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CRITICAL FIELDS OF SRF MATERIALS *

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Abstract

Nb3Sn and NbTiN are two potential alternative materials to niobium for superconducting RF cavities. In this study direct measurements of the magnetic penetration depth using the low energy muon spin rotation technique are presented, from which the lower critical field and the superheating field are derived. Comparison with RF data confirms that the lower critical field is not a fundamental limitation and predict a potential performance clearly exceeding current state of the art of niobium technology if the superheating field can be achieved. As a potential pathway to avoid premature vortex penetration and reaching the superheating field it is suggested to use a bilayer structure with the outer layer having a larger magnetic penetration depth.

INTRODUCTION

The material of choice for superconducting cavities is currently niobium, which is the material with the highest lower critical field H_{c1}. In order to achieve accelerating gradients beyond niobium technology it is necessary to operate cavities either in a mixed state with fluxoids in the material or in a metastable state above H_{c1}. The former solution would require strong pinning to avoid dissipation from vortices. The latter scenario can either be achieved by an energy barrier for vortex penetration or operating the cavities at a frequency which exceeds the time required for vortex penetration.

In this paper we present direct measurements of the London penetration depth of Nb3Sn and NbTiN using the low energy muon spin rotation technique. From these measurements we derive the lower critical field H_{c1}, the critical thermodynamic field H_c and the superheating field H_{sh}. (Table 1).

METHOD

At PSI a low energy muon beam is available [1, 2]. It can be used as a probe for local magnetism at various depths between a few and up to about 300 nm depending on the material density. Applying a field below H_{c1} this allows to measure the local field H_{int} as a function of depth by varying the muon energy and therefore the implantation depth. This enables a direct measurement of the magnetic penetration depth λ. Results from two samples are presented here. A NbTiN film has been deposited by reactive DC magnetron sputtering at JLAB [3] while Nb3Sn was deposited using vapour diffusion at Cornell [4]. Substrates are made of RRR niobium[1] in both cases. Fig. 1 displays a transmission electron microscope image of the cross section of the NbTiN sample including a High Angle Annular Dark Field (HAADF) image. There is a well defined interface between the two materials and thickness of the NbTiN film is about d=160 nm.

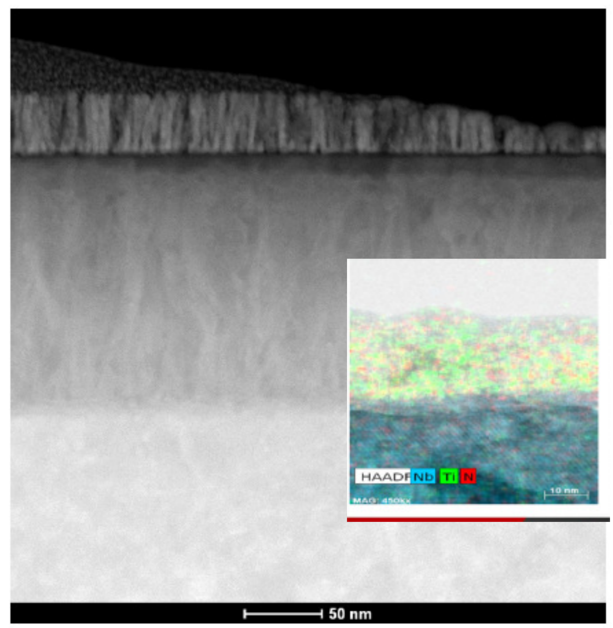

Figure 1: Transmission electron microscopy image of the cross section of a NbTiN on Nb sample from which the thickness of the sample is obtained. The uppermost layer is Pt added for protection for ion beam cutting. The inset shows a High Angle Annular Dark Field (HAADF) image revealing the elemental composition at the interface between the two materials.

RESULTS

Figure 2 displays the internal magnetic field B_{int} as a function of mean muon implantation depth $\langle x \rangle$ calculated with the muSRfit software [5] and the muon stopping distribution for NbTiN calculated with the TRIM.SP software [6] for the two samples. The thickness of Nb3Sn is about 2 μm. This is large compared to the penetration depth λ, which can therefore be simply calculated from

$$B = B_0 \exp\left(-\langle x \rangle / \lambda\right) \quad (1)$$

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[1] Niobium with a RRR> 300 is usually used for cavity fabrication and simply referred to as RRR niobium.

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Table 1: Material parameters from literature and from our measurements. The upper estimate for λ_L of NbTiN is taken from our λ measurements.

Material	λ_L[nm]	ξ_0[nm]	λ[nm]	κ	H_{c1}[mT]	H_c[mT]	H_{sh}[mT]
Nb3Sn	65 [7]-89 [8]	5.7(0.6) [9]	160(4)	60(15)	28(2)	600(100)	410(70)
NbTiN	150 [10]-170	2.4(0.4) [11]	160(10)	70(16)	24(4)	500(200)	439(80)

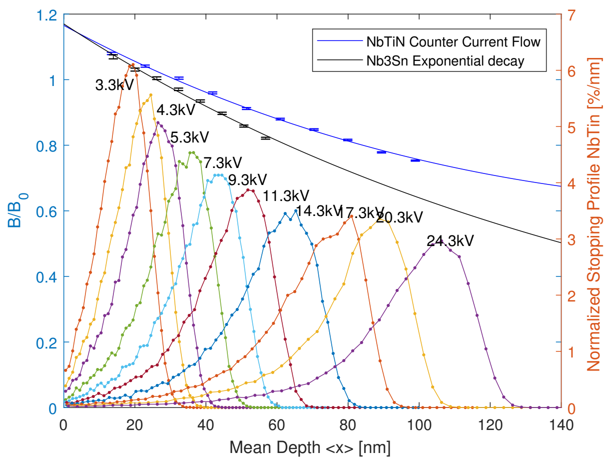

Figure 2: Normalized local magnetic field in the Nb3Sn and NbTiN samples as a function of mean muon implantation depth $\langle x \rangle$ measured with low energy muon spin rotation. On the right y-axis the stopping profile for NbTiN is displayed.

where $\langle x \rangle$ is the mean implantation depth of the muons. The fit parameters found are B_0=11.4 mT and $\lambda(5K)$=160.5(3.9) nm. λ is expected to change according to

$$\lambda(T) = \frac{\lambda(0K)}{\sqrt{1-(T/T_c)^4}}, \tag{2}$$

from which $\lambda(0K)$=160.0(3.9) nm can be derived. The value of B_0 is 14 % larger than the applied field of 10 mT. This field enhancement is close to what is expected at the edge of the sample with demagnetization factor N=0.15 [12]. The NbTiN film is so thin that counter current flow between film and substrate need to be considered [13,14] . The penetration depth of the NbTiN layer λ_{NbTiN} is thus calculated using

$$B = B_0 \frac{\cosh \frac{d-\langle x \rangle}{\lambda_{\mathrm{NbTiN}}} - \frac{\lambda_{\mathrm{Nb}}}{\lambda_{\mathrm{NbTiN}}} \sinh \frac{d-\langle x \rangle}{\lambda_{\mathrm{NbTiN}}}}{\cosh \frac{d}{\lambda_{\mathrm{NbTiN}}} - \frac{\lambda_{\mathrm{Nb}}}{\lambda_{\mathrm{NbTiN}}} \sinh \frac{d}{\lambda_{\mathrm{NbTiN}}}} \tag{3}$$

where λ_{Nb} is the penetration depth of the Nb substrate which can estimated to be 30-50 nm. λ_{NbTiN}(0K)=160(10) nm is derived which is significantly smaller to what one would calculate from Eq. 1 (233 nm). To obtain the Ginzburg Landau parameter $\kappa = \lambda/\xi_{GL}$ from the measured value of λ one has to know the Ginzburg-Landau coherence length ξ_{GL} which is a property dependent on the material purity and can therefore not directly be obtained from literature. The fact that the BCS and the Ginzburg-Landau coherence length ξ_0 and ξ_{GL} are both correlated to the magnetic flux quantum Φ_0 can be used to derive [15,16]

$$\kappa = \frac{\lambda}{\xi_{\mathrm{GL}}} = \frac{2\sqrt{3}}{\pi}\frac{\lambda^2}{\xi_0 \lambda_{\mathrm{L}}}. \tag{4}$$

λ_L and ξ_0 are both fundamental properties which do not depend on purity. Literature values can be found in Tab. 1. Now the lower critical field H_{c1} can be derived from [16]

$$H_{c1} = \frac{\Phi_0}{\pi \lambda^2} \ln(\kappa + 0.5), \tag{5}$$

where Φ_0 is the magnetic flux quantum. From this the thermodynamic critical field can be calculated using [16]

$$H_c = \frac{\sqrt{2}\kappa H_{c1}}{\ln \kappa}. \tag{6}$$

The value for Nb3Sn (Tab. 1) is consistent with 530 mT reported in [8]. Finally the superheating field can be calculated using [17]

$$H_{\mathrm{sh}} = H_c \left(\frac{\sqrt{20}}{6} - \frac{0.55}{\sqrt{\kappa}} \right). \tag{7}$$

The values, see Tab. 1 significantly exceed the superheating field of niobium (about 240 mT).

DISCUSSION

The results predict superheating fields about twice as high as for Nb for both materials. However, the RF performance of Nb3Sn and NbTiN cavities is limited to surface magnetic fields significantly below H_{sh} but well above H_{c1} [18]. The obtained temperature dependence in such tests was found to be consistent with an heuristic model called vortex line nucleation which gives an estimate for the maximum RF field as

$$H_{\mathrm{VLN}} = \frac{1}{\kappa} H_c. \tag{8}$$

However, the values of κ derived here would yield H_{VLN} well below H_{c1} and experimentally observed critical RF fields. On the other hand this model has given predictions for Nb in agreement with κ derived from low field surface impedance measurements [19]. This can be interpreted that the limitation of Nb3Sn and NbTiN, unlike for Nb, is not related to defects of the size of the coherence length on otherwise clean material with material parameters as displayed in Tab. 1.

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HOW TO REACH LARGE ACCELERATING GRADIENTS

Several approaches have been suggested to reach accelerating gradients beyond the current state of the art with new materials. Defect free surfaces would allow to reach the superheating field. As Nb is operated in a metastable state above H_{c1} this might actually be possible to achieve for other materials as well. However, the coherence length of Nb is about ten times larger than for promising alternative materials such as NbTiN and Nb3Sn. To prevent flux penetration above H_{c1} Gurevich suggested to use alternating layers of superconductors and insulators, since there are no thermodynamically stable parallel vortices in decoupled layers which are thinner than the penetration depth [20]. A superconductor exposed to an RF field will remain in a flux free state above H_{c1} if the time it takes for flux to penetrate exceeds the RF period [21]. It might therefore be possible to engineer the outer surface to retard flux penetration as has recently been suggested by Romanenko [22]. On the other hand, in a recent publication it was shown that niobium can reach the superheating field if coated with MgB2 or Nb3Sn even for a DC field [23]. The results have been interpreted that there is a second surface barrier at the interface between the two superconductors if $\lambda_2 < \lambda_1$ as theoretically derived by Kubo [14]. This effect is visualized using the concept of image vortices in Fig. 3. The reason why only the boundary between the two superconductors and not between surface and vacuum can provide shielding above H_{c1} can be related to the proximity effect acting between the two superconductors. For details we refer to [23]. Potentially a layer with a larger penetration depth could also push Nb3Sn, NbTiN or other materials such as MgB2 to their superheating field enabling accelerating gradients beyond state of the art of niobium technology.

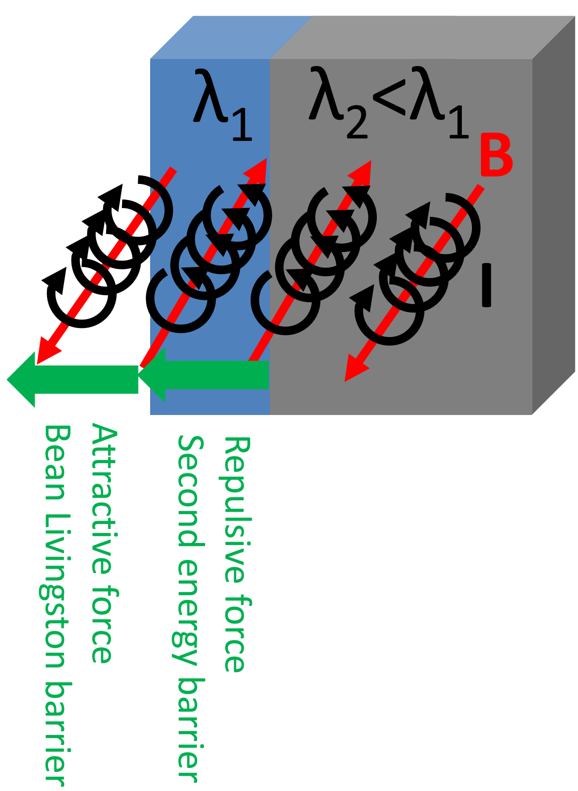

Figure 3: Consider a parallel vortex in a superconductor. To fulfill the boundary conditions at the vacuum superconductor interface an image current is introduced yielding an attractive force to the surface. An energy barrier (Bean Livingston barrier) is built up, which allows the superconductor to remain in a flux free Meissner state above H_{c1} . At the interface between two superconductors of different penetration depth there is a force on vortices towards the material with larger λ, creating a second energy barrier if $\lambda_1 > \lambda_2$.

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