Nb_3Sn ON Cu SRF CAVITIES R&D AT INFN LNL*

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Abstract

The successful development of Nb_3Sn / Cu coatings for the SRF cavities of next generation particle accelerators would allow for the operation of the SRF system at 4.5 K, resulting in a reduction of the needed cryogenic power by a factor 3 with respect to what normally needed for bulk Nb cavities, operated at 2 K. In the framework of I.FAST and ISAS collaborations, an optimized recipe for Nb_3Snfilms deposited via DCMS has been established on small samples at INFN-LNL and is discussed in this work. Films with a T_c ≥17 K at deposition temperatures ≤ 650 °C on Cu substrate pre-coated with a 30 µm thick buffer layer of Nb have been successfully produced. The same deposition recipe is RF validated on QPR samples, with the results being also discussed in this work. A surface resistance < 9 nΩ at 4.5 K (at 20 mT, 417 MHz) is measured, which is about a order of magnitude larger than the baseline specifications for the LHC Nb/Cucavities and already fulfills the requirements for the FCC-ee. Finally, the design and development of a dedicated coating system for 1.3 GHz elliptical cavities is discussed.

COATING DEVELOPMENT

T_c Coating Optimization

At INFN-LNL, a standard deposition protocol for Nb_3Snthin films on copper substrates has been developed using direct current magnetron sputtering (DCMS) [1]. The fabrication and characterization of Nb_3Sncoatings was carried out through an iterative feedback process following each deposition. The characterization procedure encompassed the following measurements:

- superconducting critical temperature T_c via inductive method;
- coating morphology analysis by scanning electron microscopy (SEM);
- Nb- Sn stoichiometry determination via energy dispersive X-ray spectroscopy (EDS);
- crystal lattice structure investigation by X-ray diffraction (XRD);

The optimized process is defined by the following parameters:

- Ar sputtering gas pressure: 2×10^{-2} mbar;
- Target surface current density: ≤ 1 mA cm^{-2}
- Substrate temperature: ≤ 650 °C
- Nb buffer layer (NbBL) thickness: ≥ 30 µm (NbBL-30);

Among these, the target surface current density and the NbBL thickness proved to be the most critical parameters in defining a reliable and optimized DCMS deposition recipe. As a result, Nb_3Snfilms deposited on Cusubstrates pre-coated with a NbBL-30 were successfully obtained, achieving a superconducting critical temperature of $T_c \simeq$ 17 K.

Rf Measurements

RF characterization was performed at the quadrupole resonator (QPR) facility [2] at HZB (Berlin, Germany). The QPR is a dedicated sample test cavity for measuring the RF surface resistance R_s of superconducting samples. It consists of a high-RRR Nb cylindrical cavity with two pole-shoe-shaped Nb pipes placed within 1 mm of an interchangeable sample surface. The sample — a 100 mm diameter, 100 mm height high-RRR Nb cylinder coated with a ≥ 1 µm Nb_3Snfilm — is thermally decoupled from the resonator, enabling calorimetric RF-DC compensation measurements of R_s.

The QPR operates at 417 MHz, 850 MHz, and 1300 MHz in superfluid He-4, covering RF fields up to 120 mT and temperatures down to 1.5 K. Beyond R_s, it also provides

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measurements of T_c, RF quench field, and London penetration depth λ_L. A comprehensive description of the setup is given in [3].

The optimized recipe was RF-tested on a bulk Nb substrate at the HZB QPR facility. A critical temperature of 17.2 K was extracted from both frequency shift and quench field data, in good agreement with the values obtained at LNL on small-scale samples through inductive measurements.

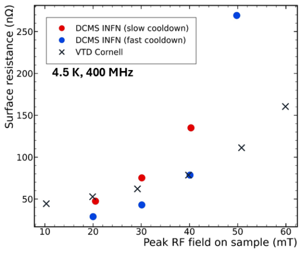

Figure 1: R_s of the coating on bulk Nb compared to a Cornell sample produced by VTD [1].

As reported in Fig. 1, the coating displayed a surface resistance R_s of 23 nΩ at 4.5 K under a 20 mT field (417 MHz). Under fast cooldown conditions, the measured R_s values match or improve upon those reported for a reference VTD-produced sample up to 40 mT; beyond this threshold, a sharp increase emerges, presumably ascribable to thermal dissipation effects. Conversely, slow cooldown runs consistently yielded higher R_s values, suggesting the presence of magnetic flux pinned within the film. The quench field for this sample reached ~ 70 mT, compared to 100 mT for the VTD reference [3] — a discrepancy possibly attributable to the same flux-trapping mechanism.

Further investigations have been carried out on two different QPR cavities, yielding the following results (to be regarded as preliminary):

- a Nb_3Sncoating on bulk Nb exhibited a T_c of 17.45 K with an $R_s \simeq 9$ nΩ at 20 mT measured at 4 K, a quench field > 85 mT estrapolated at 0 K;
- a Nb_3Sn coating on 30 µm Nb buffer layer on Cu, showing $R_s \simeq 50$ nΩ at 20 mT, together with a pronounced Q-switch, presumably caused by localized defects within the coating;

The main difference between the two Nb-substrate QPR samples lies in the average surface roughness R_a, amounting to $\simeq 6$ µm for the former and ≤ 1 µm for the latter. This discrepancy is ascribable to the different surface treatments adopted: in the first case the Nb substrate was processed only by BCP, whereas in the second one a combination of metallographic and electrolytic polishing has been applied.

CEA measurements on the NbBL-30/Cu coating yielded a superconducting energy gap of $\Delta = (2.47 \pm 0.27)$ meV, below the literature value [4] consistently with the reduced $T_c \approx 16$ K. As shown in Fig. 2, the distribution remains sharply peaked with negligible sub-gap features. The same characterization on a Nb bulk substrate was unfeasible due to the sn-rich island morphology.

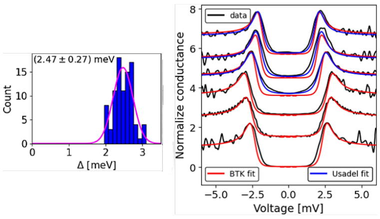

Figure 2: Superconducting gap measurements compared

SCALING TO A 1.3 GHz

In light of the results obtained on small samples and at the QPR, a strategy has been outlined for the realization of the first prototype of 1.3 GHz elliptical cavity coated with a superconducting Nb_3Sn thin film. Specifically:

1. development of a suitable system for the cavity coating;
2. scaling of the deposition recipe on a mock-up cavity in static configuration, allowing the investigation of the film at different cavity locations (cut-off, iris, equator);
3. implementation of the cavity rotation;
4. RF testing of the cavity;

A custom system has been designed and built accordingly. Starting from the requirements imposed by the optimized recipe, the specifications of the system have been defined, leading in particular to a configuration in which the sputtering source is held static while the cavity rotates around its own axis:

- ultra-high vacuum environment monitored by means of a Residual Gas Analyzer (RGA);
- a heating system capable of ensuring at least 700 °C on the cavity surface;
- an adequate thermal design of the magnetron to guarantee proper operating temperature;
- a rotation mechanism compatible with UHV conditions and the high temperatures inside the chamber;
- a sputtering source ensuring uniformity and interchangeability between targets for Nb and Nb_3Sn depositions, accounting for the different power requirements involved;

The system has been commissioned and tested; a schematic overview is shown in Fig. 3 and in Table 1.

The first depositions aimed at characterizing the sputtering source have been carried out using a Nb target, in order to benchmark the deposition quality against well-known references. Specifically, two different magnetic configurations have been tested by varying the magnet arrangement underneath the target. The corresponding $I - V - P$ curves have

Table 1: Components of The System

Number	Component
1	UHV Ferrofluidic Bearing
2	Copper shield
3	Centering bar
4	Magnetron
5	Support system for the cavity
6	Cavity
7	Closing system
8	Venting valve
9	Turbo molecular pump
10	Leak valve/Argon inlet
11	Capacitive vacuum gauge
12	Electrical feedthroughs
13	Full range vacuum gauge
14	ITEM support structure

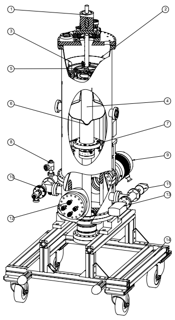

Figure 3: Scheme of the deposition system.

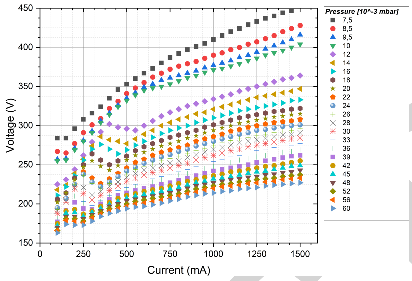

Figure 4: Magnetron characterization under strong magnetic confinement.

been recorded to better assess the operating ranges of the source (e.g.: Fig. 4).

Figure 5 highlights the difference between the deposition rates obtained with medium and strong magnetic configurations. A 1.3 GHz mock-up cavity has been machined along its major axis to host seven equally spaced windows, reported on the abscissa, where different samples could be placed for subsequent analysis. The data show, first of all, good consistency within the same run, together with a comparable increase in the deposition rate when stronger magnets are employed.

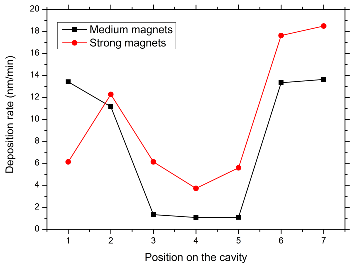

Figure 5: Deposition rate in the two configuration.

CONCLUSION

A Nb_3Snthin film has been produced on small samples by means of DCMS. The same recipe has then been employed to coat a QPR cavity, which has subsequently been tested in order to assess the RF performance of the film. In parallel, a custom system devoted to the coating of an elliptical cavity has been designed and built, and the first deposition tests have been carried out using a Nb target.

The next steps will consist in depositing a Nb_3Snthin film on the mock-up cavity and assessing the quality of the resulting coating. The first Nb_3Sncoating on a bulk Nb cavity is expected by the end of 2026, while the first one on a Cucavity with a Nb buffer layer is foreseen by the end of 2027.

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