INCREASE IN VORTEX PENETRATION FIELD ON NB ELLIPSOID COATED WITH A MgB_2 THIN FILM*

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Abstract

The magnetic vortex penetration field (H_{vp}) is an important property of superconducting radio frequency (SRF) cavities. However, measuring H_{vp} of an SRF cavity directly is usually a difficult task. As an alternative, a superconducting ellipsoid in an axial magnetic field would have a similar but inversed field geometry of an SRF cavity and would allow for the characterization of H_{vp}. In this work, we deposited a uniform MgB_2 layer on Nb ellipsoids and used those ellipsoids to mimic the behavior of MgB_2 coated Nb SRF cavities. The H_{vp} of such a structure was measured via zero-field-cool (ZFC) magnetization method. At 1.8 K, the H_{vp} for a coated Nb ellipsoid is 100 Oe higher than H_{vp} for a bare Nb ellipsoid.

INTRODUCTION

Particle accelerators are one of the most powerful tools for physicists. The pursuit for higher accelerating gradients and lower operating power dissipation is an ongoing endeavor. Superconducting radio frequency (SRF) cavity technology is the most promising candidate for creating next generation linear accelerators.[1] Total expulsion of the magnetic field initiated by the Meissner effect can significantly reduce the power dissipation caused by E-M induction, thus allowing to reach a higher accelerating gradient. The thermal breakdown of SRF cavities happens when the magnetic field near the cavity's inner surface surges beyond the threshold at which vortices start to penetrate into the SRF cavity. The vortex penetration field (H_{vp}) is affected by a number of factors, such as cavity geometry, surface roughness, and critical field of the superconductor. In the past decade, great efforts have been made to perfect bulk Nb SRF cavities. However, the maximum gradient is currently approaching the theoretical limit of the material. [2]

In 2001, the superconductivity of magnesium diboride (MgB_2) was discovered.[3] This material soon attracted significant attention in the SRF community. Its high T_c (39 K), high H_c (> 3500 Oe), lower residual resistivity (~ 0.1 μΩ·cm)[4-7] indicated that MgB_2 coated SRF cavity would potentially have a higher gradient and lower dissipation than bulk Nb cavities.

In this work, we used MgB_2 coated ellipsoids to mimic MgB_2 coated SRF cavities and measured their magnetic vortex penetration field (H_{vp}).

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COATED ELLIPSOID AS AN INVERSED SRF CAVITY

Field Similarities

In an SRF cavity, the magnetic field is parallel to the cavity surface, while no magnetic field is present on the outside. Such kind of a field distribution is different in comparison to the traditional lower critical field (H_{c1}) measurement of type-II superconductors,[8-10] in which samples are submerged in a uniform magnetic field. Simply measuring MgB_2 coated Nb slabs and deriving H_{c1} does not lead to a precise estimate of H_{vp} of an SRF cavity with a similar structure.

A better approach for H_{vp} measurements is a superconducting ellipsoid in the Meissner state (see Fig. 1), which lies in a magnetic field parallel to its long axis. For such an ellipsoid, the magnetic field remains zero at the center while the expelled field is parallel to its surface. The field distribution along the ellipsoid surface is similar but inversed in comparison to the inner surface of an SRF cavity. Therefore a coated ellipsoid is an ideal structure to study the vortex penetration in SRF cavities.

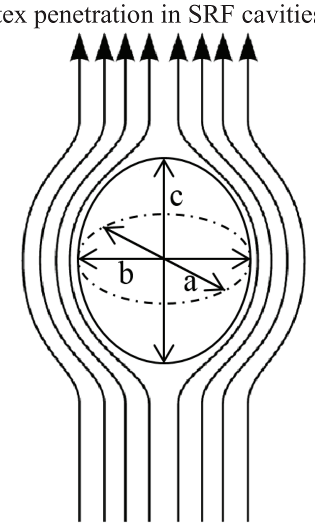

Figure 1: Schematic of a prolate ellipsoid in Meissner state.

Field Non-uniformity Caused by Meissner Current

Because of the existence of a superconducting current, the magnetic field will be equal to the applied field at the ellipsoid zenith but stronger at the equator of the ellipsoid, based on the following equation:

$$H_{eq} = \frac{1}{1-N_c} H_0, \qquad (1)$$

where H_{eq} is the magnetic field at the ellipsoid equator, H_0 is the applied field, and N_c is the demagnetization factor along the long axis. A prolate ellipsoid with a longer c-axis will have a smaller N_c and less field variance on the ellipsoid surface. Such a field variance does not result in an uncertainty of H_{vp} as it turns the ellipsoid equator into a weak point during magnetization, and the vortices will penetrate here first. Thus we can always use the equator field H_{eq} as the H_{vp} of the equivalent SRF cavity.

SAMPLE PREPARATION

Nb Ellipsoid

A large ellipsoid has been found to be beneficial for the magnetic measurement as its larger signal will increase the sensitivity. As a result, Nb ellipsoids with a maximum size as allowed by the measurement system were machined. The long axis (c) of those ellipsoids was 8 mm, while the *a* and *b* axis were 5 mm. Demagnetization factors can be calculated from equation 2.[11] Geometry calculations revealed N_a=N_b=0.39, N_c=0.22.

$$N_c = \frac{1}{e^2-1}\left[\frac{e}{2(e^2-1)^{\frac{1}{2}}} \cdot \ln\left(\frac{e+(e^2-1)^{\frac{1}{2}}}{e-(e^2-1)^{\frac{1}{2}}}\right)-1\right] \cdot \qquad (2)$$

In equation 2, $e = c/a$. $N_a = N_b = (1\text{-}N_c)/2$.

MgB_2 Coating

A layer of MgB_2 film was deposited on clean Nb ellipsoids via Hybrid Physical-Chemical Vapor Deposition.[12] A resistive heater was used in our current system to heat the sample and magnesium (see Fig. 2).

The whole coating process consists of 3 consecutive depositions. The Nb ellipsoid is rotated by 120 degree on its c axis between each deposition. 99.5% pure Mg ingots were used as the Mg source and heated with the ellipsoid to 730 °C. Boron was supplied during the deposition by introducing 20 sccm of 5% diborane (B_2H_6) gas in 400 sccm of H_2, which acts as the carrier gas. A SiC substrate was placed next to the ellipsoid to calibrate the growth rate. Ellipsoids with two different film thicknesses were coated with this method. First, a 100 nm thick MgB_2 film was deposited, as measured on the SiC reference substrate. Subsequently, a 200 nm thick MgB_2 film was deposited on a second ellipsoid. Both samples are referred to as Nb100 and Nb200 in the following discussion

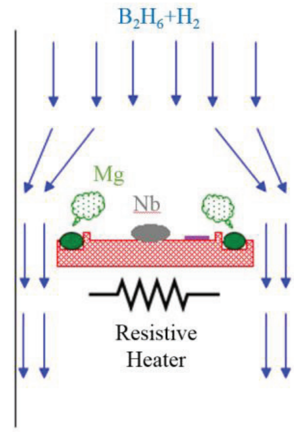

Figure 2: Diagram of the HPCVD deposition on an Nb ellipsoid.

MEASUREMENT

After the ellipsoids were coated, the morphology was studied in a FEI Quanta 450FEG Scanning Electron Microscope (SEM). The magnetic measurements were conducted in a Quantum Design™ Magnetic Property Measurement System (MPMS). For these measurments, the sample was wrapped with a thin Teflon tape and placed in a gelatin capsule. The capsule fits well within the standard MPMS straw so that the sample was not moved or tilted during the measurement.

The superconducting critical temperature (T_c) of Nb100 and Nb200 and a bare Nb ellipsoid (Nb0) were first measured with a susceptibility measurement. During this measurement, the sample was zero-field-cooled (ZFC) below T_c, then gradually warmed up in a 3 Oe magnetic field.

ZFC magnetization method is employed to measure H_{vp}. In this method, the sample is ZFC below T_c, while the magnetic field (H_0) is subsequently gradually increased. A relationship $-4\pi M = H_0/(1\text{-}N_c)$ would be expected if H_{eq} is smaller than H_{vp}. Vortex penetration occurs when H_{eq} is equal to H_{vp} Thus the *M-H* curve would deviate from the linear relationship.

RESULTS AND DISCUSSION

Surface Morphology

A complete shell enclosing the Nb ellipsoid is critical in our inversed cavity method. Since any magnetic field leaking through pinholes in the coating would produce a fake vortex penetration signal, we scanned the surface of a Nb100 sample in order to characterize the degree of coverage. Two images (with full width 500 mm and 50 mm) are shown in Fig. 3. Similar to results obtained for MgB_2 films grown on thin Nb foils and plates,[6] small MgB_2 crystals (size ~1 µm) are covering the entire ellipsoid surface. The whole film is uniform and without any observable pinholes. It was therefore deducted that a complete shell enclosing the Nb ellipsoid was successfully deposited.

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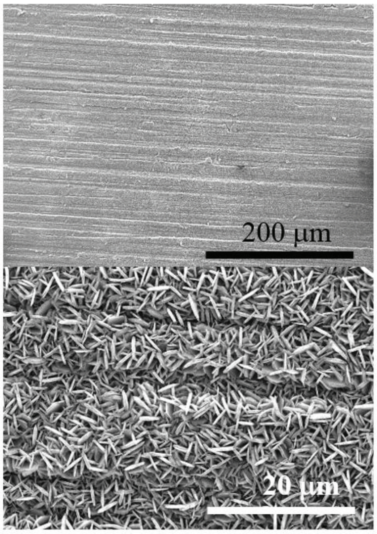

Figure 3: Surface morphology of Nb100 sample.

T_c Measurement

Figure 4 shows the susceptibility measurement curves. Our uncoated Nb ellipsoid (left) showed a sharp transition from Meissner state to non-magnetic state with a T_c of 9.3K, indicating the whole ellipsoid lost superconductivity simultaneously. In the right panel, the results for the coated ellipsoids show perfect magnetic shielding at low temperature, while the superconductivity is more gradually lost at higher temperature with a transition width of 1 K.

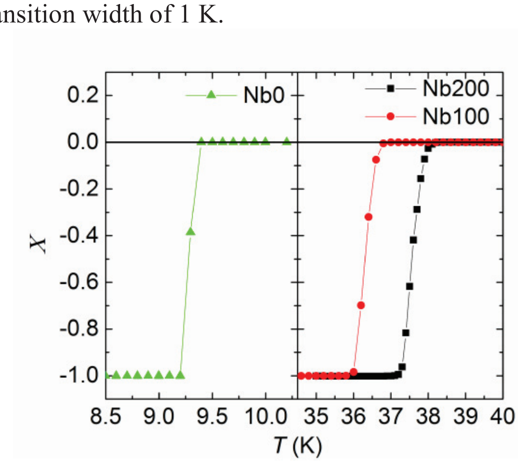

Figure 4: T_c measurement results.

The T_c onset for Nb100 and Nb200 is 36.7 K and 38.2 K, respectively, comparable to MgB_2 films grown on Nb substrates.[6] The susceptibility measurement, especially the complete magnetic shielding produced by MgB_2 coating at 35 K, further supports the statement that the superconducting shell is uniform and complete.

M-H Measurement

Figure 5 shows the sample curves for our *M-H* measurements. Fig. 5(a) displays the raw data measured on Nb200 at 1.8 K and 7 K with the MPMS. At low field, the *M-H* curve is linear. The calculated slope is -0.00987 emu/Oe, corresponding to an ellipsoid with c = 7.79 mm and a = b = 4.87 mm, similar to the dimensions of the used ellipsoid. These values are only ~3% off from the designed value. The *M-H* curves gradually diverge from the Meissner line at high field, which indicates vortex penetration.

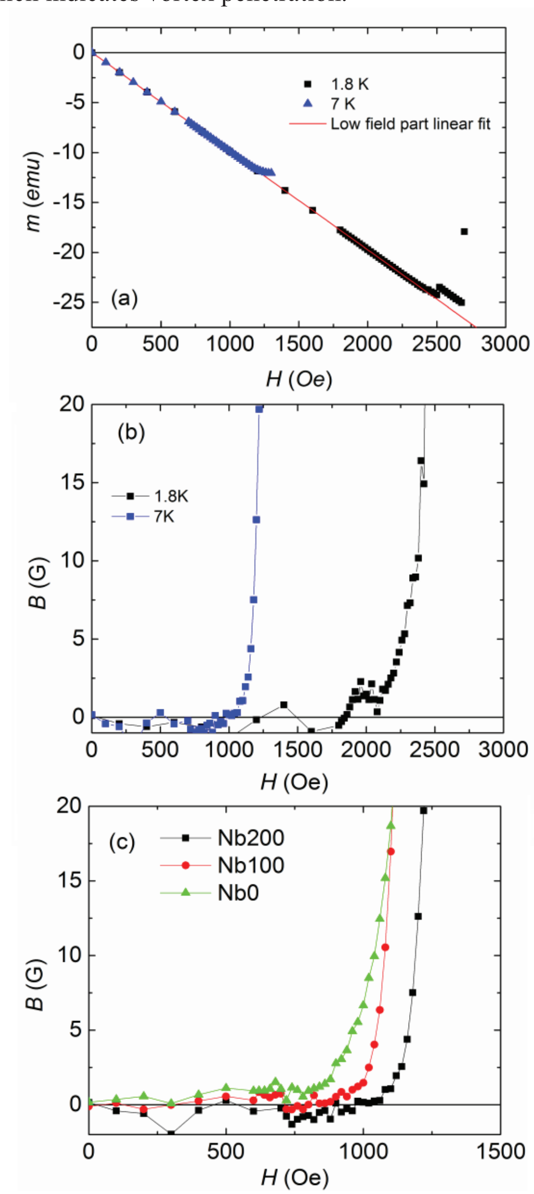

Figure 5: *M-H* measurement results. Figure 5(a) and 5(b) show sample *M-H* and *B-H* curves measured on Nb200. Figure 5(c) shows a comparison of *B-H* curves of Nb200, Nb100 and Nb0 at 7 K.

However, the divergence between the *M-H* curve and the linear fit was minuscule. Evaluating H_{vp} from Fig. 5(a) directly is therefore challenging. To amplify the divergence, Fig. 5(b) shows the *B* field in the ellipsoid versus the applied field. The average *B* field was calculated from the measured *m* and the volume of the ellipsoid and can be used as an indicator for vortex penetration. The *B-H* curve fluctuated around zero internal field at lower field and rose when *H* was above

H_{vp}. Using 5 Gauss internal B field as the criterion, the H_{vp} for Nb100 was estimated to be 2260 Oe at 1.8 K and 1160 Oe at 7 K.

Figure 5(c) shows the comparison of the *B-H* curves of samples Nb200, Nb100 and Nb0 at 7 K. From the comparison plot, H_{vp} has been determined to be 1160 Oe, 1040 Oe, and 960 Oe for Nb200, Nb100 and Nb0 at 7 K, respectively. After taking demagnetization into account, those numbers were corrected to 1487 Oe, 1333 Oe, and 1230 Oe.

The *M-H* measurement is the best method for H_{vp} quantification in the ideal case. The internal B curve shows a large slope once H increases above H_{vp}, which is advantageous for an accurate determination of H_{vp}. However, it is sensitive to the precision of the magnet. If the magnet produces 5 Oe less field than its supposed value, we would expect to have a fake 5 G internal B field after computing $B = H + 4\pi M$. As a result, at high field, where the absolute error of the magnet increases, the measured *M-H* curve always exhibits a large fluctuation compared to the low field part.

Another flaw of the *M-H* method is random flux jumps. The magnetic vortex can suddenly enter the ellipsoid when the applied field is high and changing. In the 1.8 K curve of Fig. 5(a), we can clearly see two large vortex jumps at 2500 Oe and 2700 Oe. This kind of vortex jump does not take place at lower field or in a stable field.

CONCLUSION

In this work, we have successfully coated uniform and complete MgB_2 shells on precisely machined Nb ellipsoids. The coatings showed high T_c above 36 K and produced full magnetic shielding for the underlying Nb at 35 K.

We were able to measure the vortex penetration of the inversed MgB_2 coated Nb SRF cavity. The results showed that the MgB_2 coated Nb ellipsoids have and enhanced H_{vp} compared to a bare Nb ellipsoid. The results demonstrate the potential to obtain higher acceleration gradient for a MgB_2 coated Nb SRF cavity compared with bulk Nb cavities that are currently in use.

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