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Proof-of-principle demonstration of Nb_3Sn 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_3Sn. In this paper, we present results for single cell cavities coated with Nb_3Sn 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 8×10^9. 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_3Sn cavities in future 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, with cost on the order of 100 million USD and power requirements on the order of a megawatt (see, for example, the planned Linac Coherent Light Source (LCLS) II[1] or the Cornell ERL[2]).

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 SRF accelerators. One very promising material is Nb_3Sn, which has critical temperature $T_c = 18$ K, approximately twice that of niobium, allowing Nb_3Sn cavities to have exceptionally high quality factor Q_0—which indicates extremely small dissipation—at a given temperature. It also meets 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 ξ.[9]

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Pioneering research into Nb_3Sn 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_3Sn.[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 Nb3Sn coating.[18,19] This led to a hypothesis that Nb_3Sn cavities would be limited by strong losses caused by the penetration of flux beginning at H_{c1}.[18,20]

A Nb_3Sn 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_3Sn coatings on small samples[21] via the vapor diffusion process,[22] single cell 1.3 GHz niobium cavities were coated and tested. Early results[23] 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 ~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.

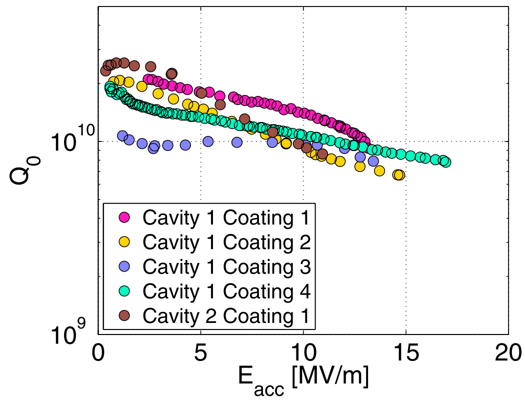

FIG. 1. Q_0 at 4.2 K as a function of E_{acc} for five Nb_3Sn coatings of single cell 1.3 GHz SRF cavities. Uncertainty in Q_0 and E_{acc} is approximately 10%.

A single cell 1.3 GHz ERL-shape[24] cavity, which shall be called cavity 1, was coated with Nb_3Sn 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.[25] A second single cell 1.3 GHz cavity with TeSLA shape,[26] 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 10^{10} was maintained to E_{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 8×10^9. 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.[28]

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 is 272 Ω for cavity 1 and 278 Ω for cavity 2). R_s is often separated into two components: the temperature-dependent BCS resistance R_{BCS}, which can be calculated from BCS theory given material parameters, frequency, and temperature,[32] and the temperature-independent residual resistance R_{res}, which is determined by factors such as impurity content and trapped flux.[33] 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_{BCS} becomes smaller than the constant R_{res}. R_{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_{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 Nb_3Sn layer.

The current state-of-the-art preparation to achieve the highest Q_0 in niobium SRF cavities is nitrogen doping.[34] 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. Nb_3Sn 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.[36,38] For example, for a bath temperature of 2 K, approximately 830 W of input power is

TABLE I. Comparison of extracted parameters and critical fields from five cavity coatings. Parameters presented are critical temperature T_c, reduced energy gap Δ/k_BT_c, mean free path l, residual resistance R_{res}, penetration depth λ, coherence length ξ, Ginzburg-Landau parameter κ, and lower critical field H_{c1}. All parameters are given at $T = 0$ and $E_{acc} \sim 1$ MV/m. London penetration depth λ_L and intrinsic coherence length ξ_0 are from Ref. 29.

Property	Cavity 1 Coating 1	Cavity 1 Coating 2	Cavity 1 Coating 3	Cavity 1 Coating 4	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	Measured from f vs T
Δ/k_bT_c	2.5 ± 0.2	2.5 ± 0.2	2.6 ± 0.2	2.25 ± 0.12	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	Combined fit to Q vs T and f vs T
R_{res} (nΩ)	9.5 ± 1.5	10.3 ± 1.2	21 ± 2	8.5 ± 1.2	7.2 ± 1.0	Combined fit to Q vs T and f vs T
λ (nm)	161 ± 25	198 ± 50	174 ± 32	139 ± 23	198 ± 50	$\lambda_L\sqrt{1+\frac{\xi_0}{l}}$ (Ref. 30)
ξ (nm)	3.0 ± 0.4	2.4 ± 0.6	2.8 ± 0.4	3.4 ± 0.5	2.4 ± 0.6	$0.739\left[\xi_0^{-2}+\frac{0.882}{\xi_0 l}\right]^{-1/2}$ (Ref. 31)
κ	54 ± 11	82 ± 28	63 ± 16	41 ± 9	82 ± 28	λ/ξ (Ref. 30)
$\mu_0 H_{c1}$ (mT)	29 ± 2	21 ± 2	25 ± 2	36 ± 3	21 ± 2	$\frac{\phi_0}{4\pi\lambda^2}(\ln\kappa + 0.5)$ (Ref. 29)
$E_{acc}\vert_{H_{pk}=H_{c1}}$ (MV/m)	6.8 ± 0.5	4.9 ± 0.5	6.0 ± 0.5	8.5 ± 0.7	4.9 ± 0.5	$H_{c1}(E_{acc}/H_{pk})$
$E_{acc,max}\vert_{T=4.2K}$ (MV/m)	13 ± 1	15 ± 1	13 ± 1	17 ± 2	11 ± 1	…

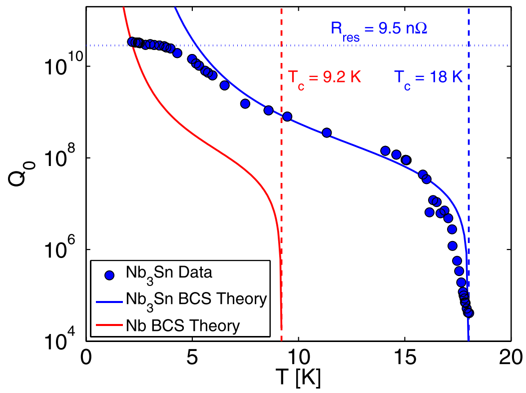

FIG. 2. Q_0 vs T from BCS theory for cavity 1 compared to measurement. Nb_3Sn, with nearly double the T_c of Nb (indicated with dashed lines), offers high Q_0 even at relatively high temperatures. The extracted R_{res} of 9.5 ± 1.5 nΩ is indicated with a horizontal line.

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

$$P_{AC} = \frac{COP^{-1} E_{acc}^2 L^2}{\frac{R_a}{Q_0} Q_0}, \qquad (1)$$

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_3Sn 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_3Sn 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_3Sn 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 $R_{res} = 5$ nΩ for LCLS II. For the Nb_3Sn 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 nΩ corresponds to E_{acc} values ∼1 MV/m, 29 nΩ corresponds to E_{acc} values ∼16 MV/m, and 3 nΩ 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_3Sn 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 nΩ 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 nΩ, power consumption would be smaller than one seventh of the specification.

In this paper, results were presented from five Nb_3Sn 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 8×10^9. 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[1] and PIP-II[37]), ∼16 MV/m. The required AC power for this Nb_3Sn cavity was compared to that of nitrogen-doped niobium cavities. The higher T_c of

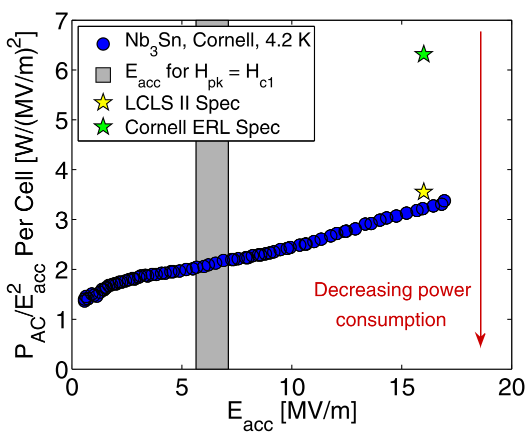

FIG. 3. Normalized AC power required to cool a 1.3 GHz cavity as a function of gradient. Coating 4 of cavity 1 exceeds the cryogenic efficiency specification for both LCLS-II and the Cornell ERL. It also exceeds the gradient specifications and shows no strong Q-slope even well above H_{c1}.

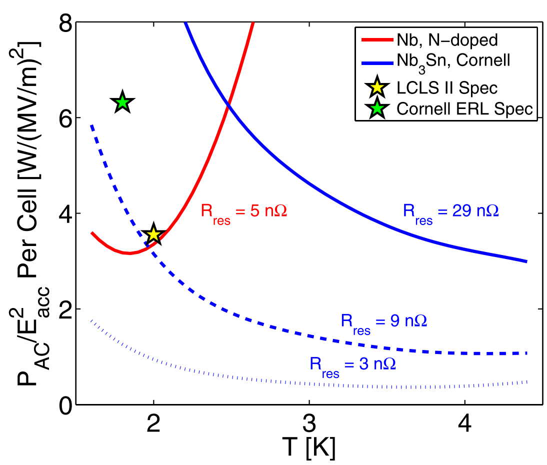

FIG. 4. Normalized AC power required to cool a 1.3 GHz cavity as a function of temperature. Depending on residual resistance, Nb_3Sn cavities at 4.2 K can have significantly improved cryogenic efficiency compared to nitrogen-doped Nb cavities at 2 K.

Nb_3Sn 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 R_{res} and in turn the power consumption of Nb_3Sn 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 multi-cell cavities as well as increasing quench fields for higher gradient applications.

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