Proof-of-principle demonstration of Nb$_3$Sn superconducting radiofrequency cavities for high $Q_0$ applications

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Superconducting radiofrequency (SRF) cavities are electromagnetic resonators used to generate large electric fields for accelerating charged particle beams in applications such as light sources,1,2 neutron sources,3,4 and colliders.5,6 The small surface resistance $R_s$ of the superconducting material on the surface of the cavities minimizes the power dissipated in the walls by surface currents, allowing the cavities to operate with up to 100% duty factor even at high fields. However, the superconducting materials require operation at cryogenic temperatures, where thermodynamic efficiency is small. As a result, high duty factor particle accelerators with many cavities require a large cryogenic plant to make up a significant part of the overall cost of the facility. This contribution is discussed.

A number of alternative superconductors are under investigation to reduce cryogenic costs,7,8 but, to date, performances have not been strong enough to justify the replacement of niobium, the standard material used in state-of-the-art high duty factor accelerators. One very promising material is Nb$_3$Sn, which has critical temperature $T_c$ and critical field $H_c$ approximately twice that of niobium, allowing Nb$_3$Sn cavities to meet many other important criteria for SRF cavities, including: ability to fabricate the material with a high degree of uniformity over a large, complex geometry; ability to clean the superconductor using known methods; and reasonably large coherence length $\xi$.9

Proof-of-principle demonstration of Nb$_3$Sn superconducting radiofrequency cavities for high $Q_0$ applications

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Many future particle accelerators require hundreds of superconducting radiofrequency (SRF) cavities operating with high duty factor. The large dynamic heat load of the cavities causes the cryogenic plant to make up a significant part of the overall cost of the facility. This contribution can be reduced by replacing standard niobium cavities with ones coated with a low-dissipation superconductor such as Nb$_3$Sn. In this paper, we present results for single cell cavities coated with Nb$_3$Sn at Cornell. Five coatings were carried out, showing that at 4.2 K, high $Q_0$ out to medium fields was reproducible, resulting in an average quench field of 14 MV/m and an average 4.2 K $Q_0$ at quench of $8 \times 10^9$. In each case, the peak surface magnetic field at quench was well above $H_{c1}$, showing that it is not a limiting field in these cavities. The coating with the best performance had a quench field of 17 MV/m, exceeding gradient requirements for state-of-the-art high duty factor SRF accelerators. It is also shown that—taking into account the thermodynamic efficiency of the cryogenic plant—the 4.2 K $Q_0$ values obtained meet the AC power consumption requirements of state-of-the-art high duty factor accelerators, making this a proof-of-principle demonstration for Nb$_3$Sn cavities in future applications. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [http://dx.doi.org/10.1063/1.4913247]

Pioneering research into Nb$_3$Sn for SRF applications began in the 1970s and involved many laboratories.10–16 An important program to highlight is that of University of Wuppertal, in which niobium cavities with shape and frequency appropriate for particle accelerator applications were coated with a thin layer of Nb$_3$Sn.17 These cavities achieved high quality factor $Q_0$ at small accelerating electric fields $E_{acc}$, but strong $Q$-slope (decrease in $Q_0$ with field) was observed, preventing the cavities from being useful in applications. This degradation was consistently observed to occur when the peak surface magnetic field $H_{pk}$ reached the lower critical field $H_{c1}$ of the Nb$_3$Sn coating.18,19 This led to a hypothesis that Nb$_3$Sn cavities would be limited by strong losses caused by the penetration of flux beginning at $H_{c1}$.18,20

A Nb$_3$Sn SRF program began at Cornell University in 2009, building on the work of previous researchers. After demonstrating the ability to reliably fabricate high quality Nb$_3$Sn coatings on small samples21 via the vapor diffusion process,22 single cell 1.3 GHz niobium cavities were coated and tested. Early results23 showed high $Q_0$ at accelerating fields significantly higher than those achieved by Wuppertal and for peak surface magnetic fields significantly higher than $H_{c1}$. This showed that $H_{c1}$ is not a fundamental limit for SRF cavities, but the maximum fields achieved were still somewhat smaller than are generally used in applications, and it had not been established if this result was reproducible. In this paper, results are presented, demonstrating (1) reproducible high $Q_0$ on the order of $10^{10}$ at 4.2 K, (2) reproducible sustaining of this high $Q_0$ to useful gradients $\sim$14 MV/m, and (3) reproducible $H_{pk}$ significantly higher than $H_{c1}$ with no strong degradation, showing that it is not a limit. The impact of these results on future high duty factor accelerators is discussed.
A single cell 1.3 GHz ERL-shape cavity, which shall be called cavity 1, was coated with Nb₃Sn at Cornell. After RF performance evaluation, it received a buffered chemical polish (BCP) to remove several micrometers of material from the surface, exposing the niobium of the substrate. The cavity was then coated and evaluated again. This process was repeated twice more for a total of four coatings. Details of the coating procedure and apparatus are discussed elsewhere. A second single cell 1.3 GHz cavity with TeSLA shape, cavity 2, was prepared with electropolish (EP), coated, and evaluated. The performance curves of these coatings are presented in Fig. 1.

In each case, \( Q_0 \) at 4.2 K on the order of 10⁶ was maintained at \( E_{\text{acc}} \) above 10 MV/m, where the cavities were limited by quench. The average quench field was 14 MV/m, and the average \( Q_0 \) at quench was \( 8 \times 10^6 \). In one coating, a maximum field of 17 MV/m was achieved. Moderate \( Q \)-slope was observed in each case, but it is far less strong than that observed by Wuppertal researchers.

The BCS material parameters from each coating were extracted from measurements of \( Q_0 \) and resonant frequency as a function of temperature \( T \), as described in Ref. 27. The results are shown in Table I, along with critical fields calculated from the material parameters. In each case, \( H_{pk} \) at the quench field is significantly higher than \( H_{c1} \), further demonstrating that it is not a fundamental limit for these cavities.

Next, we consider implications of these results for high duty factor SRF accelerators that would benefit from reduced power consumption. If the surface resistance is approximately constant over the cavity surface, \( Q_0 \) is related to \( R_s \) according to \( Q_0 = G/R_s \), where \( G \) is a constant that depends only on the geometry of the cavity (\( G = 272 \Omega \) for cavity 1 and 278 Ω for cavity 2). \( R_s \) is often separated into two components: the temperature-dependent BCS resistance \( R_{\text{BCS}} \), which can be calculated from BCS theory given material parameters, frequency, and temperature, and the temperature-independent residual resistance \( R_{\text{res}} \), which is determined by factors such as impurity content and trapped flux. At a given field, \( Q_0 \) increases exponentially due to the BCS component as the temperature is decreased below \( T_c \), then \( Q_0 \) levels off as \( R_{\text{res}} \) becomes smaller than the constant \( R_{\text{BCS}} \). \( R_{\text{BCS}} \) was calculated for the material parameters of the first coating of cavity 1 in Table I, and the corresponding \( Q_0 \) is plotted in Fig. 2, along with \( Q_0 \) vs \( T \) data measured during the experiment. At low \( T \), \( R_{\text{res}} \) dominates, and at high \( T \), the penetration depth is large, allowing magnetic field to leak into the normal conducting niobium substrate, resulting in lower \( Q_0 \) than predicted for a fully Nb₃Sn layer.

The current state-of-the-art preparation to achieve the highest \( Q_0 \) in niobium SRF cavities is nitrogen doping. Also plotted in Fig. 2 is \( Q_0(T) \) predicted by BCS theory for nitrogen-doped niobium, based on material parameters from a cavity in Ref. 35 at 16 MV/m, the planned operating gradient for cavities in both LCLS-II and the Cornell ERL.

To achieve high \( Q_0 \) in Nb cavities, it is necessary to cool the liquid helium bath to around 2 K. Nb₃Sn offers high \( Q_0 \) at considerably higher temperatures, even close to 4.2 K, the boiling point of liquid helium at atmospheric pressure. Operation near atmosphere would simplify cryogenic plants, reducing infrastructure costs. In addition, operation at higher temperatures can significantly reduce AC power requirements. The efficiency of a cryogenic plant is determined by the inverse coefficient of performance (COP⁻¹), which is strongly temperature dependent. For example, for a bath temperature of 2 K, approximately 830 W of input power is needed.

### Table I

Comparison of extracted parameters and critical fields from five cavity coatings. Parameters presented are critical temperature \( T_c \), reduced energy gap \( \Delta/k_B T_c \), mean free path \( l \), residual resistance \( R_{\text{res}} \), penetration depth \( \lambda \), coherence length \( \xi \), Ginzburg-Landau parameter \( \kappa \), and lower critical field \( H_{c1} \). All parameters are given at \( T = 0 \) and \( E_{\text{acc}} \sim 1 \) MV/m. London penetration depth \( \lambda_{L} \) and intrinsic coherence length \( \xi_0 \) are from Ref. 29.

| Property          | Cavity 1 Coating 1 | Cavity 1 Coating 2 | Cavity 1 Coating 3 | Cavity 1 Coating 4 | Cavity 1 Coating 1 | Cavity 2 Coating 1 | Derivation                                      |
|-------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|-------------------------------------------------|
| \( T_c \) (K)     | 18.0 ± 0.1         | 18.0 ± 0.1         | 18.0 ± 0.1         | 18.0 ± 0.1         | 18.0 ± 0.1         | 18.0 ± 0.1         | Measured from \( f \) vs \( T \)               |
| \( \Delta/k_B T_c \) | 2.5 ± 0.2          | 2.5 ± 0.2          | 2.6 ± 0.2          | 2.25 ± 0.12        | 2.5 ± 0.2          | 2.5 ± 0.2          | Combined fit to \( Q \) vs \( T \) and \( f \) vs \( T \) |
| \( l \) (nm)      | 3.0 ± 1.0          | 1.7 ± 1.0          | 2.4 ± 1.0          | 4.8 ± 2.0          | 1.7 ± 1.0          | 1.7 ± 1.0          | Combined fit to \( Q \) vs \( T \) and \( f \) vs \( T \) |
| \( R_{\text{res}} \) (Ω) | 9.5 ± 1.5          | 10.3 ± 1.2         | 21 ± 2             | 8.5 ± 1.2          | 7.2 ± 1.0          | 7.2 ± 1.0          | Combined fit to \( Q \) vs \( T \) and \( f \) vs \( T \) |
| \( \lambda \) (nm) | 161 ± 25           | 198 ± 50           | 174 ± 32           | 139 ± 23           | 198 ± 50           | 198 ± 50           | \( \lambda_{L} \left[ \frac{1}{1 + \frac{\xi_0}{T}} \right] \) (Ref. 30) |
| \( \xi \) (nm)    | 3.0 ± 0.4          | 2.4 ± 0.6          | 2.8 ± 0.4          | 3.4 ± 0.5          | 2.4 ± 0.6          | 0.739 ± 0.006      | \( \xi_0^2 \left[ \frac{\lambda}{\lambda_{L}} \right]^{-1/2} \) (Ref. 31) |
| \( \kappa \)      | 54 ± 11            | 82 ± 28            | 63 ± 16            | 41 ± 9             | 82 ± 28            | 82 ± 28            | \( \frac{\lambda}{\sqrt{T}} \) (Ref. 30) |
| \( \mu_0 H_{c1} \) (mT) | 29 ± 2             | 21 ± 2             | 25 ± 2             | 36 ± 3             | 21 ± 2             | 21 ± 2             | \( \frac{\lambda_0}{\mu_0} \) (Ref. 29) |
| \( E_{\text{acc}}/H_{c1} \) (MV/m) | 6.8 ± 0.5          | 4.9 ± 0.5          | 6.0 ± 0.5          | 8.5 ± 0.7          | 4.9 ± 0.5          | 4.9 ± 0.5          | \( H_{c1}(E_{\text{acc}}/H_{c1}) \) |
| \( E_{\text{acc, max}} \) at 4.2 K (MV/m) | 13 ± 1             | 15 ± 1             | 13 ± 1             | 17 ± 2             | 11 ± 1             | 11 ± 1             | ... |

FIG. 1. \( Q_0 \) at 4.2 K as a function of \( E_{\text{acc}} \) for five Nb₃Sn coatings of single cell 1.3 GHz SRF cavities. Uncertainty in \( Q_0 \) and \( E_{\text{acc}} \) is approximately 10%.
needed to remove 1 W of heat. At 4.2 K, COP\(^{-1}\) is on the order 240 W/W, a factor of 3.5 smaller than the 2 K value.

The AC power required to cool a cavity is given by

\[
P_{AC} = \frac{\text{COP}^{-1} E_{acc}^2 L^2}{R_a Q_0},
\]

where \(R_a\) is the shunt impedance, \(R_a/Q_0\) is a constant that depends only on the geometry of the cavity, and \(L\) is the active length of the cavity. It is illustrative to present cavity performance in terms of \(P_{AC}/E_{acc}^2\) instead of \(Q_0\), as this allows direct comparison of real cryogenic requirements even between different operating temperatures. By additionally presenting performance in terms of \(P_{AC}/E_{acc}^2\) per cell, cavities with similar shapes but different numbers of cells can be compared.

In Fig. 3, \(P_{AC}/E_{acc}^2\) per cell vs \(E_{acc}\) is shown for the fourth coating of cavity 1. In addition, the \(E_{acc}\) at which \(H_{pk} = H_{c1}\) extracted in Table I is shown in the shaded region, the width of which takes into account uncertainty. No strong increase in the required \(P_{AC}\) is observed at this field, illustrating that \(H_{c1}\) is not a limiting field for this cavity. Moderate \(Q\)-slope is observed, which measurements at other temperatures suggest is due to an increase in \(R_{res}\). However, even with this \(Q\)-slope, the \(P_{AC}/E_{acc}^2\) per cell of the Nb\(_3\)Sn cavity at 16 MV/m is still smaller than that of the LCLS-II and the Cornell ERL target values, which are also shown in the figure. The Nb\(_3\)Sn cavity exceeds the specifications for both accelerating gradient and cryogenic efficiency for these planned high duty factor projects.

Fig. 4 presents \(P_{AC}/E_{acc}^2\) per cell as a function of temperature. Both Nb\(_3\)Sn and Nb curves are shown, calculated from BCS theory. For the Nb cavity, calculations were performed using the BCS material parameters for nitrogen-doped niobium that were used in Fig. 2, together with the specified \(R_{res} = 5 \, \text{n}\Omega\) for LCLS II. For the Nb\(_3\)Sn cavity, material parameters from the fourth coating of cavity 1 were used in the calculation, and three different values of \(R_{res}\) are shown: 9 n\(\Omega\) corresponds to \(E_{acc}\) values \(\sim 1\) MV/m, 29 n\(\Omega\) corresponds to \(E_{acc}\) values \(\sim 16\) MV/m, and 3 n\(\Omega\) corresponds to an extremely small \(R_{res}\) value measured in a Wuppertal cavity at low fields.\(^{19}\)

The figure shows the potentially large reduction in \(P_{AC}\) for Nb\(_3\)Sn compared to Nb at optimal temperatures. With the \(R_{res}\) of cavity 1 at 16 MV/m, the power requirements at 4.2 K are approximately equal to that of Nb at 2 K, the planned operation temperature of LCLS-II. With increased development, it is expected that \(R_{res}\) values can be improved, as they have been with Nb cavities. If the low field \(R_{res}\) value of 9 n\(\Omega\) can be maintained out to 16 MV/m, the power consumption would be decreased to approximately one third of the LCLS-II specification. If \(R_{res}\) can be further decreased to 3 n\(\Omega\), power consumption would be smaller than one seventh of the specification.

In this paper, results were presented from five Nb\(_3\)Sn coatings of single cell 1.3 GHz SRF cavities. High \(Q_0\) at 4.2 K was maintained reproducibly out to medium fields, with an average quench field of 14 MV/m and an average \(Q_0\) at quench of \(8 \times 10^9\). For the coating with the best performance, the quench field was 17 MV/m, higher than the operating gradient specifications of several near future high duty factor SRF accelerators (LCLS-II\(^{11}\) and PIP-II\(^{37}\)), \(\sim 16\) MV/m. The required AC power for this Nb\(_3\)Sn cavity was compared to that of nitrogen-doped niobium cavities. The higher \(T_c\) of Nb\(_3\)Sn compared to Nb, with nearly double the \(T_c\) of Nb (indicated with dashed lines), offers four times the performance in terms of active length of the cavity. It is illustrative to present cavity performance in terms of \(Q_0\), as this allows direct comparison of real cryogenic requirements even between different operating temperatures. By additionally presenting performance in terms of \(P_{AC}/E_{acc}^2\) per cell, cavities with similar shapes but different numbers of cells can be compared.

**FIG. 2.** \(Q_0\) vs \(T\) from BCS theory for cavity 1 compared to measurement. Nb\(_3\)Sn, with nearly double the \(T_c\) of Nb (indicated with dashed lines), offers high \(Q_0\) even at relatively high temperatures. The extracted \(R_{res}\) of 9.5 \(\pm\) 1.5 n\(\Omega\) is indicated with a horizontal line.

**FIG. 3.** Normalized AC power required to cool a 1.3 GHz cavity as a function of gradient. Coating 4 of cavity 1 exceeds the cryogenic efficiency specification for both LCLS-II and the Cornell ERL. It also exceeds the gradient specifications and shows no strong \(Q\)-slope even well above \(H_{c1}\).

**FIG. 4.** Normalized AC power required to cool a 1.3 GHz cavity as a function of temperature. Depending on residual resistance, Nb\(_3\)Sn cavities at 4.2 K can have significantly improved cryogenic efficiency compared to nitrogen-doped Nb cavities at 2 K.
Nb$_3$Sn allows it to have high $Q_0$ even at high temperatures where thermodynamic efficiency is higher. As a result, the cavity was able to meet the power requirements of planned high duty factor facilities. Continued development is expected to reduce $\tau_{res}$, and in turn the power consumption of Nb$_3$Sn cavities, making them a very promising technology for future high $Q_0$ SRF accelerators. Future research will also focus on reliably achieving this performance level in multicell cavities as well as increasing quench fields for higher gradient applications.

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