STATUS OF MgB$_2$ COATING STUDIES FOR SRF APPLICATIONS *

T. Tajima#, L. Civale, D.J. Devlin, R.K. Schulze, I.O. Usov, G.C. Martinez, LANL, Los Alamos, NM 87545 USA

Abstract

MgB$_2$ has shown promising results on small samples and its coating development is entering into the stage to coat large samples and elliptical cavities. In this paper, a brief summary of the results on vortex penetration fields and RF surface resistance is given. Then, a newly built coating system at LANL is described with the results of first runs. This system has a coating furnace that can include up to one 1.3 GHz 9-cell cavity.

INTRODUCTION

The niobium (Nb) cavity technology has come very close to its full capacity on accelerating gradient (E$_{acc}$), e.g. ~50 MV/m for electron accelerators due to its well-known critical magnetic fields (B_{c1} ~ 170 mT and B_c ~ 200 mT). New and other alternative materials with Gurevich' s idea of multi-layer coating [1] could produce SRF cavities that exceed the performance of Nb cavities and open up more opportunities to use SRF cavities. MgB$_2$ has a remarkably high T_c of ~40 K comparing to conventional s-wave superconductors (T_c < 20 K), which could lead to lower BCS resistance at the same temperature and higher thermal tolerance if the cavity is operated at 4 K or 2 K. Other attractive features of MgB$_2$ include the absence of weak links (cause of losses at high fields), simple chemical composition and a wide range of coating temperatures (>~250 °C).

VORTEX PENETRATION FIELD (B_{VP})

Vortex penetration fields of MgB$_2$ samples prepared by reactive evaporation [2] were measured using a SQUID magnetometer [3] with external magnetic field parallel to the sample surface. The accuracy of the measurement is approximately within ±10 mT. Figure 1 shows vortex penetration fields as a function of temperature for 200, 300 and 500 nm films compared to RRR>300 cavity grade large grain bulk Nb and sputtered Nb films. The data on Nb are consistent with best cavity results and the data on MgB$_2$ films show a high potential of exceeding the performance of Nb. Figure 2 shows B_{vp}'s at 4.5 K as in Figure 1 as a function of film together with theoretical curves of B_{c1} assuming the penetration depth (λ) and coherence length (ξ) of 110 nm and 6 nm, respectively. The measured B_{vp}'s are higher than predicted B_{c1} possibly due to the surface barrier. Figure 3 shows the B_{vp} vs. T for the films prepared by hybrid physical chemical vapour deposition (HPCVD) compared with the STI films. So far, the films prepared by HPCVD have shown the best B_{vp} results.

While the data in Figure 2 suggest that a film of about 80 nm can sustain ≥400 mT (equivalent of E_{acc} ≥ 100 MV/m), the measurement was impossible since the signal of total magnetic moment for the films of <200 nm was too small.

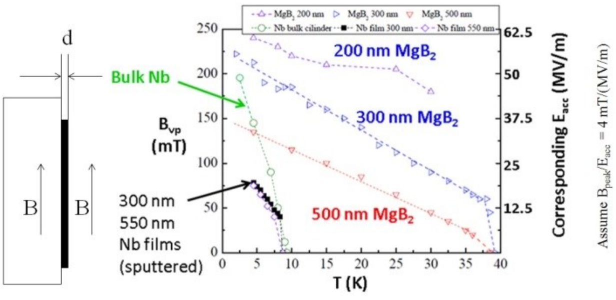

Figure 1: B_{vp} vs. temperature for MgB$_2$ films prepared by STI, together with bulk and film Nb samples.

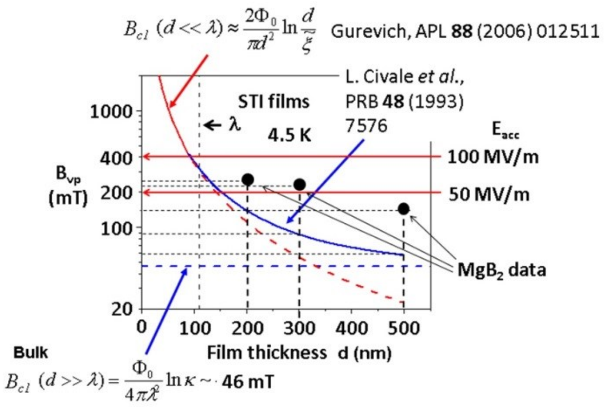

Figure 2: B_{vp} as a function of film thickness at 4.5 K compared to the theoretical curves of B_{c1}.

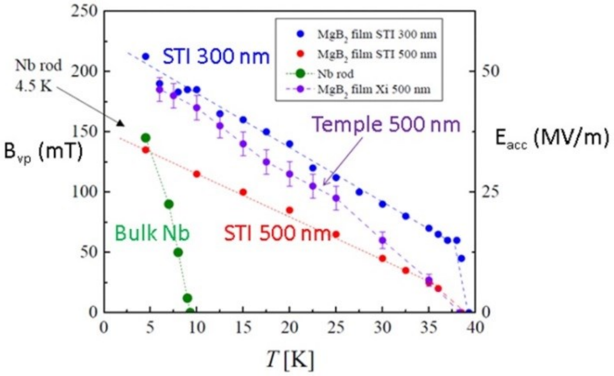

Figure 3: B_{vp} vs. T for a 500 nm film prepared by HPCVD compared with STI films.

To overcome this difficulty and realize the more cavity-like configuration, i.e., only one side of the film is exposed to the magnetic field, we plan to use a prolate

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*Work supported by US DOE Office of Science/Nuclear Physics.
#tajima@lanl.gov

spheroid (a football shape) as shown in Figure 4 since the signal of total magnetic moment is proportional to the volume of the football shape, not to the thickness of the film as shown on the left in Figure 4.

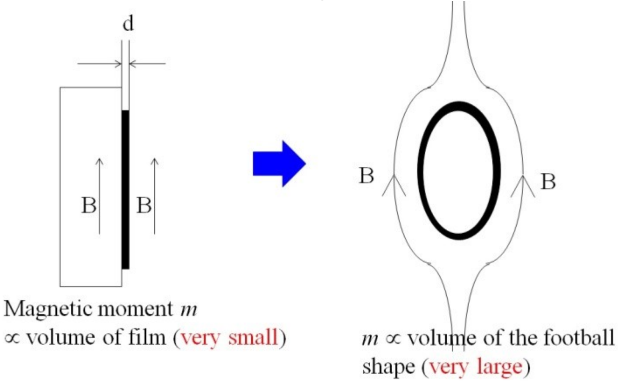

Figure 4: A plan to use a prolate spheroid to be able to measure ultra-thin (<200 nm) films and to realize the cavity-like configuration. The current samples are coated on flat substrates as shown on the left.

RF SURFACE RESISTANCE (R_S)

Figures 5 and 6 show RF surface resistance (R_s) as a function of temperature at low RF power measured at MIT [4] and Jefferson Lab [5], respectively. The films measured at MIT include samples from STI and Temple University, and the samples measured at Jefferson Lab are from Temple University.

Calculating from BCS theory using the data, the BCS resistance is supposed to be about one order of magnitude lower than Nb at 4 K and 2 K, but it seems to be flattened out at these temperatures with residual resistance dominating the R_s. Studies on this residual resistance and finding ways to reduce it will be very important for the future application of MgB_2.

Figure 7 shows R_s as a function of peak magnetic field (the unit used is Oe and 10 Oe equals to 1 mT) measured at MIT using a stripline resonator or a dielectric resonator [4]. The increase in R_s at ≥~30 mT for the films coated on sapphire might be attributed to the very low thermal conductivity of sapphire at very low temperatures [6]. The films coated on Nb have shown lower R_s than those coated on sapphire due possibly to this thermal effect. Note that the data at highest H was not limited by quench, but limited by available power. Figure 8 is a more recent data that includes a film coated on copper [7]. The data on the film coated on copper shows no increase in R_s up to ~60 mT (again limited by available power), which might be evidence that the rapid increase in R_s for the films coated on sapphire is a thermal effect, not due to vortex penetration. This data also proves that the vortex penetration for SRF cavities is not at B_{c1}, but at the superheating field (B_{sh}) that includes the surface barrier effect, which is consistent with the recent result of a Nb_3Sn cavity at Cornell [8].

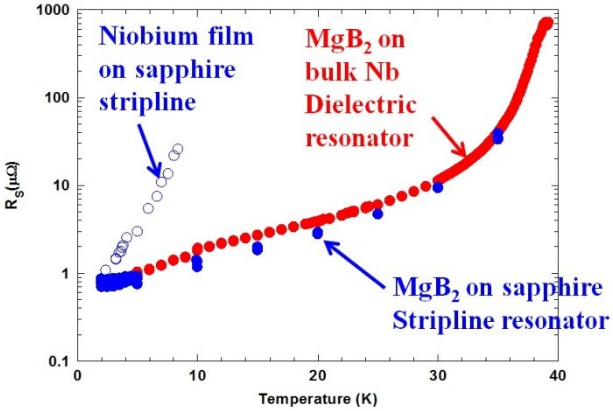

Figure 5: R_s as a function of temperature for the film prepared by STI. The R_s is scaled to 2.2 GH$_z$ assuming it scales as f^2. This graph is taken from [4].

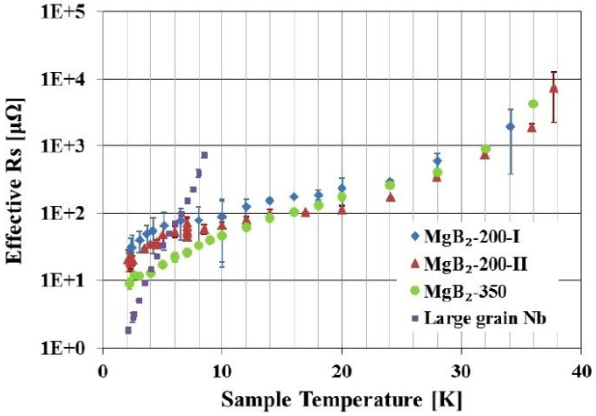

Figure 6: R_s as a function of temperature for the film prepared by Temple University and measured at Jefferson Lab at 7.4 GHz. This graph is taken from [5].

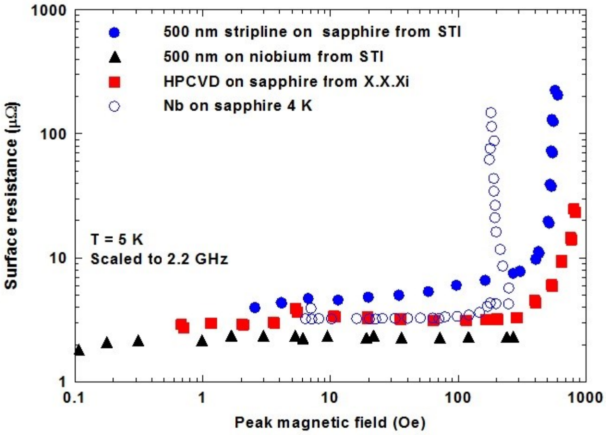

Figure 7: R_s vs. peak magnetic field for STI and Temple U. films deposited on different substrates, together with a Nb film coated on sapphire. The measurements were done at MIT using a stripline resonator or a dielectric resonator. This graph was taken from [4]. The data for 500 nm film on Nb from STI (solid triangle) was only limited by available power, not quench.

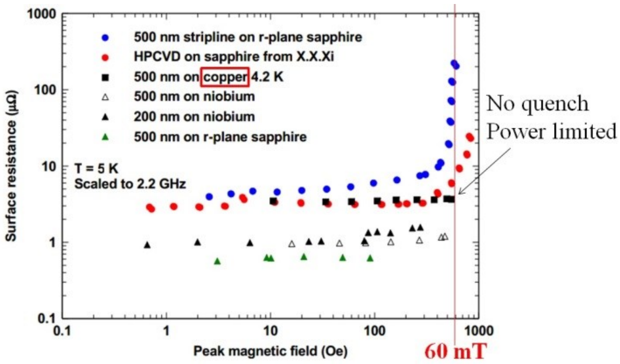

Figure 8: A recent results of R_s vs. peak magnetic field for STI and Temple U. films deposited on different substrates [7]. The measurements were done at MIT using a stripline resonator or a dielectric resonator. The data for 500 nm film on copper (solid square) was only limited by available power, not quench.

COATING SYSTEM AT LANL

A coating system that can be used to coat up to a 1.3 GHz 9-cell elliptical cavity has been built at LANL. The selected coating technique was HPCVD due to its highest T_c and highest B_{vp} among the films that we have evaluated at LANL. Also, the fact that no ultra-high vacuum is required and the coating can be done at relatively low temperatures ($T_c \geq 38$ K at coating temperatures at ≥500 °C) [9] motivated us to adopt this technique. The only drawback of this technique is a safety concern related to the use of diborane (B_2H_6) gas that has high toxicity and flammability.

Fortunately, LANL has a proper facility to use diborane gas safely at technical area 35. Figure 9 shows the coating furnace under a hood equipped with a diborane and hydrogen gas detectors and strong ventilation to outside. The entire room also has strong ventilation to outside and is kept at a negative pressure so that the gas inside the room does not leak out from the room.

Figure 10 shows the dimension of the furnace using a 1.3 GHz ILC type 9-cell cavity as a reference. The heater has 3 zones and they can be controlled independently. However, since this heater is an old one that was found in storage at LANL, it does not have an advanced control and safety feature. It indeed malfunctioned and overheated to melt a copper surrogate cavity in late 2012 when it was kept on overnight. Therefore, currently, we operate it only in the daytime.

Figure 11 shows a single-cell 1.3 GHz cavity being used for the current tests together with a stainless steel (SST) spool piece attached to the cavity, a 31.8 mm OD SST pipe for the diborane gas feed, and a piping of

Figure 9: Coating system at Technical Area 35 at LANL.

approx. 6-9 mm OD for Mg source (6.35 mm diameter and 6.35 mm long pellets). Figure 12 shows a schematic of the current coating configuration. Three mass flow controllers independently controls the mass flow of background gas (currently ultra-high purity hydrogen gas during coating and ultra-high purity Ar gas during cooling), and diborane gas. The diborane gas that has been used is 0.3 % diborane balanced with hydrogen gas. We are planning, however, to change the background gas and the gas mixed with diborane to ultra-high purity helium gas to avoid hydrogen contamination in Nb in case of coating MgB_2 films on Nb.

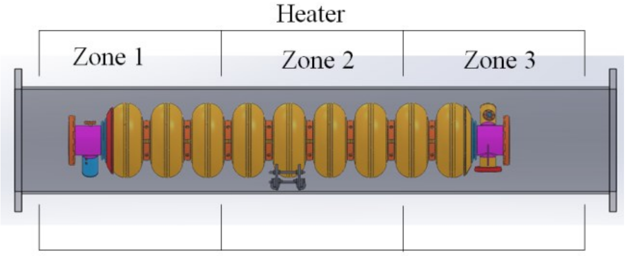

Figure 10: Furnace dimension relative to a 1.3 GHz 9-cell cavity. The heater has 3 zones that can be controlled independently.

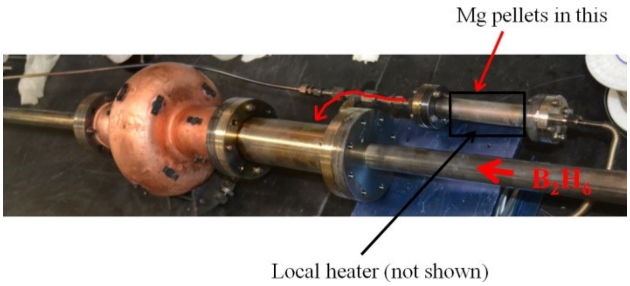

Figure 11: A photograph showing a copper surrogate cavity with samples attached and a tube that includes Mg pellets.

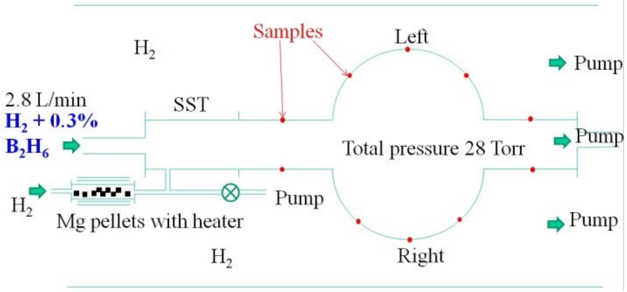

Figure 12: Schematic of current configuration of the system.

FIRST COATING TESTS AND RESULTS

We have carried out a total of 10 runs since June 2013. Due to the natural cooling which takes ~2 days to room temperature, we can do the coating only once or twice a week at this moment. We bake out the system at about 100 °C higher than the coating temperature prior to each coating run.

We have learned the following two facts so far.

- Boron does not get coated on the cavity surface at ≥500 °C probably because the diborane gas gets decomposed and consumed in the long 31.8 mm OD SST tube and in the SST spool piece before reaching the cavity.
- Insufficient Mg vapour pressure on the cavity surface even heating the Mg source to ~840 °C (maximum temperature with our current local heater). There is a possibility that the Mg gas gets cooled down before reaching the cavity especially in the small diameter tube between the Mg source and the SST spool piece and condensates on the pipes and SST spool piece.

Although we have been unable to form a stoichiometric superconducting MgB_2 film yet due probably to insufficient Mg pressure, we have obtained some data on the boron coating. Figure 13 shows the boron deposition rate as a function of cavity temperature compared with the data taken at Penn State University in the course of HPCVD research [10]. Our data are in good agreement with the data in [10]. Figure 14 shows the boron thickness profile at 3 locations, i.e., inlet beam pipe, cell equator and outlet beam pipe. The thicknesses of the samples were estimated using Rutherford Backscattering Spectroscopy (RBS) analyses. The thickness of inlet beam pipe turned out to be about twice as much as on the cell equator and on the outlet beam pipe. While the thickness profile might be different in the case of a MgB_2 film, this issue will need to be addressed by changing coating parameters if the MgB_2 thickness profile will be the same.

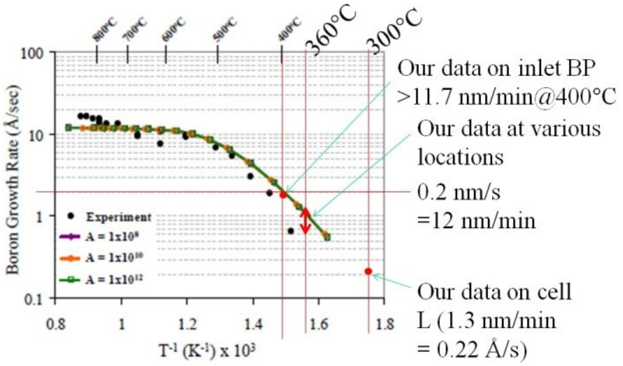

Figure 13: Boron growth rate vs. cavity temperature plotted on a curve taken from [10].

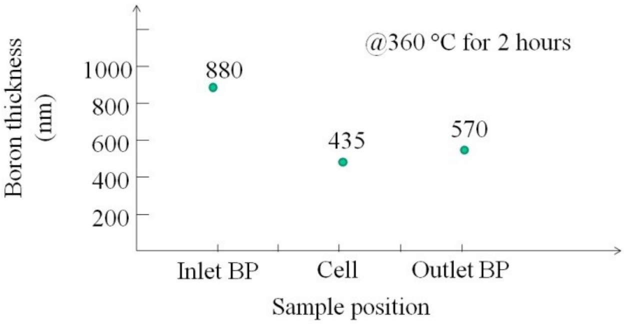

Figure 14: Boron thicknesses on the inlet beam pipe, cell equator and outlet beam pipe.

FUTURE OPTIONS

To overcome the problem of insufficient Mg vapour pressure on the cavity surfaces, we are moving the location of Mg source into the SST spool piece directly attached to the cavity. If this works, we will try coating the cavity at 500-550 °C. If, however, this does not work, we will try a 2-stage process, i.e., coat a boron layer and then react it with Mg at an elevated temperature at 700 °C or higher, but probably less than 800 °C to avoid Nb recrystallization in case of coating on Nb. Considering a coating on a Nb/Cu cavity as an attractive alternative, a low coating temperature is preferred unless a high temperature is necessary.

CONCLUSIONS

MgB_2 thin film samples especially prepared with HPCVD have shown excellent properties relevant to SRF applications, which warrants the coating of practical-size cavities and study their performance. LANL as well as other institutes and companies are trying to develop a suitable technique to coat SRF cavities and hope to produce a lot of cavity results by the next SRF conference.

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