Title
Nb3Sn for Radio Frequency Cavities

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Nb_3Sn FOR RADIO FREQUENCY CAVITIES*

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Abstract

In this article, the suitability of Nb_3Sn to improve the performance of superconducting Radio-Frequency (RF) cavities is discussed. The use of Nb_3Sn in RF cavities is recognized as an enabling technology to retain a very high cavity quality factor (Q_0) at 4.2 K and to significantly improve the cavity accelerating efficiency per unit length (E_{acc}). This potential arises through the fundamental properties of Nb_3Sn. The properties that are extensively characterized in the literature are, however, mainly related to improvements in current carrying capacity (J_c) in the vortex state. Much less is available for the Meissner state, which is of key importance to cavities. Relevant data, available for the Meissner state is summarized, and it is shown how this already validates the use of Nb_3Sn. In addition, missing knowledge is highlighted and suggestions are given for further Meissner state specific research.

INTRODUCTION

Linear accelerators utilize a linear array of RF cavities and become increasingly long, with lengths up to the tens of kilometer range, to achieve particle energies in the GeV to TeV energy range that is of present High Energy Physics (HEP) interest. Such systems will require on the order of 20,000 RF cavities. Improving the accelerating voltage per unit length will result in tremendous cost savings, since the required length to achieve a given beam energy in a linear accelerator is inversely proportional to the electric field that can be generated per unit length. In addition, power requirements are significant, ranging from 100 to 250 MW for a 500 GeV linear accelerator.

The main figures of merit for RF cavities are the quality factor Q_0 (defined by the ratio between the energy stored in the cavity and the energy loss in one RF period) and its average accelerating field E_{acc}. Q_0 values as high as 10^{11} have been achieved in superconducting cavities. Superconducting cavities exhibit approximately a factor 10^6 higher Q_0 than normal conducting cavities due to the reduced microwave surface resistance. Even when accounting for cooling penalties the required input power is still about a factor 10^3 lower when using superconducting cavities instead of normal conducting cavities, saving drastically in operating costs. The International Technology Recommendation Panel of the International Committee for Future Accelerators therefore, amongst other considerations, selected superconducting RF cavities above normal conducting cavities as the preferred technology for future linear accelerators [1].

The efficiency of a RF cavity is usually depicted by plotting Q_0 as function of E_{acc}. For an ideal superconducting cavity, Q_0 remains constant with increasing E_{acc} and collapses when a maximum E_{acc} is reached. This point is determined by the magnetic components of the RF standing wave. Once the magnetic component reaches a certain threshold value, vortices penetrate the superconductor and the Meissner state is lost. Vortices that move inside the superconductor dissipate energy and cause the cavity to 'quench'. Even though vortices can be – elastically – 'pinned' by material imperfections, their oscillations in an RF field will still cause dissipations [2]. Hence, vortex penetration has to be prevented to retain a high Q_0 and a cavity has to operate in the Meissner state.

In Type-II superconductors, vortex penetration becomes energetically favorable at the bulk lower critical magnetic field H_{c1}. However, in magnetic fields which are parallel to the surface, vortices have to overcome the Bean-Livingston positive surface energy barrier to enter the superconductor [3]. The Meissner state can therefore persist metastably beyond H_{c1}, up to the so-called superheating field H_{sh}, at which the surface barrier disappears. For Type-II superconductors with a Ginzburg-Landau (GL) parameter $\kappa \gg 1$, $H_{sh} \cong 0.75 H_c$, i.e. 75% of the thermodynamic critical field H_c [4], and its magnitude is thus the main determinant for E_{acc}. Note that in practice H_{sh} is not necessarily reached, due to earlier vortex penetration at surface irregularities [5] and demagnetization effects of transverse magnetic field components [6].

Cavity RF losses, in the absence of vortices, are mainly determined by the RF surface resistance (R_s), which is usually represented as a summation of the Bardeen-Cooper-Schrieffer (BCS) surface resistance R_{BCS} and a residual resistance term (R_{res}). R_{res} is usually on the order of a few nΩ. Provided that the surface is clean and properly manufactured, R_s is usually dominated by R_{BCS}, which can be written as [7]:

$$R_{BCS} \propto \lambda_{eff}^3 \omega^2 \ell \exp\left(-\Delta / k_B T\right), \qquad (1)$$

where, at $T = 0$ [8]:

$$\lambda_{eff} = \lambda_L \sqrt{1 + \xi_0 / \ell}. \qquad (2)$$

λ_L and λ_{eff} are the London and effective penetration depths respectively, ω is the frequency, ℓ is the mean free path, ξ_0 is the BCS coherence length (far below the critical temperature (T_c), $\xi_0 \cong \xi_{GL}$, the GL coherence length [8]), Δ is the superconducting energy gap, k_B is the Boltzmann constant, and T is the temperature. R_{BCS} reduces exponentially with T_c since $\Delta = C k_B T_c$, where $C = 1.76$

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in the weak coupling limit and increasing towards stronger interaction. In the clean limit ($\ell \gg \xi_0$), $\lambda_L\sqrt{1+\xi_0/\ell}$ reduces to λ_L. In the dirty limit ($\ell \ll \xi_0$) it can be shown that low R_{BCS} values can be obtained for low values of the normal state resistivity ρ_n [9]. In general, however, R_{BCS} is minimal for $\xi_0 \cong \ell$ [7]. Also, since the Ginzburg-Landau parameter $\kappa = \lambda_{eff}/\xi_{GL}$, R_{BCS} will be significantly reduced in low-κ superconductors. This requirement is contrary to J_c optimizations for which a high upper critical field H_{c2} is desired, since $H_{c2} = \kappa\sqrt{2}H_c$.

A high E_{acc}, high Q_0 superconducting RF cavity thus requires a superconductor with a high H_c (i.e. a high H_{sh}) and large Δ (i.e. high T_c), a low λ_{eff} and ρ_n (or more exact $\xi_0 \cong \ell$), and a perfect smooth surface to retain a high H_{sh}.

Table 1: Characteristic parameters of Nb and Nb_3Sn

Property	**Nb**	**Nb_3Sn** [a]
T_c [K]	9.2	18
$\mu_0 H_{c1}(0)$ [T]	0.17	0.038
$\mu_0 H_c(0)$ [T]	0.2	0.52
$\mu_0 H_{c2}(0)$ [T]	0.4	30
$\xi_{GL}(0)$ [nm][b]	29	3.3
$\lambda_{eff}(0)$ [nm][c]	41	135
$\kappa(0)$[d]	1.4	41
$\Delta(0)$ [meV][e]	1.4	3.4
ρ_n [$\mu\Omega$cm]	< 100(VERIFY!)	< 20

[a] Approaching stoichiometry.
[b] From $\sqrt{\phi_0/(2\pi\mu_0 H_{c2}(0))}$ [8].
[c] From $\sqrt{\phi_0\mu_0 H_{c2}(0)/(4\pi H_c^2)}$ [8].
[d] From $\kappa(0) = \lambda_{eff}(0)/\xi_{GL}(0)$.
[e] From $\Delta(0) = Ck_B T_c$, assuming a weak coupling limit for pure Nb and using $C = 2.2$ for Nb_3Sn [12].

NIOBIUM

Of the known practically usable superconductors, Nb has the highest bulk $\mu_0 H_{c1} = 170$ mT and, hence, is used for RF cavity applications. An overview of relevant material properties for Nb is presented in Table 1. The parameters are given at $T = 0$ K. Since Nb cavities will be mainly operated at about 2 K and derivatives for $T \to 0$ are zero, the zero temperature values can be expected to be sufficiently accurate. Nb cavities can exhibit a drop in Q_0 towards higher E_{acc}. This so-called Q-drop is not fully understood, but appears to be related to Nb-oxides at the cavity surface [10]. For bulk cavities, the Q-drop can be significantly reduced by baking the cavity at about 500 °C, which presumably redistributes the oxygen. For thin Nb film on Cu cavities the Q-drop cannot, for now, be prevented. The present state-of-the-art bulk Nb cavities exhibit, at $T = 2$ K, a Q_0 above 10^{10} until an E_{acc} of about 50 MV/m, at which point the cavities quench. Note that Nb cavities have to be operated in superfluid Helium (i.e. below 2.2 K) at frequencies above about 1 GHz, since at higher temperatures the BCS losses become too excessive [11], Eq. (1). An $E_{acc} \cong 50$ MV/m corresponds closely to the magnetic field limit for Nb. Note that differences between achieving H_{c1}, H_{sh} or H_c are virtually indistinguishable for Nb. Nevertheless, achieving the magnetic field limitation for Nb cavities means that Nb is exhausted for a further increase in the accelerating voltage.

NIOBIUM-TIN

Off-stoichiometry, morphology and strain

The characteristic parameters for close to stoichiometric Nb_3Sn are presented in Table 1. As for Nb, the values are given at $T = 0$ to provide a direct comparison. For 2 K operation these can be expected to be sufficiently accurate. For higher temperatures (e.g. 4.2 K), their values can be calculated since for Nb_3Sn all temperature dependence is accurately known [13]. A review of the available literature for composition, morphology and strain dependence of the critical parameters is presented in [12]. Relevant results will here be summarized.

The Nb-Sn intermetallic has a range of stable compositions from about 18 to 25 at.% Sn, generally referred to as the A15 phase. The A15 phase can be formed from the melt above 930 °C, or at lower temperatures through a solid-state reaction between Nb and the Sn-rich line compounds Nb_6Sn_5 and $NbSn_2$. Most available literature describing optimization of Nb_3Sn technology focuses on DC applications that utilize large transport currents. Requirements for DC applications are, however, significantly different (fine grains and slightly off-stoichiometric, dirty Nb_3Sn for increased pinning efficiency and high H_{c2}) than for RF superconductivity (large grains, approaching stoichiometry and clean for high T_c, H_{c1} and low ρ_n).

For transport current applications the A15 phase is usually formed in the presence of a few percent Cu which catalyzes the formation reaction by destabilizing the Sn-rich line compounds combined with a – suggested – lowering of the melt temperature. This allows for a lower temperature formation reaction, typically between 650 and 700 °C, which is in transport applications required to prevent grain growth, since the grain size increases exponentially with reaction temperature [14].

The critical parameters depend strongly on the Sn content in the A15 phase. From measurements, it is known that from 18 to 25 at.% Sn, T_c changes from about 6 K to 18.3 K, $\Delta(0)$ from about 1 to 3.4 meV, and $\mu_0 H_{c2}$ ranges from about 6 to 30 T. Fortunately, there are strong indications that the stoichiometric composition is preferred towards lower temperatures (< 1000 °C), i.e. the perfect ordered state apparently represents the lowest total energy. Above about 24.5 at.% Sn, however, the cubic A15 phase becomes unstable below $T_m \cong 43$ K and the lattice undergoes a spontaneous cubic to tetragonal distortion ($c/a \cong 1.0035$). This tetragonal distortion causes a reduction in T_c of about 0.2 K and reduces $\mu_0 H_{c2}$ from 30 T at 24.5 at.% Sn to 20 T at stoichiometry. The normal state resistivity ranges from about 90 $\mu\Omega$cm at 18 at.% Sn to below 5 $\mu\Omega$cm for a stoichiometric single crystal.

Influences of grain size are mainly reported in relation to the maximum pinning force in the vortex state. Intuitively, the critical fields and temperature are not expected to be significantly influenced by grain size (though boundary effects could influence the overall Δ, as is known from tunneling experiments) but, to the author's knowledge, no specific results are available on the dependence of T_c and critical fields on grain size. Grain size most probably influences ρ_n but again, to the author's knowledge, no specific results which relate the resistivity to grain size are available.

Strain, or lattice distortions in general, strongly influence the critical parameters of the A15 phase and indications are that the effects of strain are increased towards higher ordered (i.e. Sn-richer) A15 compositions. In general, optimal properties are obtained in the strain free state and the presence of strain will cause a reduction of the critical parameters. Strain, whether originating from neighboring materials with a different thermal contraction and/or lattice mismatch or originating from lattice imperfections, has therefore to be prevented. In [12] a correlation is suggested between off-stoichiometry, strain, thermal disorder, irradiation, tetragonal distortions, etc. All affect the long range order and thus Nb-chain continuity. In general, the superconducting properties of relevance for RF applications appear optimal when perfect ordering is achieved. In this sense, a slight off-stoichiometry at 24.5 at.% Sn could be preferable above a tetragonal distortion at stoichiometry. For transport current applications this is specifically true due to the large reduction of H_{c2} that results form only a slight tetragonal distortion of the lattice.

The above summary points out the importance to manufacture A15 in (close to) stoichiometric compositions and to prevent any strain. Of the parameters of relevance to RF superconductivity, only compositional influences on T_c, Δ and ρ_n are available. Unfortunately, to the author's knowledge, no investigations on the dependence of H_c and H_{c1} on composition are available. In addition, it will be desirable to determine the relation of grain size to ρ_n. Since a lower temperature A15 formation reaction is preferable for large scale cavity manufacture, it will also be desirable to investigate the effect of the presence of a few percent Cu on ρ_n. Intuitively, one might expect Cu to increase scattering and, hence, increase ρ_n. Nevertheless, since Cu is insoluble in A15, it is present only at the grain boundaries rendering prediction of its effect on ρ_n less straightforward. Even though limited information is available for off-stoichiometric compositions, the benefits of Nb_3Sn compared to Nb can be demonstrated for compositions approaching stoichiometry and it will be discussed below how Nb_3Sn can be beneficial for application in RF cavities in bulk form and specifically as thin film.

Potential of Nb_3Sn for bulk cavities

The prime parameter for RF losses in bulk cavities is R_{BCS}. From (1), due to an exponential dependence on T_c, the two times higher T_c with respect to Nb will result in a smaller R_{BCS} and therefore higher Q_0, despite the larger penetration depth. Demonstrated specifically at $T = 4.2$ K (and 500 MHz): For close to stoichiometric Nb_3Sn (i.e. 24.5 at.% Sn), ρ_n drops to below 20 $\mu\Omega$cm as a result of perfect ordering of the stoichiometric phase, providing the potential for $R_{BCS} < 2$ nΩ (from the nomogram in [9]), which is significantly lower than around $55\text{n}\Omega$, as provided by Nb cavities. Q_0 for bulk Nb_3Sn cavities thus has the potential to be significantly higher than found in Nb cavities. Nb_3Sn cavities, manufactured through a Sn vapor technique, indeed exhibit a Q_0 that is a factor two larger than for Nb at $T = 2$ K [15]. More importantly, however, at $T = 4.2$ K, Q_0 is nearly two orders of magnitude larger for Nb_3Sn than for Nb and comparable to Nb at $T = 2$ K, due to the ratio T_c/T in (1). This demonstrates the ability for Nb_3Sn cavities to operate at $T = 4.2$ K, i.e. much more cost effective than Nb at superfluid Helium at $T = 2$ K. It should be noted, that Nb_3Sn layers which are grown through such a diffusion process, exhibit composition gradients [16] that are very comparable to gradients found in wires [17] and similar property distributions can therefore be expected.

The thermodynamic critical field of Nb_3Sn is much higher than for Nb (Table 1), yielding the potential to more than double E_{acc}. Unfortunately, high Q_0 values in Nb_3Sn cavities are only retained up to about 15 MV/m, after which a linear Q-drop is observed [15] and the highest E_{acc} achieved is limited to below 30 MV/m. This means that, for now, bulk Nb_3Sn cavities do not reach their theoretical limit (> 100 MV/m). This might be attributable to inhomogeneity effects, surface impurities, or simply a shape effect causing a lowered vortex penetration field (i.e. surface irregularities and/or perpendicular field components), causing the penetration field to be closer to the bulk H_{c1} than to H_{sh}. It should be noted that, even though the presence of a superheating field can be demonstrated theoretically, it is not possible to verify whether H_{sh} has indeed been achieved in a practical Nb cavity, as a result of the closeness of H_{c1}, H_{sh} and H_c.

Potential of Nb_3Sn thin films

If a superconducting film is deposited with a thickness d that is smaller than the penetration depth, the Meissner state can retain at magnetic fields that are much higher that the bulk H_{c1}, resulting from an increased parallel H_{c1} in a thin film with $d < \lambda_{eff}$, given by [18]:

$$\mu_0 H_{c1} = \frac{2\phi_0}{\pi d^2} \ln \frac{d}{\tilde{\xi}} \qquad (3)$$

where $\widetilde{\xi} = 1.07\xi_{GL}$. For example, a thin Nb_3Sn film with $d = 20$ nm increases H_{c1} of Nb_3Sn to 5.7 T. In a Nb_3Sn thin film deposited on a normal conductor, however, small perpendicular magnetic field components will destroy the Meissner state since H_{c1} will be reduced by a demagnetization factor d/w, where w represents the width of the Nb_3Sn thin film [6]. Nevertheless, the increased H_{c1} of a thin Nb_3Sn film can be applied to shield bulk Nb from magnetic fields. For example, following [6], if a Nb cavity that can withstand an internal magnetic field of 150 mT is coated with an insulating film and a 50 nm Nb_3Sn layer, the external magnetic field can be as high as about 320 mT. Hence, a Nb_3Sn film coating more than doubles the vortex penetration field of a Nb cavity, potentially enabling an E_{acc} of order 100 MV/m. Obviously, these ideas are very promising for a reduction of the required length of a linear accelerator, but involve significant technological challenges and their practical validity remains to be demonstrated.

SUGGESTIONS FOR FUTURE RESEARCH

The potential of Nb_3Sn to enhance the prime parameters for superconducting cavities, i.e. Q_0 and E_{acc} with respect to Nb is evident. Nevertheless, further research is required to determine the practical validity. Since most available literature on Nb_3Sn focusses on transport current capacity optimizations, specific research that is specifically targeted at RF superconductivity is desired.

Composition dependence of H_{c1} and H_c Compositional inhomogeneities are inevitable in diffusion based A15 formation processes and, even though it might be possible to create – quasi – homogeneous thin films, stoichiometry is not necessarily the optimal composition (minimum R_{BCS} for $\xi \cong \ell$, tetragonal distortions). It is therefore required to know how the key critical magnetic fields, H_{c1} and H_c vary with composition.

Presence of Cu The fact that a few percent Cu can significantly reduce the A15 formation temperature can be very desirable for large scale cavity manufacture. It is evident that Cu is insoluble in the A15 phase and most literature suggests that Cu therefore is present only at the grain boundaries. It is unclear, however, how a – limited – presence of Cu influences ρ_n. This should be investigated to find out whether a lower temperature formation reaction is a realistic option for cavity manufacture.

Effects of grain size Granularity will negatively affect ρ_n. It is not known for Nb_3Sn, however, how severe this effect is and therefore how much care should be taken to manufacture large grains. This is related to the presumed presence of Cu at the grain boundaries or, more general, what exactly is present at the grain boundaries. From transport current optimizations it is clear that the grain boundaries act as the main pinning centers, but it is unknown what causes minima in the superconducting wave function at grain boundaries. Investigating specifically the morphology and composition of grain boundaries is a subject that only recently emerged in the transport current community, but is also of major importance to the RF community. Investigating how ρ_n varies with grain size and which physics at grain boundaries presumably increases ρ_n is therefore important to both communities.

Manufacturing issues Experiments need to be performed to investigate to what extend Nb_3Sn can be formed in bulk and thin films, with properties that are optimized for RF superconductivity applications. Bulk materials can be manufactured from powder or through diffusion based processes. The Wuppertal Nb_3Sn cavities [15] demonstrate the possibility to manufacture large scale bulk systems. Nevertheless, small-scale bulk samples are useful for basic property characterizations (H_{c1}, H_c, ρ_n, etc.), provided they are sufficiently homogeneous and dense.

Thin films with well-defined properties have been successfully manufactured already in the late 1970's (see e.g. the work of Beasley and co-authors referenced in [12]) and proved very useful in investigating property dependencies on composition. Using more modern and promising techniques such as vacuum arc deposition [19] could be a route to single- and multilayer thin films that incorporate Nb_3Sn. Specifically vacuum arc deposition is highlighted since this technique results in very dense films with a nano-meter scale surface roughness on Nb films [20] and appears scalable to cavity-size manufacture. However, its applicability for Nb_3Sn has not yet been investigated.

SUMMARY

It is clear that Nb_3Sn has significant potential for RF cavity applications, due to the materials' superior intrinsic properties compared to Nb. Specifically for bulk cavities, it has the potential to increase the cavity quality factor at 4.2 K about two orders of magnitude above Nb values and to more than double the accelerating efficiency per unit length. In multi-layer coated bulk Nb cavities, it has the potential to shield the bulk from vortex penetration, rendering even higher gains in accelerator efficiency per unit length possible. Further research is required, however, to investigate to what extend these promises can be fulfilled.

Much literature is available on the fundamental properties of Nb_3Sn, but most is specifically focussed on transport current improvements. Important data on fundamental properties for RF superconductivity are missing, specifically in relation to Nb_3Sn's composition dependence. Further research is therefore suggested to expand the available results towards fundamental properties that are of key importance to RF superconductivity.

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