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RF Critical Magnetic Field Measurement of MgB_2 and NbN Thin Films Coated on Nb

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Abstract. Niobium (Nb) Superconducting RF (SRF) cavities have been used or will be used for a number of particle accelerators. The fundamental limit of the accelerating gradient has been thought to be around 50 MV/m due to its RF critical magnetic field of around 200 mT. This limit will prevent new projects requiring higher gradient and compact accelerators from considering SRF structures. There is a theory, however, that promises to overcome this limitation by coating thin (less than the penetration depth) superconductors on Nb. We initiated measurements of critical magnetic fields of Nb coated with various thin film superconductors, starting with NbN and MgB_2 using polymer assisted deposition and reactive evaporation techniques, respectively, with the goal to apply this coating to SRF cavities. This paper will present test results of the RF critical magnetic field of thin MgB_2 coated on Nb using a 50-MW short-pulse (1 μs or less) Klystron and a hemispherical cavity at SLAC.

1. INTRODUCTION

Having evolved over the years from accelerating gradients of 3 MV/m in the early 70s to over 40 MV/m now, niobium cavities have proved viable and useful for accelerator applications. A number of large-scale accelerator projects such as the International Linear Collider and European X-Ray Free Electron Laser are based on SRF technology and will be employing a large number of SRF cavities. Optimization of the cell shape further increased the accelerating gradient, bringing the current state of art in niobium RF superconductivity to its fundamental limit, dictated by the RF critical field of niobium [1]. For further improvement in the accelerating gradient we need to use superconductors that have higher RF critical fields.

Since the surface resistance of a BCS superconductor, R_s, for $T< T_c/2$, $\hbar\omega << \Delta$, $\hbar\omega << k_bT$ can be approximated by $R_s \propto \sqrt{\rho_n} \cdot exp(-\Delta/k_bT)$ [2], in order to have a low R_s, the superconductor must have a large energy gap and a low normal-conducting resistivity just before the transition. These properties are available in some niobium compounds, such as NbN, NbTiN, and A-15 compounds such as Nb_3Sn or V_3Si. Also, MgB_2 unlike other high T_c superconductors holds some promise due to its BCS-like behavior and low intergrain losses. So far, however, to the best of our knowledge only once has a superconducting accelerating structure made of a superconductor other than niobium performed better than a niobium one, showing higher low-field quality factor at 4.2 K than that of niobium at 2 K [3].

In 2005, a possibility to increase the accelerating gradient was suggested based on the fact that the H_{c1} in the direction parallel to the magnetic field increases if the superconductor gets thinner than the London penetration depth [4]. Out goal is to demonstrate the enhancement of the RF critical magnetic field using this theory. First, we decided to use NbN and MgB_2 due to their available technologies [5], [6].

2. EXPERIMENTAL

2.1. SAMPLE PREPARATION

After a few unsuccessful attempts to deposit a good-quality film on polycrystalline niobium samples, we decided to concentrate our efforts on single grain niobium samples. The niobium samples are 2-inch disks, about 1/32 inch thickness with a residual resistivity ratio (RRR) $\cong$ 300. Before deposition these disk are polished with a buffered chemical polishing (BCP) solution (HF: HNO_3: H_3PO_4 = 1:1:2 (vol.)), the standard procedure for preparation of SRF cavities. X-ray diffraction (XRD) θ-2θ scans showed that orientation of samples was largely (110). Atomic force microscopy indicated surface roughness around 50 nm for 100 x 100 μm^2 scans as shown in Fig. 1. Also, ten 1 x 1 cm^2 Nb substrates were prepared from one of the 2-inch disks that underwent the same chemical polishing procedure for the optimization of the coating processes.

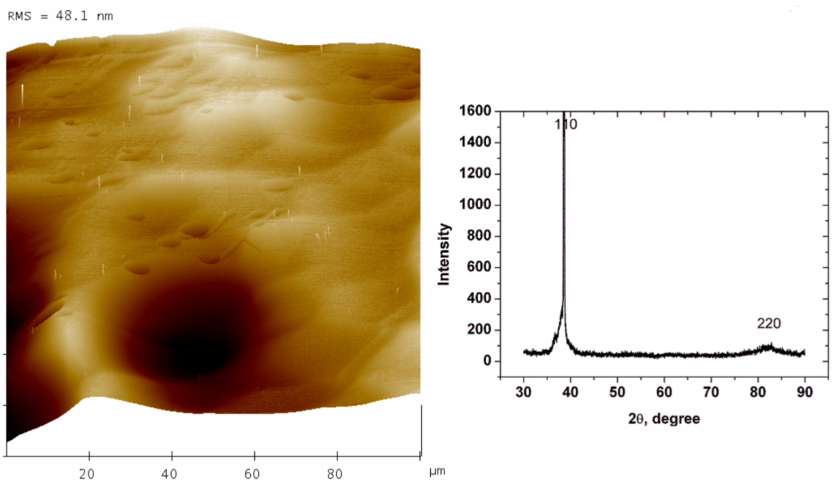

Figure 1. Images of single crystal niobium surface: (left) atomic force microscopy reconstructed image, (right) XRD θ-2θ scan.

Niobium nitride layers were coated by the polymer assisted deposition (PAD) technique [5]: an aqueous solution of niobium ion bound to polymer was spin coated on niobium samples, which then was annealed at 900 °C for 5 hours in gaseous ammonium. MgB_2 films were deposited at Superconductor Technologies, Inc., (STI) by the reactive evaporation technique [6]. Samples were coated with 10 nm of B on top of niobium, and then 100 nm of MgB_2 was deposited on top of the boron layer.

2.2. MEASUREMENT SETUP

The RF cavity method was employed for RF measurements. A description of the setup and measurement techniques can be found in [7] and [8]. A hemispherical copper cavity with a resonant frequency of $\sim$ 11.4 GHz for the TE_{013} mode was used. The demountable plate was made to accommodate 2 inch samples. The low-power RF properties were measured with a network analyzer and the high-power tests were carried out by connecting the cavity to a 50 MW Klystron. The temperature was monitored by 4 diode temperature sensors, two on the hemispherical part, one on the RF input iris and one touching the sample from non-RF side.

3. RESULTS

The first experiments were conducted on polycrystalline niobium samples coated with MgB_2 and NbN. The results did not show any superconducting transition for samples coated with NbN, and showed a transition for MgB_2 at temperatures close to 9.2 K corresponding to the niobium substrate. We concluded that these poor results are due to the fact that the surface was too rough for the coating thickness, i.e., the roughness of a few hundred nm compared to 100 nm of coating. The next experiments were conducted with MgB_2 deposited on the single grain sample. Figure 2 shows the quality factor of the cavity as a function of temperature in red, together

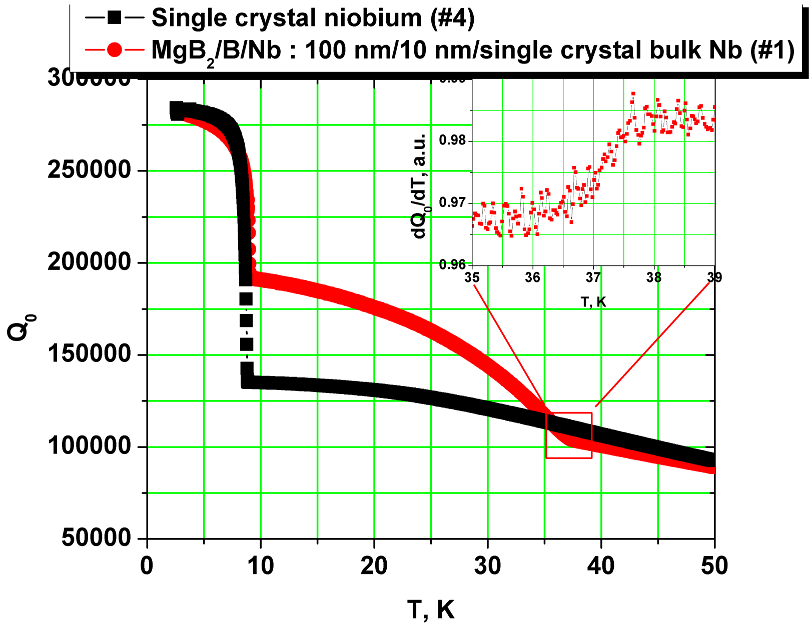

Figure 2. Quality factor as a function of temperature for single grain niobium sample coated with B(10 nm)/MgB_2(100 nm). For comparison the quality factor vs. temperature for niobium measured with the same setup is presented. The inset shows $\frac{dQ_0}{dT}$ calculated from the data near MgB_2 transition point. These data indicate T_C = (37.1±0.6) K.

with the niobium data measured with the same setup. We observed a superconducting transition of the MgB_2 film around 37 K. The second transition corresponding to niobium was observed around 9 K. The lower temperature quality factors of Nb/B/MgB_2 and bulk Nb coincide, which indicates that the RF surface resistance of MgB_2 is comparable to that of niobium. The inset of Fig. 2 shows the $\frac{dQ_0}{dT}$ calculated from the data. The change in slope indicates the transition from normal conducting to superconducting state in MgB_2 film, which occurs at T_C= (37.1±0.6) K. Resonant frequency measurements, however, did not show a related change in screening, Fig. 3. The frequency variation is caused by the change of dimensions due to thermal contraction and by the change in the penetration depth of the sample. If we consider the cavity's effective radius, $r_{eff}(T)$, it is expressed as:

$$r_{eff}(T) = \frac{G}{\pi \mu_0 f_{res}(T)}, \tag{1}$$

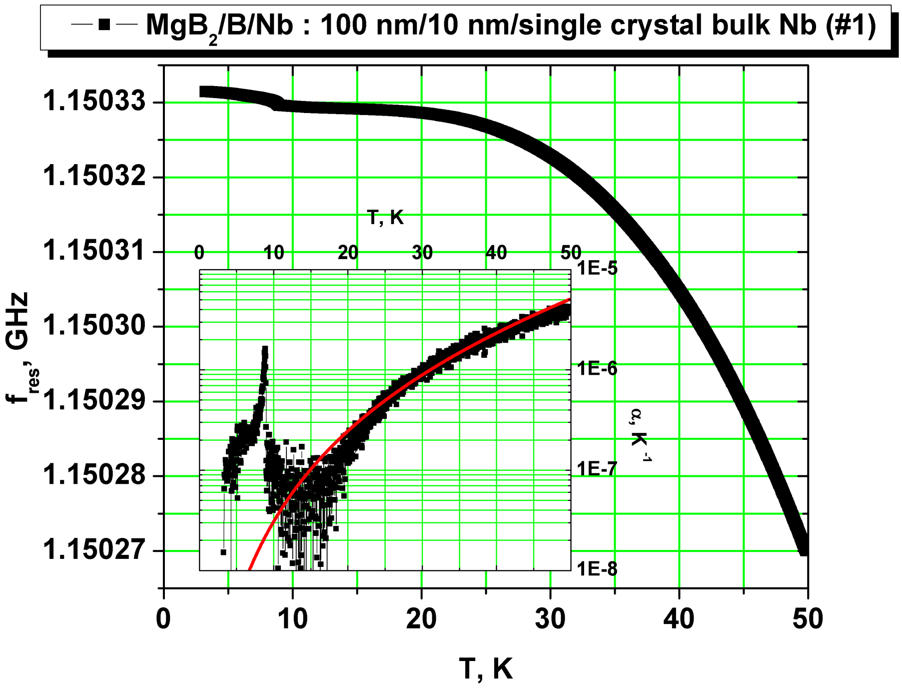

Figure 3. The cavity resonant frequency as a function of temperature for a niobium sample coated with B(10 nm)/MgB_2(100 nm). In the inset $\frac{-1}{f_{res}(T)} \cdot \frac{df_{res}(T)}{dT}$ calculated from the frequency data (black dots) and the thermal expansion coefficient of copper from [9] (thin red line) are shown as a function of temperature.

where G is the geometrical factor of the cavity, then we can derive the change in the effective length from the change in frequency:

$$\frac{1}{r_{eff}(T)} \frac{dr_{eff}(T)}{dT} = \frac{-1}{f_{res}(T)} \cdot \frac{df_{res}(T)}{dT} \qquad (2)$$

In the inset of Fig. 3 we plot $\frac{-1}{f_{res}(T)} \cdot \frac{df_{res}(T)}{dT}$, calculated from the frequency data and the linear thermal expansion coefficient of copper [9] versus temperature, which indicates that above 20 K the thermal expansion dominates the frequency change.

Following the low power measurements with a network analyzer, the cavity was connected to a 50 MW klystron. To avoid thermal effects 1 μs pulses at 10 Hz repetition rate were typically used to excite the TE_{013} mode in the cavity. The loaded cavity quality factor was determined from the decay time in the reflected power signal. Figure 4 shows the quality factor as a function of field. Quality factor degradation occurred at a relatively low field of $\mu_0 H_{peak} \approx 40$ mT as shown in Fig. 4. For comparison, also shown in Fig. 4 is the result of a Nb sample measured previously under the same conditions. The key question was whether it was the niobium substrate or the MgB_2 film that caused the degradation at this field. To answer this question we measured the quality factor as a function of temperature for different field levels around the quench field as shown in Fig. 5. This measurement showed that the early degradation in the quality factor occurred in the niobium substrate, while the MgB_2 film remained superconductive for all field levels.

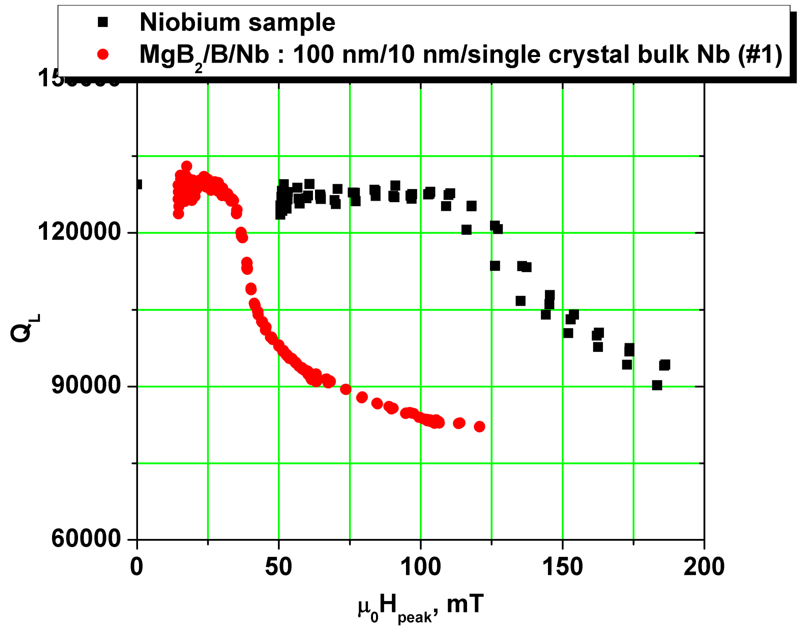

Figure 4. The cavity loaded quality factor as a function of the peak magnetic field on the surface of the sample for the single grain niobium sample coated with B(10nm)/MgB_2(100nm) (red circles). For comparison the data for niobium measured in the same setup is presented (black squares). Early degradation of the quality factor for the Nb/B(10nm)/MgB_2(100nm) sample happened due to a quench in the niobium substatrate as follows from the measurements presented in Fig. 5.

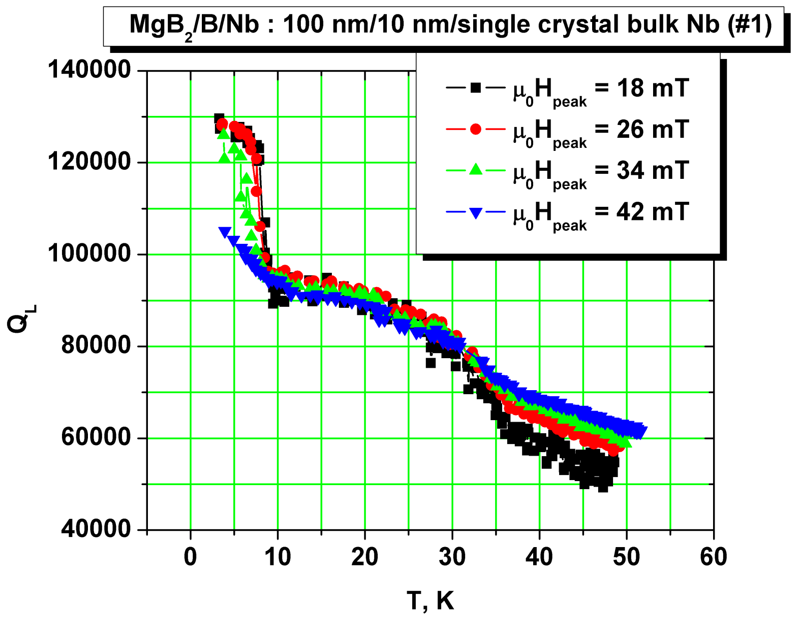

Figure 5. The cavity loaded quality factor as a function of temperature for different field levels for single grain niobium sample coated with B(10nm)/MgB_2(100nm).

4. CONCLUSION

Following the theory that predicts breaking through the niobium limitation by coating thin superconductors on Nb, we initiated measurements of critical magnetic fields of Nb coated with various thin film superconductors, starting with NbN and MgB_2 using PAD and reactive evaporation techniques, respectively. We have tested a single-crystal Nb sample coated with 10 nm of B and 100 nm of MgB_2. The low-power Q measurement showed 2 transitions, one at 37.1 K (MgB_2) and the other at 9 K (Nb), and that the total RF surface resistance of the sample after the Nb transition is dominated by the copper losses. The pulsed high-power test showed a low quench field of $\sim$ 40 mT caused by a quench on the Nb surface and not by the MgB_2. We plan to investigate the cause of this quench at low field in the near future as well as to test more samples with various thicknesses and layers.

5. ACKNOWLEDGEMENT

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