WOULD >50 MV/m BE POSSIBLE WITH SUPERCONDUCTING RF CAVITIES?*

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Abstract

Several laboratories are working on the development of thin-film superconductor technology to overcome the fundamental limit of ~50 MV/m accelerating gradient with niobium SRF cavities. Efforts at LANL attempt to enhance the sustainable surface magnetic field by coating thin layers of superconductors, such as MgB_2 on top of niobium. The coating techniques being developed and the results of RF critical field and surface resistance measurements that were obtained in collaboration with other national laboratories, universities and industry will be presented.

INTRODUCTION

Superconducting RF (SRF) cavities have been successfully used for various sciences since 1970s [1]. Regarding the maximum accelerating gradient (E_{acc}), Fig. 1 shows the evolution of maximum E_{acc} since late 1980s [2]. Significant efforts to improve E_{acc} started in 1992 when the worldwide TeV Energy Superconducting Linear Accelerator (TESLA) collaboration started. In addition to continuous improvement of fabrication techniques by industry, contamination control with high-pressure ultra-pure water rinsing has contributed to the increase of $E_{acc,max}$ until the plateau in 1995-2004. From around 2004, an effort to further optimize the design parameters to increase E_{acc} started, especially to reduce H_{peak}/E_{acc} ratio assuming achievable E_{acc} is limited by the critical magnetic field. This effort has been very successful and has increased the $E_{acc,max}$ to very close to the theoretical value (H_{peak} ~ 2000 Oe) as shown in Fig. 1.

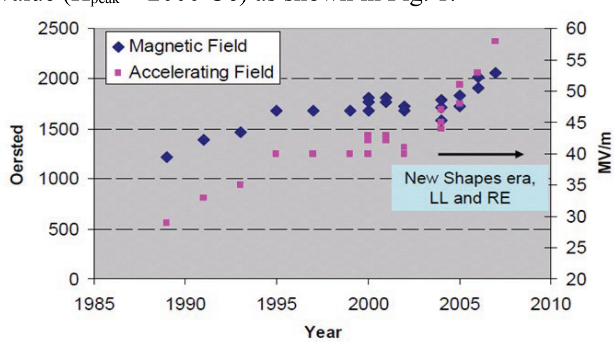

Figure 1: Evolution of accelerating gradient [2].

Figure 2 shows the Q_0-E_{acc} curve of a re-entrant shape cavity that has a world record of E_{acc} [3]. In the figure, the surface peak magnetic fields corresponding to H_{c1} (1700 Oe) and H_c (2000 Oe) of Nb are shown. The Q_0 drop possibly due to the vortex penetration can be seen, suggesting that the cavity should be operated at H below H_{c1}.

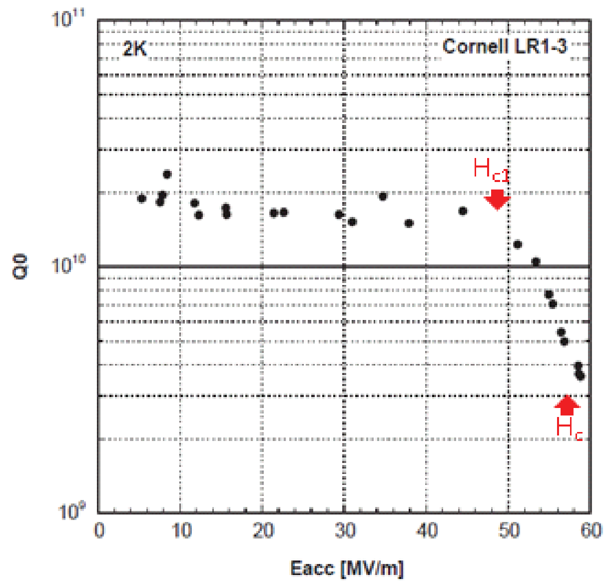

Figure 2: Q_0 – E_{acc} curve of a Cornell 1.3 GHz re-entrant shape single-cell cavity that has the world record of E_{acc} [3].

While there have been other ideas such as running the cavity with a traveling wave mode to increase the E_{acc} and real estate gradient [4], an innovative idea to increase the surface critical magnetic field using ultra-thin films of another superconductor was proposed by Gurevich in 2005 [5]. His idea is based on an assumption that the H_{c1} of a thin film superconductor that is close to or thinner than its magnetic penetration depth (λ) increases (see Fig. 3) when the applied magnetic field is in parallel with the surface, suggesting the possibility of screening the high magnetic field with superconductor layers that have H_{c1}'s higher than penetrated magnetic fields so that the decayed field that reaches Nb surface is below its H_{c1}. This concept is illustrated in Fig. 4.

There have been some attempts to demonstrate the increase of H_{c1}, e.g., Antoine reported >5x increase (from 180 Oe to 960 Oe) with 25 nm NbN film coated on MgO (~15nm)/Nb(250nm)/Sapphire [6]. At LANL, magnesium diboride (MgB_2) has been studied for SRF applications since 2002 [7-15]. The primary reasons for us to choose this material are 1) lack of weak links that cause the cavity Q_0 degradation with increasing fields, 2) good RF properties in polycrystalline form, and 3) wide range of MgB_2 phase in the Mg-B phase diagram [16], e.g., it can be deposited at as low as 120 °C [17], which might be crucial for successful thin film coating without inter-diffusion of harmful elements such as oxygen [18]. In the following sections, sample preparation, DC and RF measurement results on MgB_2 are reported as well as encountered issues and proposed techniques for coating

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SRF cavities with dielectric and MgB_2 layers to form multi-layers.

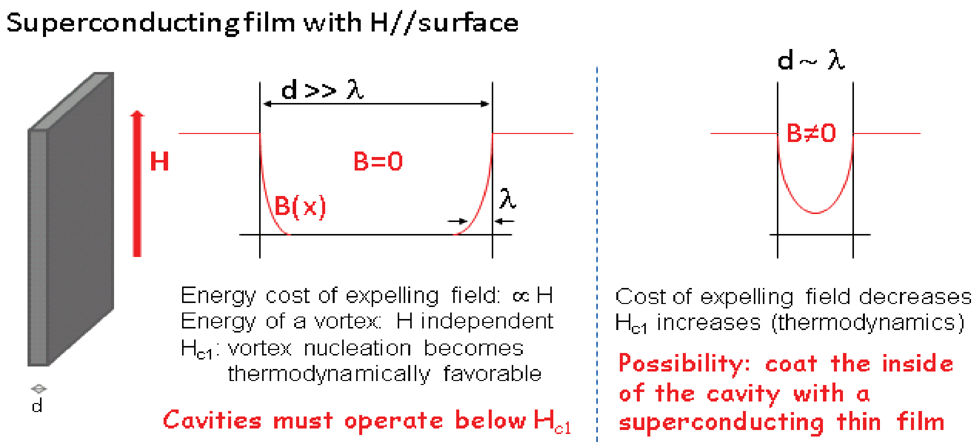

Figure 3: Illustration of 2 cases; 1) the film thickness is larger than the penetration depth (left) and 2) the film thickness is smaller than the penetration depth (right).

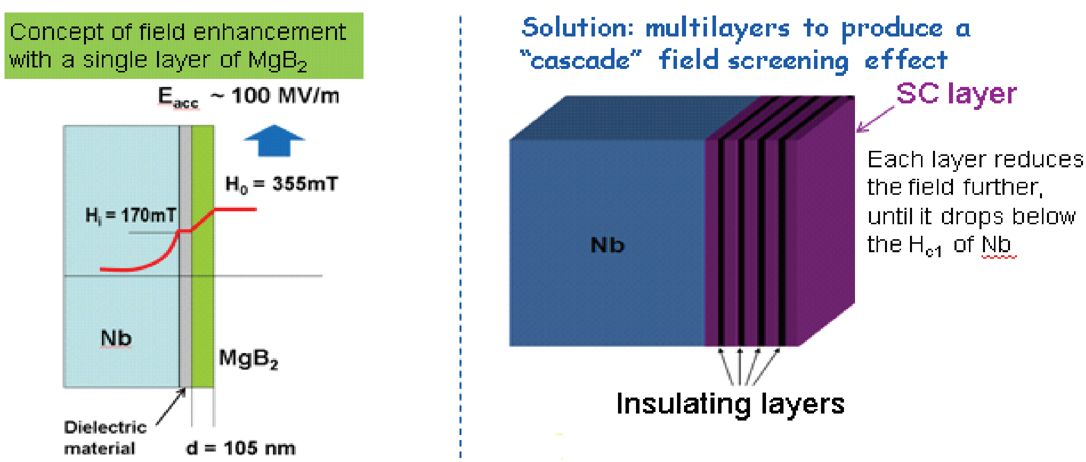

Figure 4: Concept of an increase in the sustainable magnetic field and corresponding E_{acc} with a MgB_2 thin film coated on Nb with a dielectric layer in between (left) and more layers for "cascade" effect.

SAMPLES

Substrates

For DC measurements, approximately 5 mm x 5 mm samples have been used. For RF measurements at SLAC, 2-inch diameter wafers have been used. In most cases, c-plane sapphire and single-grain chemical-mechanically polished (rms roughness<1 nm) substrates have been used.

Coating

For MgB_2 coating, the samples prepared with 2 techniques were measured. One technique is a reactive co-evaporation developed at STI, California, U.S.A. [19], and the other is an electron beam co-evaporation developed at Kagoshima Univ., Kagoshima, Japan [17]. The latter technique has an advantage of lower substrate temperature (250 °C for our samples) compared to the former technique (550 °C), but the T_c's and H_{c1}'s of the samples we measured were lower than those of STI films [15]. We will show only the results of STI films since they have continuously shown better results so far.

DC H_{C1} MEASUREMENTS

A Quantum Design SQUID Magnetic Property Measurement System (MPMS) has been used to measure the lower critical field (H_{c1}) or the magnetic field at which a large number of vortices start to penetrate into the superconductor. Some detail of the measurement is described in [15]. Briefly, H_{c1} was defined as the point where the magnetization curve starts to deviate from Meissner slope, which is a straight line in the M-H curve.

Figure 5 shows H_{c1} as a function of temperature for 300 nm and 500 nm MgB_2 films coated on c-plane sapphire together with the data for solid Nb as a reference. As one can see in Fig. 5, H_{c1} of 300 nm film showed higher than that of 500 nm film. A schematic to show the theoretical derivation of this effect is shown in Fig. 6. Although we have not measured a film thicker than 500 nm yet, the H_{c1} of a 500 nm film, which seems to be significantly thicker than typical λ (40-150 nm [18]), is already comparable with Nb at 4.5 K as shown in Fig. 5, and the H_{c1} of 300 nm film is ~25 % higher than that of Nb. In Fig. 5, the vertical axis at right shows the corresponding accelerating gradient, assuming the cavity design parameter of H_{peak}/E_{acc} = 40 Oe/(MV/m).

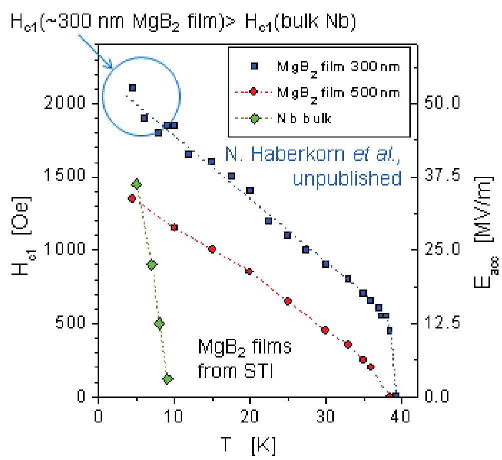

Figure 5: H_{c1} as a function of temperature for 300 nm and 500 nm thick MgB_2 films as compared to bulk Nb.

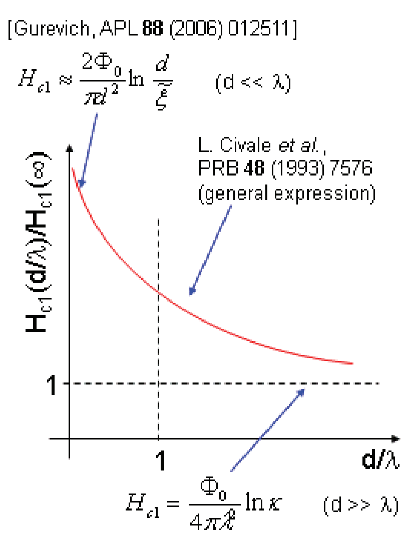

Figure 6: A schematic showing the increase of H_{c1} with thin films that have the thickness close to the magnetic penetration depth (λ).

RF MEASUREMENTS

Oates et al. have measured RF surface resistance of MgB_2 films prepared by STI [21-24]. They have used a parallel plate technique [9] or a stripline-resonator technique for the samples coated on dielectric substrates such as sapphire, and a sapphire-puck Hakki-Coleman dielectric resonator for the samples coated on metallic substrates [23]. They have shown that the surface resistance (R_s) of MgB_2 coated on sapphire is comparable with Nb film coated on sapphire at a given reduced temperature, i.e., T/T_c [23]. This means that, since the T_c's of Nb and MgB_2 are 9.2 K and 39 K, respectively, the R_s of MgB_2 at the same temperature is significantly lower than that of Nb. Regarding the power handling capability, they have shown that a 500 nm MgB_2 film coated on Nb showed no increase in the surface loss up to ~300 Oe using a dielectric resonator, which is limited by the available power [24]. It was also noticed that the result from stripline-resonator measurement on a MgB_2 film coated on sapphire shows higher R_s and some small linear increase with H_{RF} up to ~400 Oe following a rapid increase at higher fields.

RF Measurements at SLAC at 11.4 GHz

After an encouraging result of little loss up to ~120 Oe (available field at that time) using a TE_{011} mode cavity at Cornell at 6 GHz [9], we have been carrying out RF measurements of 2-inch diameter samples in collaboration with SLAC using their 50 MW Pulsed Klystron and a TE_{013}-like mode hemispherical cavity made of copper at 11.4 GHz. More detail of the current system is described in [25]. The typical pulse length and repetition rate we have been using are 1 to 1.5 μs and 0.1 to 0.5 Hz, respectively.

Figure 7 shows the R_s calculated from the cavity Q_0 as a function of temperature.

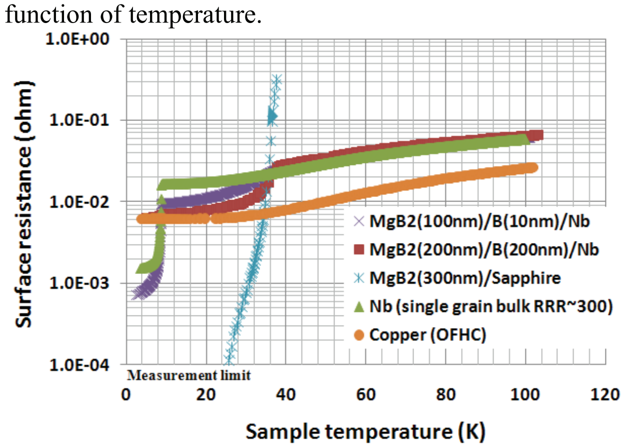

Figure 7: Surface resistance vs. temperature at low field at 11.4 GHz and 3 K for various MgB_2 coatings together with Nb and copper as references.

It should be noted that the lowest measurable R_s is ~100 μΩ [25] caused by the losses of copper part of the cavity [26]. Considering the fact that the BCS surface resistance of Nb at 11.4 GHz and at 3 K is ~1.5 x 10^{-5} Ω [27], the surface resistance of Nb was 2 orders of magnitude higher than expected at 3 K (lowest temperature reachable with the current SLAC set up). Later, it was found that shielding the magnetic field and baking the Nb sample improves the R_s significantly [28]. The R_s of MgB_2 on sapphire is consistent with Oates' data, considering the scaling with f^2, and it does not seem to be affected by the ambient magnetic field as much as Nb does. It was also noticed that the MgB_2 films coated on Nb with boron (B) or Alumina in between have been degraded and show significantly higher R_s than MgB_2 alone on sapphire possibly due to the decomposition of stable Nb_2O_5 layer on Nb into harmful sub-oxides and diffused elements in Nb such as B and O causing more RF losses.

Figure 8 shows an example of the interface layers after coatings of Alumina (300 nm) and MgB_2 (200 nm) on Nb at room temperature and 550 °C, respectively. A thick layer (~100 nm) of a mixture of Nb, Al and O was observed, indicating that the 550 °C being used for MgB_2 coating at STI diffused the Al and O into Nb. This seems to be the reason for higher RF surfaces losses with the coating on Nb. Palmer et al. mentions in Ref. [29] that the stable Nb_2O_5 starts to decompose into sub-oxides at ~250 ºC, and the oxygen diffusion into the depth where RF losses occur (40 – 80 nm) significantly increases the RF surface resistance.

Therefore, to prevent this increased RF loss due to inter-diffusion of elements during coating, a coating technique that can be performed at a temperature lower than 250 ºC or that can create loss-less layer even at a high temperature will need to be developed.

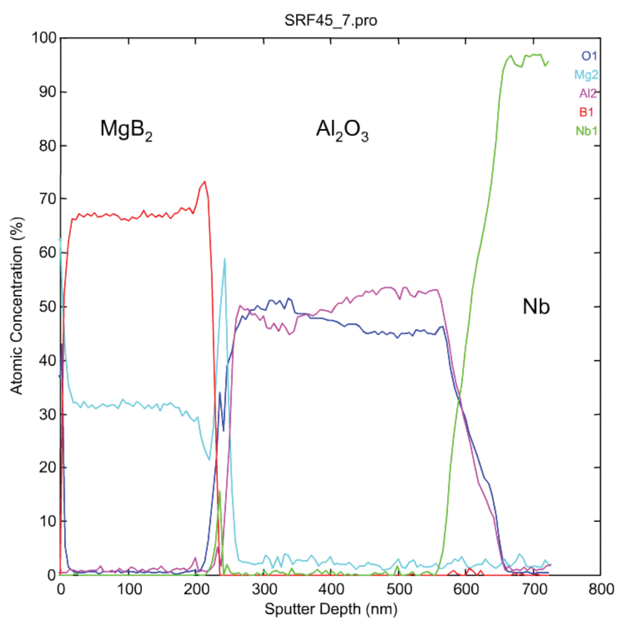

Figure 8: Auger spectroscopy sputter depth profile of a nominal MgB_2(200nm)/Alumina(300nm) coating on unbaked Nb. A thick (~100 nm) inter-diffusion layer consisting of Nb, O and Al is observed [18].

Figure 9 shows the cavity Q_0 as a function of peak magnetic field (H_{peak}) for a 300 nm MgB_2 film coated on c-place sapphire. Since the sample surface resistance was negligibly small compared to the copper hemispherical part of the cavity, Q_0 looks flat (upper limit). A clear degradation of Q_0 at ~250 Oe was observed. Since we expected a quenching field of >2000 Oe from the result of DC measurements shown in Fig. 5, this result is puzzling.

CONCLUSION

At this point, it is not clear yet if >50 MV/m SRF cavities are possible with the proposed multilayer coatings of superconductors. However, DC magnetization measurements showed that the H_{c1} of 300 nm MgB_2 film exceeds that of Nb by ~25 %, giving us hope that at least the fundamental limit of Nb could be overcome by thin film MgB_2. Thinner films are being tested and expected to show higher H_{c1}. A coating technique that can be performed at <250 °C or that can create loss-less inter-layers even at high temperatures will need to be developed to avoid degradation of Nb layer causing high RF losses. A discrepancy of the results of 300 nm MgB_2 films between the high H_{c1} (>2000 Oe) from DC measurements and the low RF quenching field (~250 Oe) at 11.4 GHz exists and it is being investigated.

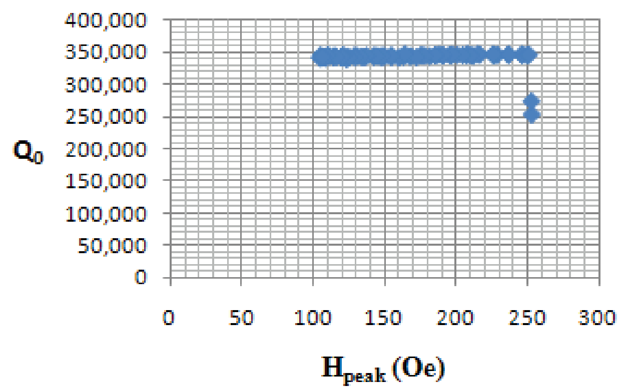

Figure 9: Q_0 as a function of peak magnetic field at 3 K for a 300 nm MgB_2 film coated on a c-cut sapphire substrate at STI [15].

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