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Rapid Communication

Demonstration of $E_{acc} = 10$ MV/m with Nb_3Sn cavities in a cryomodule

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Abstract. Cryomodules with superconducting cavities are a common part of many modern accelerators. There is a significant benefit to a wide range of accelerators, if niobium material, commonly used now, can be replaced with Nb_3Sn material. A cryomodule was built for the first time with two five-cell 1.5 GHz superconducting radiofrequency Nb cavities coated with Nb_3Sn. It has attained an accelerating gradient of $\geq$10 MV/m with low cryogenic loss at 4 K.

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1. Introduction

Many large accelerators for nuclear physics and high energy physics research, which are built or proposed to be built, plan to use cryomodules with superconducting accelerating structures[1, 2, 3, 4, 5, 6, 7, 8, 9]. Several smaller accelerators for fundamental research also stand to gain from and use or plan to use cryomodules[10, 11, 12, 13, 14]. Efficient high-gradient cryomodules can be enabling technology for future particle physics as well as a number of industrial applications. Several research and development efforts are underway to develop such solutions[15, 16, 17, 18].The efficiency, energy gain, and operation temperature of the modules drive the operating and capital costs. Advances in these areas are enabling future accelerators. While superconducting cavities are currently made of niobium (Nb), Nb_3Sn—with its superconducting transition temperature and superheating field approximately twice that of Nb—is poised to replace Nb, substantially improving operating efficiency at any given temperature and increasing energy gain.

Superconducting accelerators, which are being built or planned to be built, utilize superconducting cavities made out of niobium. Niobium material for superconducting applications has been highly developed over the years and offers high gradients and high quality factors for $\approx$ 1 GHz cavities. Niobium cavities also typically require operation at 2 K, which is supported by sophisticated cryogenic facilities that provide sub-atmospheric helium baths for SRF cavities. An alternative, which can provide a better performance at 4.2 K, is Nb_3Sn compound. With its superconducting transition temperature of about 18 K, this material offers almost two orders of magnitude high quality factors and have potential to sustain a factor of two higher accelerating fields.

Over the past 15 years, research efforts have significantly improved RF properties of Nb_3Sn material in SRF cavities. The best Nb_3Sn-coated R&D cavities reach accelerating gradients of 23-24 MV/m with Q0 $\approx 10^{10}$[19]. Such accelerating gradient is still a factor of two lower than what can be reached with niobium material, but its attainment at 4 K versus 2 K is very attractive for smaller accelerator, where the cost of 2 K cryoplant and its operation makes such facility not feasible. This appeal lead to the development of Nb_3Sn coatings on practical accelerator cavities and to the significant progress, where multi-cell accelerator cavities such as CEBAF 5-cell accelerator cavities and ILC 9-cell accelerator cavities reached accelerating gradients of 15 MV/m[19, 20].

2. Cavity qualification

An original CEBAF quarter cryomodule was refurbished with two Nb_3Sn-coated cavities. Two CEBAF-style 5-cell 1.5 GHz cavities, 5C75-RI-NbSn1 and 5C75-RI-004, built by RI Research Instruments, GmbH, were used as substrates for Nb_3Sn coating. C75-RI-NbSn1 cavity cells were made out of fine grain material, and 5C75-RI-004 cavity cells were made out of large grain niobium material. For the baseline surface preporation, 100 - 120 μm were removed with electropolishing from RF surface of the cavities. The cavities were then annealed in a vacuum furnace at 800 °C for 2 - 3 hours, and were electropolished for 25 - 30 μm more as the final surface removal step. Both cavities exhibited quality factors and maximum gradients typical of the applied SRF cavity processing, Fig. 1.

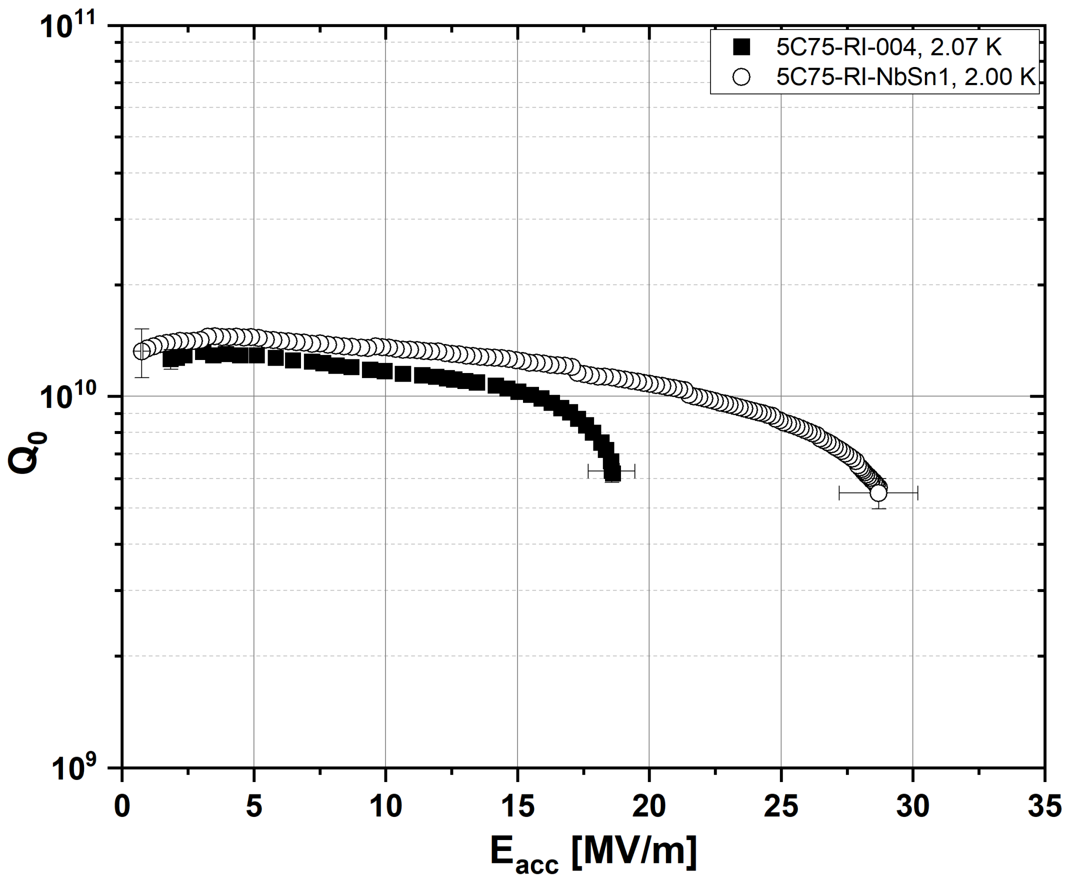

Figure 1. Baseline test of two niobium cavities used as substrates for Nb_3Sn coating.

Before Nb_3Sn coating, 5C75-RI-NbSn1 needed to be re-processed. It received 25 μm electropolishing removal at Argonne National Lab to reset the niobium surface. The cavity was then anodized in the diluted sulfuric acid solution using 30 V DC.Anodized cavity was installed horizontally into the cavity coating chamber in the vacuum furnace at Fermilab. The cavity was annealed for 23 hours at 140 °C for de-gassing, then the coating process was initiated. The coating process included a fast ramp of Sn and $SnCl_2$ sources to about 700 °C followed by reducing and keeping the temperature at 500 ° C for 5 hours. The furnace temperature was raised to 1100 °C, while the sources were at ≈ 200 °C higher temperature than the furnace. These temperatures was maintained for 3 hours before turning the coating sources off and annealing for 1 hour with the furnace heaters only. 5C75-RI-004 cavity was coated at Jefferson Lab. The cavity coating assembly included three coating sources positioned inside the vertically oriented cavity: first source at the upper cell, second source at the middle cell, and the third source at the lower cell of the cavity. The coating sources included Sn shots and $SnCl_2$ powder packaged in separate niobium foils. The coating temperature profile consisted of 12 h of baking at 120 ± 5°C for degassing, 6 h of nucleation at 540 ± 5 °C, and 6 h of coating growth at 1200 ± 10°C coating steps[21]. The cavity was found uniformly coated during visual inspection after coating.

After the cavity qualification tests, Fig. 2, the cavities were assembled into the cavity pair. During pumpdown of the cavity pair, a vacuum leak was discovered in the ceramic window of a fundamental power coupler waveguide. The cavities were completely disassembled, ultrasonically cleaned, high pressure water rinsed, assembled with vertical cavity test hardware and tested at 4 K and 2 K. Low-field surface resistance of 5C75-RI-004 cavity increased to about 27 nΩ. While the quality factor of the cavity was still above 10^{10} at 4 K, the cavity now exhibited Q-slope above E_{acc} = 3 MV/m reaching E_{acc} = 8 MV/m with $Q_0 \approx 2{\cdot}10^9$, Fig. 2. 5C75-RI-NbSn1 cavity did not

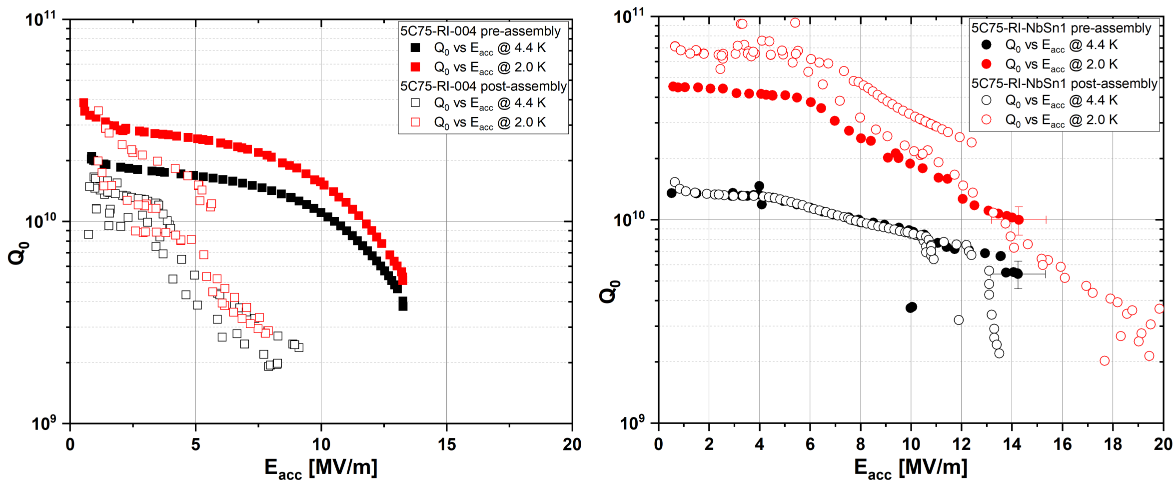

Figure 2. Nb_3Sn-coated cavity performance before[solid points] and after[empty points] the pair assembly with the new mitigation measures implemented. Note that the low-field surface resistance was preserved, but strong Q-slope limits the maximum accelerating gradient for 5C75-RI-004[right plot], and no change in the cavity performance was observed for 5C75-RI-NbSn1[left plot]. After the pair assembly, the cavity reached close to 20 MV/m accelerating gradient.

show any notable change in its performance from the pre-pair assembly qualification test, Fig. 2. Multipacting barrier was observed at around E_{acc} = 15 MV/m both at 4 K and 2 K. After multipacting barrier was processed in the vertical test at 2 K, the cavity reached $E_{acc} \simeq$ 20 MV/m, corresponding to 80 mT of the peak surface magnetic field. This is the best performance and the highest accelerating gradient to-date in Nb_3Sn-coated SRF multicell cavities.

3. Cryomodule cooldown and testing

Special provisions were made for uniform cooldown of this cryomodule, with the target set for below 0.3 K temperature difference across the pair length, when the temperature of the cavities is between 10 K and 20 K.

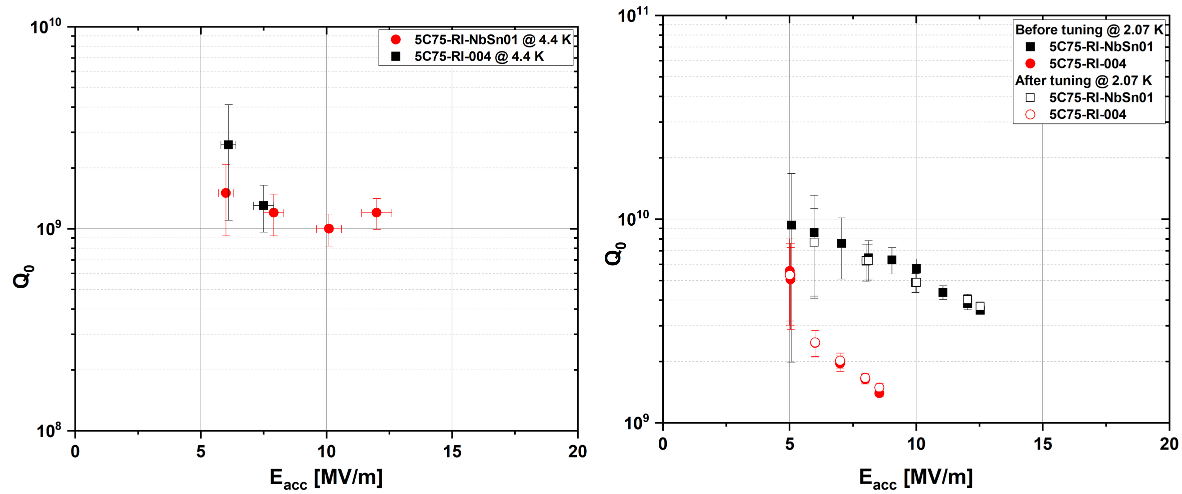

Figure 3. Quality factor as a function of field measured at 4 K[left plot]. Quality factor as a function of field measured at 2K[right plot].

The tuner was not engaged so as to prevent mechanical stresses in the cavity during cooldown. In addition, frequency shift as a function of temperature was monitored and tuner was exercised several times during cooldown to confirm that the cavity was not engaged.

In Fig. 3, quality factor as a function of field at 4.4 K is shown. The quality factor was measured using liquid helium boil-off rate[22]. For both cavities the quality factor was measured to be slightly above 10^9, which is about one order of magnitude improvement over the quality factor of niobium at this frequency and temperature.

In Fig. 3, quality factor as a function of field at 2.07 K is shown. The quality factor was measured using the standard rate of pressure rise technique[22]. The quality factors were close to 10^{10} at low field and exhibited the field dependence similar to what was observed in the last vertical test. Both cavities reached accelerating gradient close to what was measured in the last vertical test. The accelerating gradient results indicate that the cavities did not experience degradation, which was observed in the past and was attributed to mechanical deformation of cavities at room temperature. The cavities, however, had a higher residual resistance than what was observed in the vertical test. The reason for a high residual resistance is not clear yet, but it could be due to different cooldown conditions in the horizontal configuration of cryomodule as compared to the cryogenic cooldown in the vertical dewar.

4. Conclusion

Two Nb_3Sn-coated 5-cell 1.5 GHz SRF cavities were assembled into a cryomodule and tested. The cavities reached the accelerating gradients of $E_{acc} \approx 8$ MV/m and 12 MV/m which are similar to the results in the last vertical dewar test. The Q_0 values reached

10^9 at the highest fields at 4 K.

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References

[1] M Howell et al, SNS proton power upgrade, 2017 IOP Conf. Ser.: Mater. Sci. Eng. 278 012185 DOI 10.1088/1757-899X/278/1/012185

[2] A. L. Klebaner, C. Boffo, S. K. Chandrasekaran, D. Passarelli, and G. Wu, "Proton Improvement Plan – II: Overview of Progress in the Construction", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 182. doi:10.18429/JACoW-SRF2021-MOOFAV05

[3] F. Schlander *et al.*, "The Superconducting Accelerator for the ESS Project", in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 24–28. doi:10.18429/JACoW-SRF2017-MOYA01

[4] Venturini Delsolaro, W., Garlasche, M., Peauger, F. et al. Progress and R/D challenges for FCC-ee SRF. EPJ Techn Instrum 10, 6 (2023). https://doi.org/10.1140/epjti/s40485-023-00094-5

[5] Zhu Z., Zhao Z., Wang D., et al., SCLF: An 8-GeV CW SCRF Linac-Based X-Ray FEL facility in Shanghai 38th Int. Free Electron Laser Conf, FEL'17, Santa Fe, NM, USA, August 20–25, 2017, JACOW, Geneva, Switzerland (2018), pp. 182-184, 10.18429/JACoW-FEL2017-MOP055

[6] L. Gu, X. Su, Latest research progress for LBE coolant reactor of China initiative accelerator driven system project, Front. Energy, 15 (4) (2021), pp. 810-831

[7] R. A. Rimmer, J. P. Preble, K. S. Smith, and A. Zaltsman, "An Overview of RF Systems for the EIC", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1179–1181. doi:10.18429/JACoW-IPAC2021-MOPAB385

[8] T. O. Raubenheimer, "The LCLS-II-HE, A High Energy Upgrade of the LCLS-II", in *Proc. FLS'18*, Shanghai, China, Mar. 2018, pp. 6–11. doi:10.18429/JACoW-FLS2018-MOP1WA02

[9] B. Hong, Overview of the Rare isotope Accelerator complex for ON-line experiments (RAON) project, Journal of Physics: Conference Series, vol. 2586, no. 1, p. 012143, Sep. 2023. doi:10.1088/1742-6596/2586/1/012143

[10] A. Bartnik et al., CBETA: First multipass superconducting linear accelerator with energy recovery, Phys. Rev. Lett. 125, 044803 (2020)

[11] Thomas Planche et al.,ARIEL Accelerator Overview, 2022 J. Phys.: Conf. Ser. 2391 012003

[12] A. Neumann *et al.*, "bERLinPro Becomes SEALab: Status and Perspective of the Energy Recovery Linac at HZB", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1110–1113. doi:10.18429/JACoW-IPAC2022-TUPOPT048

[13] A. A. Aksoy, A. A. Aydin, C. Kaya, B. Ketenoglu, and O. Yavas, "TARLA: The First Facility of Turkish Accelerator Center (TAC)", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2776–2778. doi:10.18429/JACoW-IPAC2017-WEPAB087

[14] F. Hug *et al.*, "Status of the MESA ERL Project", in *Proc. ERL'19*, Berlin, Germany, Sep. 2019, pp. 14–17. doi:10.18429/JACoW-ERL2019-MOCOXBS05

[15] S. Posen et al., "High gradient performance and quench behavior of a verification cryomodule for a high energy continuous wave linear accelerator," Phys. Rev. Accel. Beams, vol. 25, no. 4, Apr. 2022. doi:10.1103/physrevaccelbeams.25.042001

[16] G. Ciovati et al., "Design of a cw, low-energy, high-power superconducting linac for environmental applications," Phys. Rev. Accel. Beams, vol. 21, no. 9, Sep. 2018. doi:10.1103/physrevaccelbeams.21.091601

[17] R. C. Dhuley et al., "Design of a 10 MeV, 1000 kW average power electron-beam accelerator for wastewater treatment applications," Phys. Rev. Accel. Beams, vol. 25, no. 4, Apr. 2022. doi:10.1103/physrevaccelbeams.25.041601

[18] N. A. Stilin *et al.*, "Status Update on Cornell SRF Compact Conduction Cooled Cryomodule", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1299–1302. doi:10.18429/JACoW-IPAC2022-TUPOTK037

[19] S Posen et al Advances in Nb3Sn superconducting radiofrequency cavities towards first practical accelerator applications 2021 Supercond. Sci. Technol. 34 025007

[20] G. Eremeev et al., "Nb3Sn multicell cavity coating system at Jefferson Lab," Rev. Sci. Instrum., vol. 91, no. 7, Jul. 2020. doi:10.1063/1.5144490

[21] U. Pudasaini, C. E. Reece, and J. K. Tiskumara, "Managing Sn-Supply to Tune Surface Characteristics of Vapor-Diffusion Coating of Nb3Sn", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 516. doi:10.18429/JACoW-SRF2021-TUPTEV013

[22] T. Powers, "Theory and Practice of Cavity RF Test Systems", in *Proc. SRF'05*, Ithaca, NY, USA, Jul. 2005, paper SUP02, pp. 40–70.