SRF CAVITIES BEYOND NIOBIUM: CHALLENGES AND POTENTIAL[*]

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Abstract

With niobium cavities now approaching the fundamental limits of the material, SRF researchers have begun a significant R&D effort to develop alternative materials to continue to keep up with the demands of new accelerator facilities. In this paper, the benefits of new materials are explored, as well as the critiria for selecting superconductors to use for SRF applications. The materials Nb_3Sn and MgB_2 are discussed in detail, including an exciting new result from a Nb_3Sn cavity that shows the great potential of alternative SRF materials. NbN and multilayers are also briefly discussed. The current status and the outlook for the future of alternative materials are reviewed.

WHY LOOK BEYOND NIOBIUM?

To accelerate beams of charged particles, superconducting radio-frequency (SRF) cavities are the technology of choice for many facilities. They can reach large accelerating gradients E_{acc} on the order of tens of MV/m, and though they require cryogenics for cooling below the superconducting transition temperature T_c of the material they are made from, they achieve high wall-power-to-beam-power efficiency due to their small surface resistances R_s. Modern SRF facilities use cavities made of niobium, either formed from bulk sheets, or sputtered in films onto copper. Early niobium cavities could operate at only small gradients of a few MV/m, but through years of research, preparation techniques were developed to avoid non-fundamental limitations, such as multipacting and field emission [1]. State-of-the-art production methods regularly produce cavities that operate very close to the fundamental limits of niobium: they have surface resistances R_s very close to the ideal BCS value at operating temperatures, and they sustain electromangetic fields very close to the material's superheating field B_{sh}, the field at which vortices penetrate the superconductor—creating unmanageable levels of heating in RF fields—for an ideal surface [2]. In Fig. 1, the qualification curve of a high-performing TESLA 9-cell niobium cavity (the proposed cavity design for ILC) is plotted. The curve tracks two figures of merit: E_{acc} and Q_0, which is inversely proportional to R_s. It shows that this cavity performs very close to the fundamental limits of the material.

To continue to keep up with continually increasing demands of future accelerator driven sciences, SRF researchers have begun a significant effort to develop alternative materials, chosen to have higher fundamental limits

Figure 1: Q_0 vs E_{acc} for a High Performing ILC 9-cell Niobium Cavity [3]. The maximum E_{acc} and the Q_0 over the entire range are very close to the fundamental limits of the material.

than niobium. The optimal material may depend on the type of facility. For low-duty-cycle high energy linacs, an alternative material would be chosen that can sustain very large surface magnetic fields, as this is what fundamentally limits E_{acc}, and therefore sets the minimum number of cavities requied to reach a given energy. On the other hand, for modern CW SRF linac designs, cryogenics is the cost driver, not the number of cavities. For niobium, low R_s operation requires the cavity to be cooled to $\sim$2 K, where cryogenic efficiency often pushes the cost-optimum arrangement to using only modest gradients, because losses go quadratically with E_{acc}. At $\sim$2 K, cavities made from an alternative material with lower R_s than niobium would have smaller losses at a given E_{acc}, so they would allow the cryogenic plant to be smaller and require less grid power, or they could operate at higher gradients, and therefore require fewer cavities. Furthermore, the temperature dependent part of R_s scales with $e^{-T_c/T}$, so if the alternative material had a large T_c, low R_s operation could be possible at 4.2 K, greatly simplifying the cryogenic plant by allowing it to operate at atmospheric pressure. Low R_s operation at even higher temperatures would open up the possibility of using helium gas for cooling.

Long term R&D will be needed to reach the full potential of these alternative materials, but already new results (which will be shown later) on a Nb_3Sn cavity fabricated by Cornell show performances now superior to niobium for some applications requiring modest fields only.
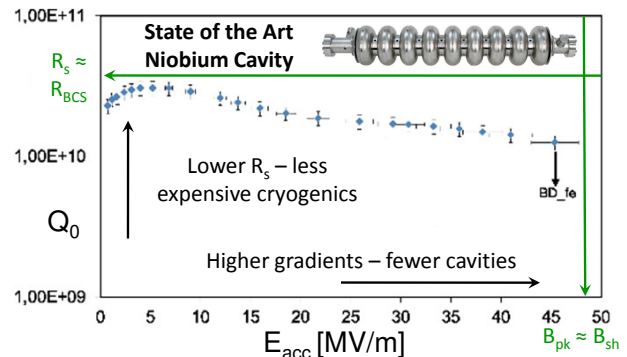
WHAT PROPERTIES TO LOOK FOR IN ALTERNATIVE MATERIALS?

To determine which superconductors are viable candidates for producing high-performing SRF cavities, one should look for certain properties. To achieve large E_{acc}, a large superheating field B_{sh} is desirable, as this is the relevant critical field for RF applications. This is different from B_{irr}—the irreversibility field at which at which vortices that have penetrated into the sample become depinned—which is relevant for magnet applications. In SRF cavities, the objective is to exclude flux, not to pin it inside the superconductor; pinned normal conducting vortex cores dissipate strongly in RF fields. It is energetically favorable for vortices to be inside the superconductor above the first critical field B_{c1}, and only an energy barrier prevents flux penetration above this field. For an ideal surface, the barrier disappears at B_{sh}, making it the ultimate limit for SRF applications, but surface defects with size on the order of the coherence length ξ—roughly, the spacial amplitude of the superconducting wavefunction—can reduce the barrier to vortex penetration, such that fields close to B_{sh} cannot be realized without vortex entry. It is therefore important to have a large enough ξ to not be affected by small defects that would be present even on a well prepared surface, e.g. grain boundaries. It has been an open question how large of ξ is large enough—niobium cavities have reached fields quite close to B_{sh} and its ξ is $\sim$20 nm—but recent results (presented in a later section) on a Nb$_3$Sn cavity have shown that operation well into the metastable regime where only the energy barrier prevents vortex penetration is possible for $\xi\sim$3 nm.

For small R_s, one must first consider the temperature-dependent surface resistance from BCS theory, R_{BCS}. As discussed previously, $R_{BCS}\propto e^{-T_c/T}$, so it is important for materials to have high T_c. Materials that have small R_{BCS} also tend to have small normal resistivity ρ_n [4]. However, there is also a temperature independent part of R_s, the "residual resistance" R_{res}: $R_s(T) = R_{BCS}(T) + R_{res}$. The factors contributing to R_{res} are not well understood, but previous SRF experience has made it clear that weak links between grains contribute to large R_{res} [1].

To be useful for cavity operation, alternative materials must also possess the following qualities: 1) it must be possible to fabricate it in a way that it conforms to a complex geometry over large area; 2) it must have decent thermal conductivity (and be able to be deposited on a substrate with decent thermal conductivity) for cooling to avoid thermal runaway; 3) it must have minimal surface roughness to avoid field enhancement; 4) it must be able to be made clean (for example, it cannot release potentially field emitting dust, and there must be a method to clean surface contaminants without affecting quality).

Some of the most promising alternative SRF materials and relevant properties are shown in Table 1, along with those of niobium. Experimental references for these properties were chosen to try to display realistic properties for polycrystalline films. However, material parameters vary depending on how the superconductor is fabricated, and some improvement in SRF qualities can be expected with R&D.

Table 1: Material Properties of Niobium and Three Promising Alternative SRF Materials. The penetration depth λ is calculated using Eqn 3.131 in [5]. The coherence length ξ is calculated using the equations in [6]. For Nb a RRR of 10 was assumed. For MgB$_2$, λ and ξ are not calculated, as the experimental values are given in the reference. B_{sh} for Nb is found from [7] and for others calculated from [2]. For B_{sh} calculations, $B_c = \phi_0/(2\sqrt{2}\pi\xi\lambda)$ is used, where ϕ_0 is the flux quantum [5]. Nb data from [8], Nb$_3$Sn data from [9], NbN data from [10], and MgB$_2$ data from [11] and [12]. Note that the two gap nature of MgB$_2$ may require more careful analysis than is performed here.

Material	$\lambda(0)$ [nm]	$\xi(0)$ [nm]	B_{sh} [mT]	T_c [K]	ρ_n [$\mu\Omega$cm]
Nb	50	22	210	9.2	2
Nb$_3$Sn	111	4.2	410	18	8
MgB$_2$	185	4.9	210	40	0.1
NbN	375	2.9	160	16	144

Potential and Challenges

Nb$_3$Sn is a material with tremendous potential for SRF applications. It has extremely small R_s, as a result of its small ρ_n and large $T_c\sim$18 K (twice as high as niobium), as well as its small R_{res}, shown in cavity measurements [13]. It also is an excellent candidate for achieving large E_{acc}, with very large predicted $B_{sh}\sim$400 mT (again twice as high as niobium), and a decent $\xi\sim$3-4 nm. Furthermore, it can be coated onto niobium substrates, allowing existing niobium cavities to be upgraded. It is also non-reactive with water, and it adheres strongly to niobium when coated onto it, so that Nb$_3$Sn cavities can be cleaned using the high-pressure-water-rinsing methods developed for niobium.

Nb$_3$Sn is brittle, and it has low thermal conductivity, so it has to be used in film form. Therefore it faces challenges associated with using SRF films. These are detailed in a later section.

Preparation Methods

The Nb$_3$Sn fabrication method that has produced the most encouraging SRF results is vapor diffusion. The technique was developed at Siemens AG [14] and University of Wuppertal [15], and it is now being employed by researchers at Cornell University [16] and Jefferson Lab [17]. A niobium cavity is placed in an ultra-high-vacuum furnace with a small amount of tin. The temperatures of both are

raised to around 1000°C, so that the tin has a high enough vapor pressure to reach the cavity, and once it reaches the surface, the temperature is high enough to encourage diffusion and alloying.

Researchers at several institutions have recently attempted to fabricate Nb_3Sn using other methods: liquid tin dipping and multilayer sputtering at INFN [18]; cathodic arc deposition at Alameda Applied Sciences Corp. [19]; and pulsed laser deposition at KEK [20] (note that AASC and KEK fabricated MgB_2 via the same methods). However, so far these studies have not produced encouraging RF results.

Development Status

Jefferson Lab has fabricated Nb_3Sn samples with excellent T_c. They have also performed low-field R_s measurements in a 7.4 GHz host cavity. A dedicated furnace has been delivered, and is currently being commissioned to coat full single-cell cavities. The apparatus is shown in Fig. 2.
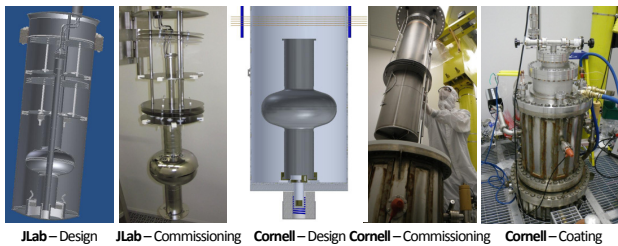

JLab – Design **JLab** – Commissioning **Cornell** – Design **Cornell** – Commissioning **Cornell** – Coating

Figure 2: Apparatuses for coating cavities with Nb_3Sn at Jefferson Lab (left) and Cornell University (right).

The Nb_3Sn program at Cornell University (see coating apparatus in Fig. 2) has been ongoing for several years, and recently produced its second 1.3 GHz cavity, shown in Fig. 3, which showed exceptional performance in RF test [16]. As shown in Fig. 4, it achieved fields ∼12 MV/m at 4.2 K with a Q_0 of 10^{10}, 20 times higher than niobium. It is the first alternative material accelerator cavity to achieve significantly smaller R_s than niobium at useful gradients and temperatures. Previous Nb_3Sn cavities suffered from a strong increase in R_s with field, leading to speculation that the coherence length was too small, causing the barrier to vortex penetration to fail at surface imperfections. However, this new cavity proves that even with a ξ of only ∼ 3 nm, the energy barrier prevents observable vortex dissipation, the first clear indication that such a small ξ will not cause a fundamental limitation for cavities made from alternative materials.

MAGNESIUM DIBORIDE

Potential and Challenges

MgB_2 was discovered relatively recently, so it is not as well developed as Nb_3Sn, but it also has exciting poten-
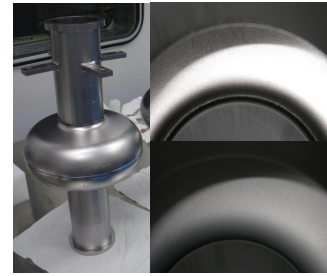

Figure 3: Cavity coated with Nb_3Sn at Cornell (left); view looking down into cavity before (top right) and after coating (bottom right). Notice the dark, matte gray appearance of the Nb_3Sn coating.
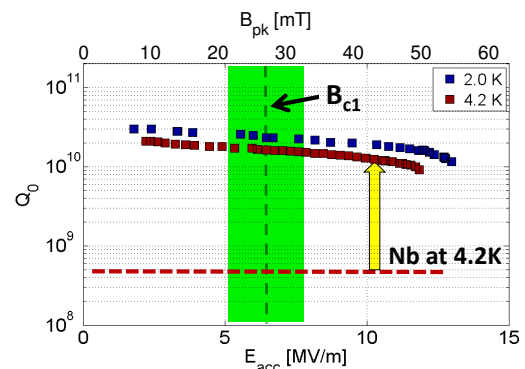

Figure 4: Q_0 vs E_{acc} for Cornell's Nb_3Sn cavity. At 10 MV/m, the Q_0 is a factor of 20 times higher than Nb at 4.2K. The maximum surface magnetic field is approximately 2 times higher than B_{c1}=27±5 mT, which was calculated using Ginzburg Landau theory from measured material parameters.

tial. With a T_c of approximately 40 K, and a small ρ_n, it can have a very small R_{BCS} even well above liquid helium temperatures. Its superheating field is not clear at this early stage of development, but it could range from ∼200-600 mT, depending on the material properties. More development of SRF-quality MgB_2 films is needed to make a better estimate. It also has a decent ξ∼5 nm.

There are some challenges to developing MgB_2 as an SRF material. In fabrication, it is necessary to obtain a very small oxygen background in the coating chamber, as the magnesium is highly reactive with it. The coatings also react with water, which makes cleaning difficult. It might be necessary to coat an additional dielectric "capping" layer to allow a MgB_2 cavity to be cleaned. Additionally, because it is a two-gap material, its R_s is predicted to increase with field, but there might be methods to reduce this effect [21]. MgB_2, like Nb_3Sn is being developed in film form, so it will have the same film challenges detailed in a later section.

Preparation Methods

Excellent preliminary results have been obtained using hybrid physical chemical vapor deposition at Temple University [22] and using reactive co-sputtering at Superconducting Technologies Inc. (STI) [23].

Development Status

Coating of accelerator cavities with MgB_2 is being developed by X. Xi at Temple University [22]. Studies of samples produced at Temple have repeatedly shown films with T_c very close to the ideal literature value, and ρ_n of only 0.1 μΩcm [12]. Encouraging RF results have been obtained by researchers at Los Alamos and MIT Lincoln labs on MgB_2 stripline and dielectric resonators fabricated by STI, as shown in Fig. 5. Measurements still need to be done at smaller frequencies to determine if R_{res} can be small enough for SRF cavities, and if this can be maintained up to useful fields.
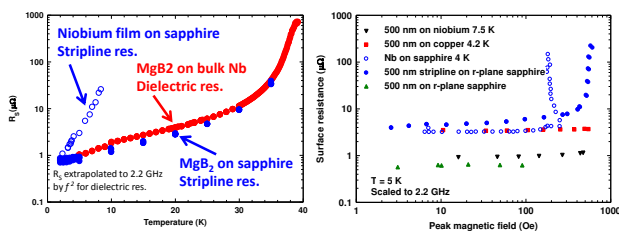

Figure 5: RF measurements of MgB_2 stripline and dielectric resonators show excellent R_s at high temperatures and high frequencies. Experimental data from D. Oates [23]. Note that scaling of the data from high frequencies may significantly underestimate the residual resistance at 2.2 GHz.

NIOBIUM NITRIDE

With a high $T_c\sim$15-17 K, the δ phase of NbN has the potential to have R_{BCS} significantly smaller than niobium. For the relatively dirty films that are generally produced, it has a predicted B_{sh} of only around 150-200 mT, with a decent $\xi\sim$3 nm. However, one additional argument in favor of pursuing NbN is that it might be possible to coat large niobium cavities in existing UHV furnaces—one of the methods of producing NbN involves bringing niobium to high temperatures in the presence of nitrogen gas, then quickly cooling it [24].

NbN has a very complex phase diagram, which makes it very challenging to achieve the superconducting δ phase. This is achievable with sputtering, but with heat treatment in a nitrogen atmosphere, no reliable procedure has been developed that could be applied to cavities. Recently an R_s reduction was observed in niobium cavities that were treated with nitrogen gas in a UHV furnace at Fermilab, and it was initially speculated that the cause was the growth of superconducting NbN. However, T_c and XRD measurements of samples revealed that another mechanism must

have been responsible [25]. Another challenge is R_{res}—tests of sputtered NbN have shown a relatively high value. Additional investigations are needed to determine if this can be avoided.

MULTILAYERS

In 2006, A. Gurevich proposed that bulk films of alternative materials would be inferior to "SIS multilayer" films, which consist of alternating layers of thin superconductor (S) and insulator (I) on top of bulk superconductor, as shown in Fig. 6 [26]. It was suggested that the enhancement of the critical fields in thin films would help small-ξ materials to avoid vortex penetration from small surface defects. Several labs over the world have made excellent progress in the difficult process of fabricating SIS films, including CEA [27], Argonne [28], JLab [29], William and Mary [30], and Grenoble IPT [31]. However, recent theoretical work has shown that compared to bulk films, SIS multilayers can offer only a small enhancement of the superheating field, and only for a small parameter range [32].
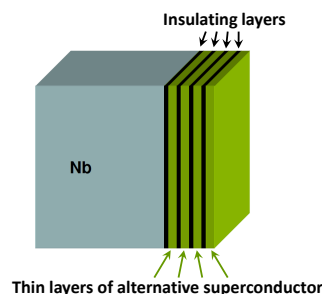

Figure 6: SIS multilayer structure proposed to protect alternative materials from vortex penetration. New theoretical work suggests that multilayers will not be superior to bulk films. Image adapted from [26].

FILM CHALLENGES

The alternative materials being researched are primarily used in film form over metal substrates. There are unique challenges associated with SRF films that are not encountered in cavities made form bulk material. The cooldown of a film cavity must be done slowly and uniformly to avoid temperature gradients over the surface. Gradients can cause thermocurrents due to the interface of the two materials, which in turn can create and trap flux that causes excess R_{res}. This also means that after a quench, the cavity must be warmed above T_c and cooled slowly again to regain a small R_s. Films cavities have fewer options available in case of a contaminated surface after coating—because the film is usually only a few μm thick, only light chemistry is available to clean the surface. Large cavities also present a significant challenge with films, since applying a film to a completed structure requires a very large coating apparatus. Coating pieces before welding is not possible in most cases because this would destroy the quality of the film at the weld.

OTHER MATERIALS

Other potentially promising materials not presented here but for which there has been some recent activity include V_3Si, Mo_3Re [33], and Nb_3GaAl [34]. In addition, though they have very complex structures, the oxypnictides are an exciting possibility. More research is needed into these materials to understand if they might be useful for SRF applications.

CONCLUSIONS

Alternative SRF materials offer lower R_s, higher T_c, and higher B_{sh} than niobium. Cavities made from these materials would be much more cryogenicically efficient (likely a factor of 10-100), and they are predicted to reach higher gradients (up to a factor of $\sim$2), meaning that fewer cavities would be required to reach a given beam energy. Many labs worldwide are contributing to the effort, and while it is expected to be a long term R&D project, there has been significant progress recently. A Nb_3Sn cavity produced at Cornell achieved a breakthrough performance: at 4.2 K and $\sim$12 MV/m, it had a Q_0 of 10^{10}, 20 times higher than Nb, making it the first alternative material accelerator cavity to far outperform niobium at useful gradients and temperatures. MgB_2 is also showing great promise in small-scale RF tests, and the first MgB_2 accelerator cavities are planned to be produced soon.

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