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FIRST RESULTS FROM A Nb_3Sn-COATED 1.5-CELL 650 MHz SRF CAVITY FOR CRYOGEN-FREE INDUSTRIAL ACCELERATORS*

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Abstract

Fermilab is advancing the development of a compact, high-power electron beam accelerator using superconducting radio frequency (SRF) technology as a non-radioactive alternative to traditional radiological sources. The current design targets continuous-wave (CW) operation at 1.6 MeV and 20 kW. To ensure suitability for industrial environments, the system is being designed for cryogen-free operation, driving the adoption of a novel Nb_3Sn-coated 1.5-cell SRF cavity operating at 650 MHz. This contribution reports on the fabrication, surface preparation, and Nb_3Sn coating process of the cavity, as well as first results from vertical test stand (VTS) measurements performed in a liquid helium bath. These initial tests mark a key milestone toward demonstrating the viability of conduction-cooled Nb_3Sn SRF cavities for industrial-scale deployment.

INTRODUCTION

A meter-long compact linear accelerator (linac) are nowadays being considered to replace traditional radiological sources in many industrial applications driven by growing concerns about security and availability. To compete with alternative methods, the linear accelerator must accelerate electron beams with 1-10 MeV energy, average beam power of hundreds of kW, and in continuous wave (CW) mode. Moreover, it must be robust, cost-effective, and adaptable in harsh industrial settings [1]. Such requirements can be made possible thanks to the recent advancements in the area of, but not limited to, superconducting radio-frequency cavities and conduction cooling technologies [2].

The Illinois Accelerator Research Center (IARC) of Fermilab has currently started the design, construction, and validation of a prototype linac employing a 1.5 cell 650 MHz cavity capable of delivering 12.5 mA of beam current with a beam power of 20 kW, 1.6 MeV beam energy, and in CW mode [3]. Figure 1 shows the schematic of the compact 20 kW linac. The cryostat housing the SRF cavity is about a meter long and a meter in diameter. A small thermionic cathode and low-loss RF coupler are integrated into the cavity, thoroughly designed to minimize the amount of heat generated into the system. Two commercial cryo-coolers are connected to the cavity through 5N aluminum thermal links to provide the necessary cooling capacity via conduction. A key enabler to the usage of this conduction cooling

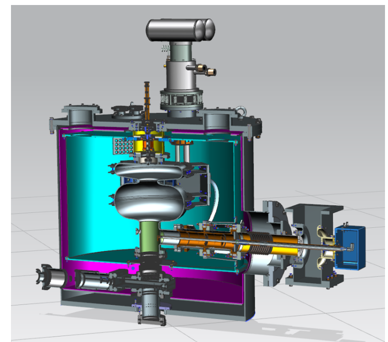

Figure 1: Schematic of 20 kW, 1.6 MeV linac employing 1.5 cell 650 MHz cavity.

technology and therefore allowing cryogen-free operation is the Nb_3Sn superconductor coating on the inner surface of the cavity. The successful demonstration recently of a single cell Nb_3Sn coated 650 MHz cavity showed that a Q_0 above 1×10^{10} and $E_{acc} = 7$ MV/m is feasible for the 1.5 cell 650 MHz cavity geometry [4]. The cavity would induce heat loss to only about 1.5 W, which is less than the 2 W capability of commercial cryo-coolers to remove heat at 4 K [2]. In this contribution, we report the cavity preparation, Nb_3Sn coating, and the first-ever RF result of a Nb_3Sn-coated 1.5 cell 650 MHz cavity under a helium bath. This progress marks a major step towards the first demonstration of a compact superconducting linac for industrial purposes.

CAVITY BASELINE PREPARATION

The SRF cavity used in this work has a length, $L = 0.30$ m, surface geometric factor, $G_s = 197\ \Omega$, peak magnetic field, $B_{pk} = 4.41 * E_{acc}$, and normalized shunt impedance, $r/Q = 178\ \Omega$. For conduction cooling, Nb rings (SRF grade, RRR = 300) were e-beam welded on each cell.

To prepare the inner surface of the cavity for Nb_3Sn coating, we followed the standard procedure for the treatment of the cavities for the International Linear Collider (ILC) with a modified hydrogen degassing step [5]. The Nb cavity received 120 µm bulk EP, 350 °C/12 h baking and 600 °C/10 h for hydrogen degassing, field flatness tuning, and 20 µm light EP with last 10 µm cold EP. Figure 2 illustrates the normalized electric field amplitude along the axis of the cavity between simulated and measured values, the latter obtained using the 'bead-pull' method for field flatness tuning. To reach the desired frequency and the field level between the full cell and the half cell, the full cell was compressed and tuned by 730 kHz.

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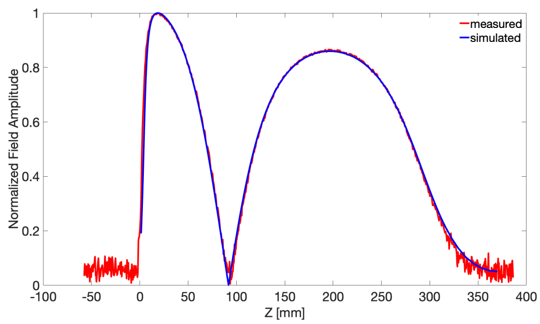

Figure 2: Normalized field amplitude between simulation and measurement.

After the necessary treatment, the cavity was tested under He bath at 2 K and 1.5 K. Instrumentation for this test includes Helmholtz coils to compensate for the ambient magnetic field and ensure that the magnetic field as read by the flux gates (located at the equator of the full cell) is as low as possible. The flux gates read below 3 mG.

Figure 3 shows the unloaded quality factor vs the accelerating gradient at 2 K and 1.5 K. The cavity quenched at E_{acc} = 20 MV/m. The equivalent surface resistance is comparable to what can be expected in cavities processed in the same way and at the same frequency, although this cavity reached a lower maximum E_{acc} [5, 6]. We find that this result is sufficient to proceed with the Nb_3Sn coating.

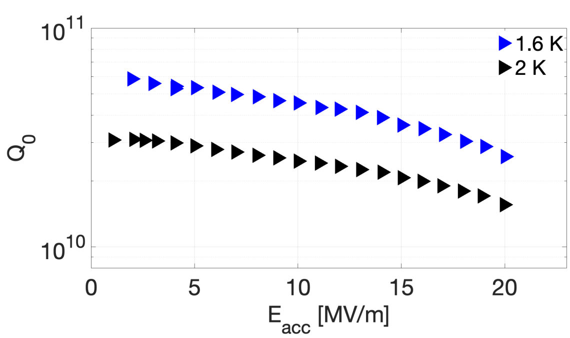

Figure 3: Unloaded quality factor vs the accelerating gradient of the 1.5 cell 650 MHz cavity made of Nb, i.e., baseline.

Nb_3Sn COATING AND RF RESULTS

A number of preparations were needed prior to coating. This cavity has a different geometry than what is often used for basic science studies; hence, a different Nb frame, fork, and flange covers to minimize Ti diffusion from NbTi flanges were designed and fabricated. Figure 4 shows the cavity sitting on the Nb frame. The Nb cavity was anodized, which is a standard step for optimal nucleation of Sn. Moreover, since the cavity is expected to be heated up to 1100 °C for 5 h, creep simulations were performed to quantify the maximum stress on the cavity wall using COMSOL®. Results showed that the maximum stress on the cavity wall is only about

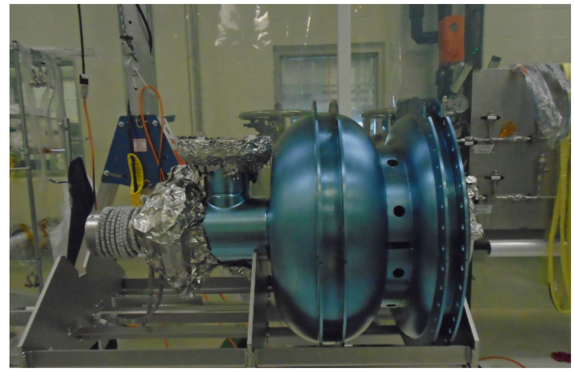

Figure 4: Anodized 1.5 cell 650 MHz prepared for Nb_3Sn coating.

0.85 MPa, less than the estimated rupture stress of 3.8 MPa of refractory Nb [7].

The Nb_3Sn coating was performed using the standard procedure of the vapor-diffusion method with high-temp nucleation [8]. The cavity was degassed for 23 h, then high-temp nucleation was initiated by ramping the source temperature to 700 °C, while the furnace temperature to 500 °C. The furnace remained at 500 °C for 5 h. Afterwards, the source was ramped to 1250 °C for 4.5 h and furnace to 1100 °C for 5 h. Normal cool down of the furnace was done after.

Figure 5 shows the cavity surface after coating. The cavity surface achieved a smooth surface in both cells, often an indication of a sufficiently good coating [8]. Sn spots were observed in some areas, such as the coupler port and the beam tube. However, these areas are less important in terms of RF dissipation.

Figure 5: A photograph of the inner surface of the cavity after coating.

The frequency at room temperature after the coating and prior to the vertical RF test is often monitored to identify if the cavity has cracked along the process, since Nb_3Sn is brittle in nature. It can be seen in the Table 1 that a 500 kHz increase in frequency was observed, even though it is expected that Nb_3Sn coating will have a negligible effect on frequency. Prior to the frequency measurement, the cavity

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received standard vertical RF preparation. The shift in frequency could potentially be due to either the coating or the vertical RF test preparation performed (e.g., full assembly and high-pressure rinse). Although we don't have a current understanding of whether this frequency could induce significant power dissipation, this shift is less than the frequency shift often found in other Nb_3Sn cavities that showed degraded performance [9]. Thus, we proceeded to the vertical RF test of the cavity under a helium bath. Two cool downs were performed to ensure that the cavity performance is not limited by the cool down. We added more thermocouples and flux gates at the half cell during the second cool down. Between these tests, the frequency changed in the order of tens of kHz only.

Table 1: Frequency Obtained at Room Temperature Between VTS Tests

VTS Tests	Pre-VTS [MHz]	Post-VTS [MHz]
Baseline	648.920	N/A
1st cool down	649.398	649.412
2nd cool down	649.412	649.410

Figure 6 shows the temperature and magnetic field level close to the transition where the cool down in Nb_3Sn is critical. It is noticeable that the RTDs have very close temperature readings, while the flux gate readings remained lower than 2 mG of magnetic field.

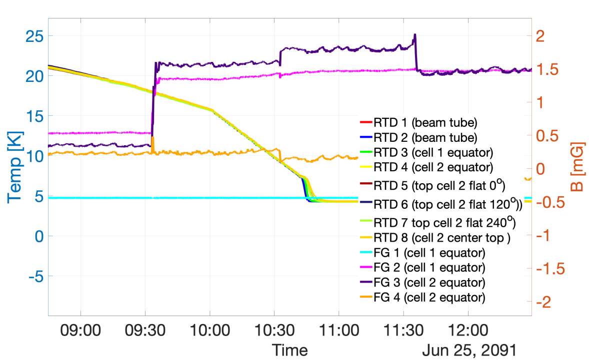

Figure 6: Temperature and magnetic field level close to superconducting transition of Nb_3Sn during second cool down for the vertical RF test.

Figure 7 shows the unloaded quality factor at 4 K and 2 K between cool downs. The two cool downs differ only in how they were performed for 2 K measurements. On the first cool down, after the measurement at 4 K, we cooled down directly to 2 K. Whereas, on the second cool down, after 4 K measurement, we warmed up and cooled down to 2 K. Between cool downs, there is no difference at 4 K as expected. The cavity achieved 5 MV/m with 9.7×10^8, limited by the available RF power. This is significantly lower than what is expected in Nb_3Sn coatings [4]. At 2 K, the second cool down achieved gradient of 8.7 MV/m compared to 6.9 MV/m of the first cool down. This suggests that the residual resistance of the Nb_3Sn coating is sensitive to the cool-down procedure. However, it can be noticed that the Q_0 at low fields is not far from that at 4 K, indicating a high residual resistance in this coating.

We also measured the '0' mode of this cavity. Given the surface geometrical factors and Q_0 of the '0' mode and the 'π' mode, one can estimate the surface resistance in each cell of the cavity. At 2 K and 2 MV/m, we estimated the surface resistance of the full cell to roughly 10 nΩ. On the half cell, the surface resistance is more than an order of magnitude higher. We suspected that the lower performance of the Nb_3Sn coating in the half cell could be due to insufficient nucleation, especially at the equator, as it is far from the line of sight of Sn vapor, although cracking of the Nb_3Sn film could also be a potential source of dissipation.

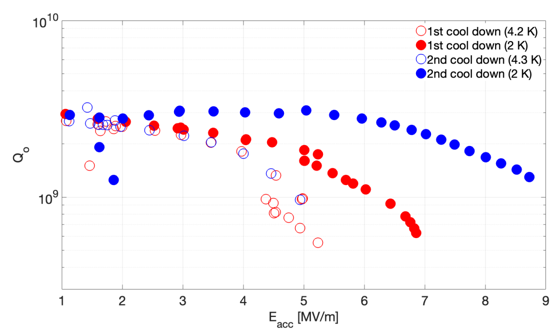

Figure 7: Unloaded quality factor vs the accelerating gradient after Nb_3Sn coating.

SUMMARY AND NEXT STEPS

We have coated the 1.5 cell 650 MHz cavity with Nb_3Sn for the 1.6 MeV and 20 kW prototype superconducting compact linac. Vertical RF test under He bath at 4.4 K achieved maximum accelerating gradient of 5 MV/m with $Q_0 = 9.7 \times 10^8$. Measurement at 2 K showed high residual resistance, but achieved maximum accelerating gradient of 8.7 MV/m with an adequate cool-down method. This poor performance could be due to poor Sn nucleation at the equator of the half cell. Although this performance is lower than what is expected, the next step is to understand if such performance can be used to demonstrate the capabilities of a superconducting linac.

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