POSSIBILITY OF MGB2 APPLICATION TO SUPERCONDUCTING CAVITIES*

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Abstract
A metallic superconductor, magnesium diboride (MgB2), 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 MgB2 as compared to Nb and Nb3Sn. Also, a possible method of fabricating a MgB2 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 (MgB2) was found to have a critical temperature (Tc) of 39 K in early 2001 [1]. It has triggered a tremendous amount of research activity due to its high Tc, 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 MgB2 is a conventional BCS (s-wave) superconductor [7]. One of the most important features of MgB2 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, Nb3Sn, Nb films [6, 8, 9].

2 CRITICAL FIELDS

In this paper we will focus on the comparison of MgB2 with bulk Nb and Nb3Sn. Though YBCO cuprates have higher Tc, 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 Hc, Hc1, Hc2 and Hsh

BCS Type II superconductors such as the ones being treated here are characterized by a thermodynamic critical magnetic field (Hc), a lower critical magnetic field (Hc1), an upper critical magnetic field (Hc2) and a superheating critical magnetic field (Hsh).

Hc, Hc1 and Hc2 are related to each other by the Ginzburg-Landau parameter \(\lambda_L/\xi_0\) as follows, where \(\lambda_L\) and \(\xi_0\) are the London’s penetration depth and the coherence length [4].

\[ H_c = \frac{H_{c2}}{\sqrt{2\kappa_{GL}}} \]  
\[ H_{c1} \cdot H_{c2} = H_c^2 \cdot \ln(\kappa_{GL}). \]  

\( H_{sh} \) is related with \( H_c \) for Nb (\( \kappa_{GL} \approx 1 \)) and for Nb3Sn and MgB2 (\( \kappa_{GL} >> 1 \)) as follows [4].

\[ H_{sh} \approx 1.2 H_c \quad \text{for} \quad \kappa_{GL} \approx 1, \]  
\[ H_{sh} \approx 0.75 H_c \quad \text{for} \quad \kappa_{GL} >> 1. \]  

It has been shown at least for Nb at 0.5 < T/Tc < 1 that the theoretical field limit for RF cavities is \( H_{sh} \) [10]. Table 1 shows the results of \( H_{sh} \) for Nb, Nb3Sn and MgB2 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).

\[ H_{sh}(T) = H_{sh}(0)\left\{1 - \left(\frac{T}{T_c}\right)^2\right\}. \]  

The result shows that Nb3Sn and MgB2 have 94 % and 63 % higher theoretical gradients than Nb at 4 K operation. Also, MgB2 has a limit similar to Nb even for operation at 20 K.

<table>
<thead>
<tr>
<th>Material</th>
<th>Tc [K]</th>
<th>GL Parameter ( \kappa_{GL} )</th>
<th>( H_c ) [Oe]</th>
<th>( H_{c1} ) [Oe]</th>
<th>( H_{c2} ) [Oe]</th>
<th>( H_{sh} ) [Oe]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb (0K)</td>
<td>9.2</td>
<td>0.78</td>
<td>2000</td>
<td>1700</td>
<td>2400</td>
<td>2400</td>
</tr>
<tr>
<td>Nb3Sn (0K)</td>
<td>18.2</td>
<td>22.8 [2]</td>
<td>5350 [2]</td>
<td>520</td>
<td>173000</td>
<td>4010</td>
</tr>
</tbody>
</table>

Table 1: Critical fields for Nb, Nb3Sn and MgB2. The superheating field \( H_{sh} \) was calculated for Nb from \( H_{sh} = 1.2 H_c \) (\( \kappa_{GL} \approx 1 \)) and for Nb3Sn and MgB2 from \( H_{sh} = 0.75 H_c \) (\( \kappa_{GL} >> 1 \)) [4].

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Operation Temp. [K]</th>
<th>Theoretical Limit $E_{\text{acc}}$ [MV/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>4</td>
<td>49</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>4</td>
<td>95</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>20</td>
<td>52</td>
</tr>
</tbody>
</table>

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 ($R_{\text{BCS}}$) and residual resistance ($R_{\text{res}}$)

$$R_s = R_{\text{BCS}} + R_{\text{res}}.$$  \hspace{1cm} (6)

3.1 BCS resistance, $R_{\text{BCS}}$

$R_{\text{BCS}}$ can be expressed as follows.

$$R_{\text{BCS}} = A \cdot \frac{f^2}{T} \cdot \exp \left( -\frac{\Delta}{k_B T_c} \cdot \frac{T_c}{T} \right),$$  \hspace{1cm} (7)

where $A$ is a constant, dependent on the material parameters of the superconductor, such as $\lambda_{\parallel}$, $\xi_0$, mean free path ($l$), $f$ the frequency, $T$ the temperature, $2\Delta$ the energy gap and $k_B$ the Boltzman constant [4].

Since $R_{\text{BCS}}$ 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 $2\Delta/k_B T_c$ is a constant (~3.5) [5], $R_{\text{BCS}}$ 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 $2\Delta/k_B T_c = 3.5$ is assumed for all the materials [5]. Normalization by the number for Nb operated at 4 K was performed.

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ [K]</th>
<th>Op. Temp. [K]</th>
<th>$1/T \exp \left( -\frac{\Delta}{k_B T} \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>9.2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.2</td>
<td>4</td>
<td>0.0195</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>39</td>
<td>4</td>
<td>0.00000217</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>39</td>
<td>20</td>
<td>0.369</td>
</tr>
</tbody>
</table>

It shows that $R_{\text{BCS}}$ 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$_3$Sn 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 $E_{\text{peak}}>10$ MV/m.

3.2 Residual resistance, $R_{\text{res}}$

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

$$R_{\text{res}} = R_{\text{res}} (H_{\text{rf}}) + R_{\text{fl}} (H_{\text{rf}}, H_{\text{ext}}, T).$$  \hspace{1cm} (8)

where $H_{\text{rf}}$, $R_{\text{fl}}$ and $H_{\text{ext}}$ 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 $R_{\text{res}}$ of coated surfaces such as Nb-coated copper cavities and Nb$_3$Sn cavities increases steeply at high $H_{\text{rf}}$ 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 $H_{\text{rf}}$ and $H_{\text{ext}}$.

Though MgB$_2$ has shown absence of these weak links, to our knowledge, there has been no report on the dependence of $R_{\text{res}}$ on high $H_{\text{rf}}$ 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 $R_{\text{BCS}}$ is supposed to be much lower than Nb, this $R_s$ is probably attributed to $R_{\text{res}}$. Further studies on the origins of $R_{\text{res}}$ 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 °C 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
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.

5 ACKNOWLEDGMENTS
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6 REFERENCES
[7] For example, T. Takahashi et al., cond-mat/0103079.