POSSIBILITY OF MGB2 APPLICATION TO SUPERCONDUCTING CAVITIES*

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Abstract

A metallic superconductor, magnesium diboride (MgB_2), which has a transition temperature of ~ 39 K, was discovered in early 2001. Published data taken at 10 GHz demonstrate that the material has a surface resistance comparable to niobium. This paper discusses the possibility of MgB_2 as compared to Nb and Nb_3Sn. Also, a possible method of fabricating a MgB_2 cavity using the hot isostatic press (HIP) technique is proposed.

1 INTRODUCTION

The technology to fabricate and handle Nb bulk cavities is becoming mature and achieved field gradients are approaching the theoretical limit. Although it is still important to establish the recipe to get high-quality Nb cavities, it is also important to make efforts to develop new superconducting (SC) materials that will lead to higher accelerating gradients and quality factors. This will in turn lead to further reduction of construction and operation costs of future accelerators.

Magnesium diboride (MgB_2) was found to have a critical temperature (T_c) of 39 K in early 2001 [1]. It has triggered a tremendous amount of research activity due to its high T_c, simple crystal structure, large coherence lengths, high critical current densities and fields, and transparency of grain boundaries to current [6]. A number of studies have shown that MgB_2 is a conventional BCS (s-wave) superconductor [7]. One of the most important features of MgB_2 is that it does not exhibit weak-link electromagnetic behavior at grain boundaries or fast flux creep, which limit the performances of YBCO cuprates, oxidized Nb, Nb_3Sn, Nb films [6, 8, 9].

2 CRITICAL FIELDS

In this paper we will focus on the comparison of MgB_2 with bulk Nb and Nb_3Sn. Though YBCO cuprates have higher T_c, they are omitted due to the fact that their application to accelerator cavities does not seem to be promising in the near future.

2.1 H_c, H_{c1}, H_{c2} and H_{sh}

BCS Type II superconductors such as the ones being treated here are characterized by a thermodynamic critical magnetic field (H_c), a lower critical magnetic field (H_{c1}), an upper critical magnetic field (H_{c2}) and a superheating critical magnetic field (H_{sh}).

H_c, H_{c1} and H_{c2} are related to each other by the Ginzburg-Landau parameter $\kappa_{GL} = \lambda_L/\xi_0$ as follows, where λ_L and ξ_0 are the London's penetration depth and the coherence length [4].

$$H_c = \frac{H_{c2}}{\sqrt{2}\kappa_{GL}} \;, \tag{1}$$

$$H_{c1} \cdot H_{c2} = H_c^{\,2} \cdot \ln(\kappa_{GL})\,. \tag{2}$$

H_{sh} is related with H_c for Nb ($\kappa_{GL} \approx 1$) and for Nb_3Sn and MgB_2 ($\kappa_{GL} >> 1$) as follows [4].

$$H_{sh} \approx 1.2 H_c \quad \text{for } \kappa_{GL} \approx 1, \tag{3}$$

$$H_{sh} \approx 0.75 H_c \quad \text{for } \kappa_{GL} >> 1. \tag{4}$$

It has been shown at least for Nb at $0.5 < T/T_c < 1$ that the theoretical field limit for RF cavities is H_{sh} [10]. Table 1 shows the results of H_{sh} for Nb, Nb_3Sn and MgB_2 using Eqs. (1) through (4).

2.2 Theoretical limit for accelerating gradients

The theoretical limits for accelerating gradients using the calculated H_{sh} and the following formula are shown in Table 2, assuming H_{peak}/E_{acc}=40 Oe/(MV/m).

$$H_{sh}(T) = H_{sh}(0)\left\{1-(T/T_c)^2\right\}\,. \tag{5}$$

The result shows that Nb_3Sn and MgB_2 have 94 % and 63 % higher theoretical gradients than Nb at 4 K operation. Also, MgB_2 has a limit similar to Nb even for operation at 20 K.

Table 1: Critical fields for Nb, Nb_3Sn and MgB_2. The superheating field H_{sh} was calculated for Nb from H_{sh} = 1.2 H_c (κ_{GL} ~1) and for Nb_3Sn and MgB_2 from H_{sh} = 0.75 H_c (κ_{GL} >> 1) [4].

Material	T_c [K]	GL Parameter κ_{GL}	H_c [Oe]	H_{c1} [Oe]	H_{c2} [Oe]	H_{sh} [Oe]
Nb (0K)	9.2	0.78	2000	1700	2400	2400
Nb_3Sn (0K) [2]	18.2	22.8 [2]	5350 [2]	520	173000	4010
MgB_2 (4 K)	39	36.3	4290	300 [3]	220000 [3]	3210
MgB_2 (20 K)	39	25.4	2780	250 [3]	100000 [3]	2090

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Table 2: Theoretical limit of accelerating field in the case of H_{peak}/E_{acc}=40 Oe/(MV/m).

Material	**Operation Temp. [K]**	**Theoretical Limit E_{acc} [MV/m]**
Nb	4	49
Nb_3Sn	4	95
MgB_2	4	80
MgB_2	20	52

3 SURFACE RESISTANCE R_S

Since the cavity quality factor $Q_0 = G/R_s$, where G is the geometrical factor, Q_0 is inversely proportional to R_s, i.e., proportional to the cryogen heat load. Therefore, it is very important to reduce R_s to reduce the refrigeration cost.

R_s consists of the sum of BCS resistance (R_{BCS}) and residual resistance (R_{res})

$$R_s = R_{BCS} + R_{res} \quad . \tag{6}$$

3.1 BCS resistance, R_{BCS}

R_{BCS} can be expressed as follows.

$$R_{BCS} = A \cdot \frac{f^2}{T} \cdot \exp\left(-\frac{\Delta}{k_B T_c} \cdot \frac{T_c}{T}\right), \tag{7}$$

where A is a constant, dependent on the material parameters of the superconductor, such as λ_L, ξ_0, mean free path (l), f the frequency, T the temperature, 2Δ the energy gap and k_B the Boltzman constant [4].

Since R_{BCS} is proportional to f^2, Nb SC cavities operated at >500 MHz must be cooled below 4 K to reduce the heat load to the refrigerator. However, since the energy gap $2\Delta/k_BT_c$ is a constant (~3.5) [5], R_{BCS} decreases dramatically as T_c gets higher.

Table 3 shows this effect relative to the value for Nb at 4 K.

Table 3: Effect of operating temperature on the BCS resistance. Energy gap $2\Delta/k_BT_c = 3.5$ is assumed for all the materials [5]. Normalization by the number for Nb operated at 4 K was performed.

Material	**T_c [K]**	**Op. Temp. [K]**	$\frac{1}{T}\exp\left(-\frac{\Delta}{k_B T}\right)$
Nb	9.2	4	1
Nb_3Sn	18.2	4	0.0195
MgB_2	39	4	0.00000217
MgB_2	39	20	0.369

It shows that R_{BCS} of MgB_2 is more than 5 orders of magnitude less than that of Nb at 4 K, assuming that the constant A is not too different. This implies that MgB_2 cavities can be operated at 4 K or even at 20 K. This benefit has already been demonstrated with a Nb_3Sn cavities [11], which showed the same Q_0 at 4.2 K as that of Nb at 2 K, although it showed a Q_0 degradation problem at E_{peak}>10 MV/m.

3.2 Residual resistance, R_{res}

R_{res} can be written as follows [12].

$$R_{res} = R_{res}(H_{rf}) + R_{fl}(H_{rf}, H_{ext}, T), \tag{8}$$

where H_{rf}, R_{fl} and H_{ext} are the RF magnetic field in the cavity, the residual resistance caused by trapped magnetic flux and the external magnetic field, respectively.

It has been found that R_{res} of coated surfaces such as Nb-coated copper cavities and Nb_3Sn cavities increases steeply at high H_{rf} as compared to bulk Nb cavities [11, 12]. Especially, YBCO films show an unacceptable increase [13]. As mentioned earlier, this increase has to do with the weak links at the grain boundaries, i.e., weak coupling across grain boundaries that limits SC current flow and makes the surface sensitive to H_{rf} and H_{ext}.

Though MgB_2 has shown absence of these weak links, to our knowledge, there has been no report on the dependence of R_{res} on high H_{rf} relevant to the Nb cavity fields. A report, however, on microwave properties of MgB_2 at 10 GHz [14] has shown an R_s comparable with bulk Nb at 4 K. Since R_{BCS} is supposed to be much lower than Nb, this R_s is probably attributed to R_{res}. Further studies on the origins of R_{res} are necessary.

3 FABRICATION OF MGB$_2$ CAVITY

To facilitate a smooth transition from basic material research to cavity applications, it may be interesting to consider ways to fabricate MgB_2 cavities. There are three likely techniques that might be used in fabricating a MgB_2 cavity, (1) coating of MgB_2 on a cavity surface, (2) forming a MgB_2 bulk cavity and (3) making a composite of MgB_2 and another metal such as copper. Though it is too early to state which is the best way, method (1) must be the best way if it is possible, considering that additional engineering developments, e.g., how to attach flanges, can be avoided. Technique (2) may not be useful due to the fact that the thermal conductivity of MgB_2 is much lower than that of other metals, although it is metallic [15]. Technique (3) may have the highest potential in terms of achievable accelerating gradients due to smaller granularity as compared to coated cavities.

Here, we propose one possible implementation of technique (3) using a hot isostatic press (HIP) technique. It has already been demonstrated that a good quality MgB_2 bulk quality can be obtained with HIP at 200 MPa and 1000 ºC for 200 minutes [16]. This HIP condition is readily available in industry.

Figure 1 illustrates the process of making a MgB_2 cavity. Commercially available MgB_2 powder is filled between two copper pipes under vacuum. This sub-assembly is

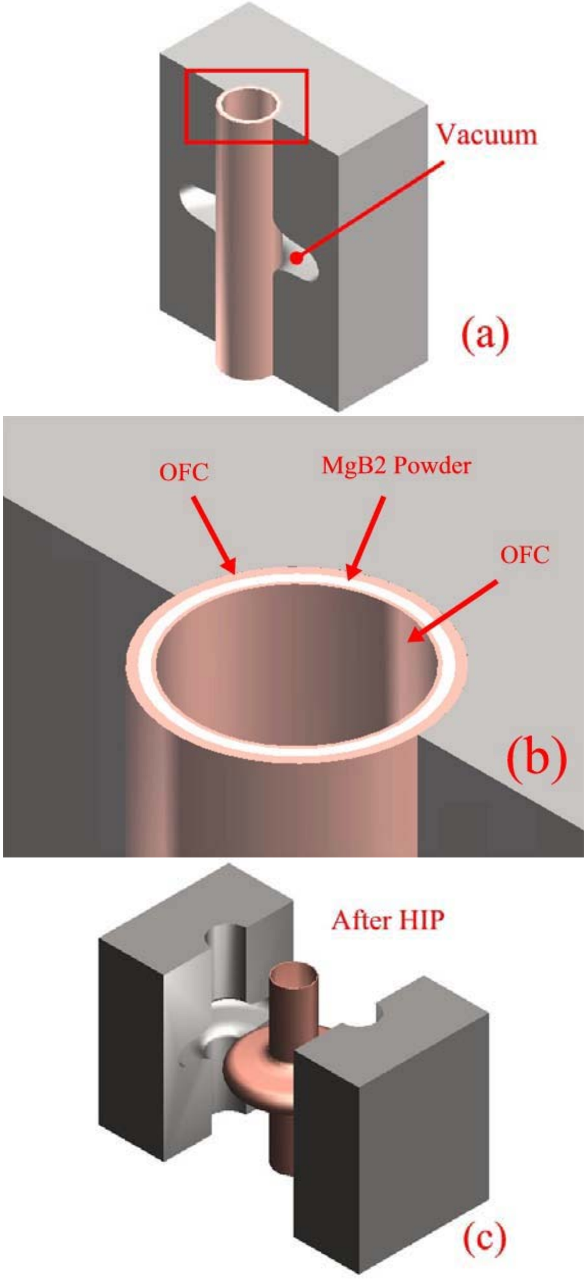

Figure 1: Concept for fabrication of a MgB_2-layered single-cell copper cavity with HIP. (b) is the blow-up of the square in (a). MgB_2 powder is filled between two OFC pipes and assembled with blocks in vacuum and sealed at the end of the beam pipes. After the HIP process (c) the inner copper layer is removed by a chemical such as HF or machined.

then attached with two half dies having the shape of a cavity. This is then sealed at the end of the beam pipes under vacuum. After putting this assembly in a HIP furnace, Ar gas is filled in the furnace, and its temperature and pressure are raised according to an optimized pattern. With this HIP, the MgB_2 powder will probably be sintered and bonded to the copper simultaneously. After HIP, the inner copper layer is removed with a chemical, e.g., hydrofluoric acid, or machining. A technique has been successfully developed elsewhere in making a ferrite layer from powder on the inner surface of copper pipes up to 30 cm in diameter [17].

One known disadvantage of MgB_2 so far is that it degrades with prolonged exposure to water [18, 19]. Although accelerating cavities will be used in a good vacuum, it may need to undergo high-pressure water rinsing, etc. Thus, further study of this effect is necessary for this application.

4 SUMMARY AND FUTURE PLANS

Possibility of using MgB_2 as a candidate for a material to make superconducting cavities was discussed.

Although further basic studies are necessary, MgB_2 cavities seem to have a good potential for exceeding performance of present Nb cavities.

One way of making a MgB_2 cavity with HIP has been proposed. We plan to try this technique as well as other coating techniques.

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