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BETA-SRF - A NEW FACILITY TO CHARACTERIZE SRF MATERIALS NEAR FUNDAMENTAL LIMITS

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Abstract

Demands of CW high-power LINAC require SRF cavities operating at the frontier of high accelerating gradient and low RF power dissipation, i.e. high quality factor (Q_0). This requirement poses a challenge for standard surface treatment recipes of SRF cavities. In a recent breakthrough, elliptical SRF cavities doped with Nitrogen have been shown to improve Q_0 by a factor of 3, close to the fundamental SRF limit. The fundamental mechanisms at microscopic level and optimum doping recipe, however, have still not fully been understood. Materials other than Nb have also been proposed for SRF cavities to overcome the fundamental limit already reached with Nitrogen doping, e.g. Nb_3Sn, MgB_2, and Nb-SIS multilayer. At TRIUMF, a unique experimental facility is currently being developed to address these issues. This facility will be able to probe local surface magnetic field in the order of the London Penetration Depth (several tens of nm) via β decay detection of a low-energy radioactive ion-beam. This allows depth-resolution and layer-by-layer measurement of magnetic field shielding effectiveness of different SRF materials at high-parallel field (up to 200 mT). Design and current development of this facility will be presented here, as well as commissioning and future measurements strategies for new SRF materials.

BACKGROUND AND MOTIVATION

SRF (Superconducting RF) cavities are the backbone of modern LINACs (Linear Accelerators) due to the low power dissipation and high accelerating gradient. The base performance of SRF cavities can be characterized by the Q_0 (Quality Factor) vs E_{acc} (accelerating gradient) curve. Higher Q_0 reduces the cryogenic power consumption while larger E_{acc} (in the unit of MV/m) reduces the overall length of the LINACs. For CW (continuous wave) LINACs, Q_0 plays a more important role while for pulsed high-gradient LINACs, E_{acc} is more crucial. Pushing the performance of SRF cavities has been made possible through decades of intensive research into the fabrication, assembly, surface processing, and metallurgy for over five decades [1]. Most of SRF cavities have been made with bulk Niobium (Nb). Recently the discoveries of Nitrogen-doping [2] and Nitrogen-infusion [3] of Nb SRF cavities have pushed its performance on both Q_0 and E_{acc}[1] close to its fundamental limit. Understanding the mechanism of this doping effect require microscopic studies of the Niobium composition and superconducting properties (such as critical magnetic field of the Meissner state) at the nanometer scale. Active research in alternative materials such as Nb_3Sn and MgB_2 has also been pursued since the bulk Nb SRF cavities have almost reached the maximum performance. These alternative materials are based on thin-films due to the fact that only several nm of the inner RF surface layer determine the performance of the SRF cavities.

TRIUMF SRF group conducts both SRF cavities design & fabrication, and fundamental SRF studies. Currently there are two SRF LINACs, ISAC-II and ARIEL e-LINAC (electron LINAC), operating. TRIUMF SRF group also collaborates in the fabrication of both cavities and cryomodules for international projects such as RISP (South Korea) and VECC (India) rare-isotope projects. In the field of fundamental SRF, previous studies of N-doped Nb and novel thin film SRF materials have been done with μ-SR (muon spin resonance) technique [4] to measure the field of first magnetic flux entry. Nb, which is a type-II superconductor, is operated in the Meissner superconducting state in SRF cavities. Local magnetic probe techniques such as μ-SR can measure more accurately the fraction volume inside the superconductor which is not in the Meissner state. Therefore this technique is a powerful method to characterize the critical Meissner field that can be achieved. The higher the critical field of the Meissner state, the higher accelerating gradient that the SRF cavity can achieve. Recently, the TRIUMF SRF group has commissioned a RF induction furnace for doping and heat-treatment studies of both sample and test cavities. Two multi-mode coaxial test resonators (a quarter-wave and a half-wave resonator) have also been fabricated to study the doping and heat-treatment effects at lower frequency (low beta) cavities [5]. The purpose of this proceeding is to describe a new facility, β−SRF for the specific purpose of investigating thin-films and multi-layer SRF materials.

BETA-SRF FACILITY

Beta-detected NMR (β−NMR) Technique

Beta-NMR (nuclear magnetic resonance) is a unique material characterization technique where the local magnetic field near an implanted ion probe is detected via asymmetric beta-decay correlated with the precession of the nuclear spin. The frequency of the spin precession (Larmor frequency) is proportional to the strength of the local magnetic field. This

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[1] This is true in the case of N-infusion, while N-doped SRF cavities have higher Q_0 at lower E_{acc}.

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technique provides ten orders of magnitude higher sensitivity compared to the conventional NMR technique and can be performed in any magnetic field environment, including zero field. Hyperpolarized radioactive nuclei are achieved using an optical polarization scheme, which is the reason why in most cases $^{8}Li^{+}$ is used as the β–NMR probe since it is the easiest to polarize. This technique uses the same principle as µ-SR, with the main difference in the use of radioactive nuclei instead of muon. This is only made possible at RIB (Radioactive Ion Beam) facilities such as ISAC at TRIUMF. The advantage of β–NMR over the µSR technique at TRIUMF is that the low energy radioactive ion beam can be decelerated at the sample to provide a depth-resolved local magnetic field study of thin-films, multi-layer, and interface of materials. This is particularly suitable for novel thin-film SRF materials study. The geometry of the implanted beam and the magnetic field measured inside the superconductor is shown in Fig.1.

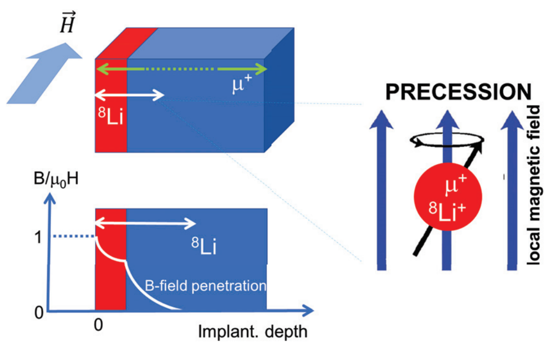

Figure 1: Measurement of local magnetic field with β-NMR and µSR for fundamental SRF studies. In both cases an external magnetic field are applied parallel to the sample with the sample in the superconducting state. In the case of µSR the muon is implanted in the near surface and acts like a bulk probe while in β-NMR the ion acts as a surface probe. In each technique, information about the Meissner state can be determined including the field of first fluc penetration with µSR while the details of the field attenuation through the London layer (or layers) can be studied through the variable depth of the ion probe. The inset shows nuclear spin precession of the ion probe in the local magnetic field.

The existing beamline layout is shown in Fig.2 with two main spectrometers: a high magnetic field and a low-field spectrometers. The high-field spectrometer is capable of applying 9 Tesla magnetic field via superconducting solenoid with field orientation normal to the sample surface. The low-field spectrometer, on the other hand, is capable of generating low magnetic field (0-24 mT) parallel to the sample surface [6]. In order to study the maximum critical field of the Meissner state, i.e. superheating field H_{sh}, higher magnetic fields parallel to the sample are required on top of the depth resolved capability already available at the current β–NMR beamline. The low field spectrometer beamline, therefore, needs to be extended to higher fields by adding a Helmholtz coil with higher field and modifying the existing low-field branch. At the moment, only one facility in the world utilizing low-energy µSR (LE-µSR) is capable of performing similar studies but at lower magnetic fields. The new β-SRF facility will provide a unique instruments for the SRF community for the study of SRF materials.

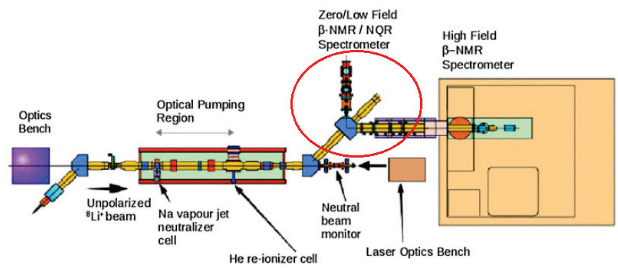

Figure 2: Present β-NMR beamline with two spectrometers covering different magnetic field ranges [6]. The low-field spectrometer section (circled in red) is the location for the upcoming β-SRF extension facility.

Beta-SRF Beamline Extension

A mechanical 3D model of the extended beamline is shown in Fig.3 including the stronger Helmholtz coil operating up to 200 mT and its upstream beam diagnostics components. Both the spin polarization of the probe beam and the magnetic field is parallel to the sample surface. Beam optics have been designed to provide controllable ^{8}Li beam energy between 1-30 keV with 2 rms (half width) beam size of 2 mm. The sample is located at the center of each Helmholtz coil (both the low and high-field coils) with an electrostatic decelerator to control the implantation of the energy of the ion beam.

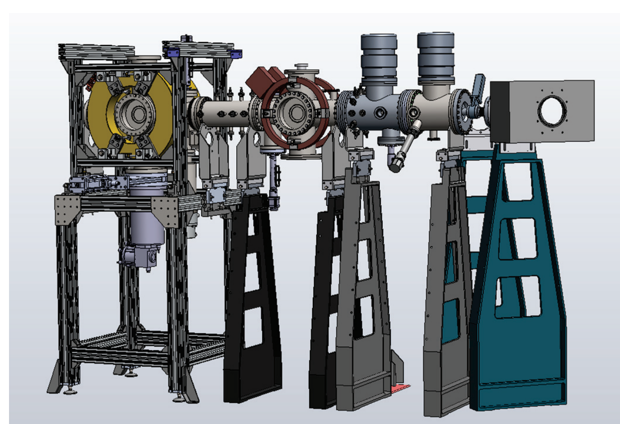

Figure 3: Mechanical design of the extended β-NMR beamline for β–SRF facility. The added stronger Helmholtz coil is shown in the far left (gold colour) coil together with its support frame.

In the low energy spectrometer, the compensation of the beam deflection due to low field Helmholtz coil is compensated by an electrostatic steerer. The high-field Helmholtz coil, however, require stronger compensation strength and is

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achieved via a newly designed variable steerer/decelerator system. The steerer/decelerator is segmented into four electrodes. Details of the beam optics design and beam diagnostic components will be described in future publications. Currently, the β−SRF beamline mechanical design has been finalized and beamline components have been ordered. The high-field Helmholtz coil (Fig.4), fabricated by Stangenes Industries Inc., has been received together with different parts of the beam diagnostics and HV optics. Additional sample chamber with the same design of the low-field counterpart will also be installed and allow both low-field and high-field future operation in exchange.

CONCLUSION

This paper described the science case for the newly designed $\beta - SRF$ facility. The need for high parallel magnetic field and depth-resolved Meissner state probe in high external magnetic field has not been accommodated by currently available µSR or β−NMR facilities around the world. This is the reason for building an extension to the available surface probe at the TRIUMF β−NMR facility with the suitable parallel magnetic field and spin geometry at the higher magnetic field of 200 mT. Beam deflection compensation strategy and beamline design have been described briefly and further details will be provided in a separate future publication.

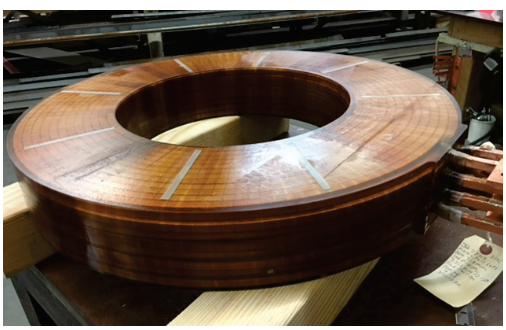

Figure 4: Photo of Helmholtz coil operated at 200 mT which has been recently received at TRIUMF.

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