sudden drop in Asymmetry is observed. The remaining difference in H_{c1} values between the samples can possibly be contributed to the pinning strength of the samples. Sample CF1, composed of a $2 \mu\text{m}$ shell Nb_3Sn formed around bulk Nb arguably displays the best performance. With a T_c of 18.1K (double that of Nb), an H_{c1} and H_{c2} of 30 mT, 3 T respec-

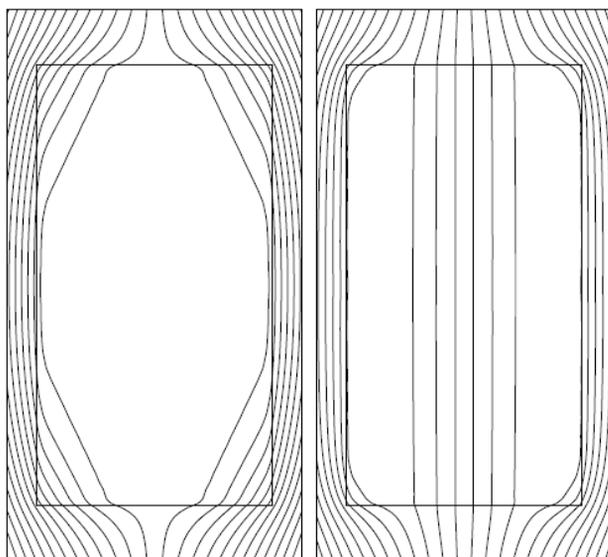


Figure 6: Flux entry into a superconductor in parallel geometry as calculated by Brandt [6] where the aspect ratio $b/a = 2$

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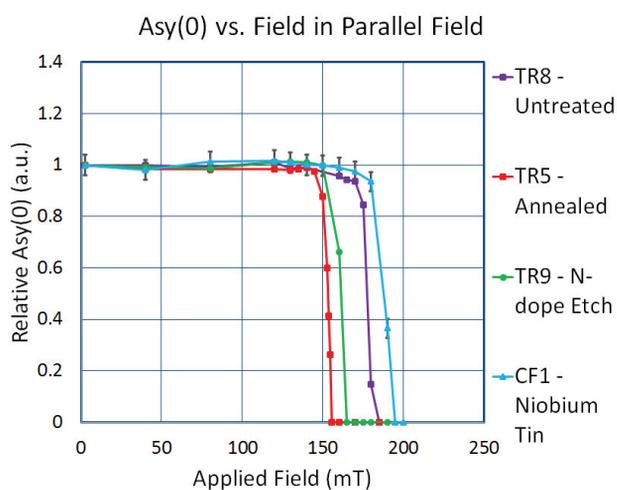


Figure 7: Results from the parallel μ SR experiment. The reduction of the relative $Asy(0)$ signifies the entry of flux.

tively, Nb_3Sn as a cavity coating is theoretically capable of achieving twice the acceleration gradient of Nb cavities under the same operation conditions with significantly lower BCS surface resistance for a given temperature [7]. RF tests conducted by Cornell have concluded that the alloy has shown very promising results in being a candidate for RF cavity material [8]. Further testing is recommended for more conclusions.

REFERENCES

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