DEVELOPMENT OF A NEW SYSTEM FOR NB$_3$SN THIN FILM DEPOSITION ON 1.3 GHz CAVITIES*

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Abstract

Nb3Sn in the form of thin film on copper is one of the most promising routes in the field of superconducting radiofrequency accelerating cavities for future colliders. At INFN – Legnaro National Laboratories, thin films of Nb$_3$Sn have been successfully deposited on small copper samples via DC magnetron sputtering. The process enabled the production of films with critical temperature ≥ 17 K, at deposition temperatures of 600 °C - 650 °C and with the implementation of a Nb buffer layer of 30 µm thickness. The design and development of a dedicated system to scale this deposition recipe from small samples to a full-size 1.3 GHz copper cavity are presented in this work. The main challenges involve both the high substrate temperatures, requiring careful thermal management and mechanical design, and the need to ensure uniform thin film deposition over a extended and curved surface. Since a planar magnetron is employed, a rotational motion must be maintained during the process, achieved in this case by rotating the cavity itself. The system's core features include substrate heating using four infrared lamps, the insertion of a custom planar magnetron inside the cavity, and a ferrofluidic rotation mechanism compatible with ultra-high vacuum conditions. To this day, the system has been successfully built and tested. The next step will be the deposition of the Nb toward the first RF validation.

INTRODUCTION

The Nb$_3$Sn thin films developed at INFN – Legnaro National Laboratories exhibit a critical temperature $T_c > 17$ K and promising surface resistance at $R_s \approx 20$ nΩ at 4.5 K. The deposition recipe [1] used for these films involves a max power density of approximately 250 mW/cm^2, a substrate temperature ≥ 600 °C, and a Nb buffer layer between the Nb$_3$Sn coating and the Cu substrate with a thickness ≥ 30 µm.

Scaling this recipe and its requirements from small samples to a 1.3 GHz cavity requires not only the ability to reproduce an equivalently performing film on a more complex and larger surface, but also the design of a dedicated sputtering chamber. This chamber must ensure that the key conditions driving film formation — such as power density and substrate temperature during deposition — can be accurately achieved.

Given the relatively low power density and the high substrate temperatures required, it is mandatory to design a system capable of withstanding several hours of significant thermal gradients between its components while maintaining ultra-high vacuum conditions. Moreover, it is crucial that the system allows fast and straightforward interchangeability between the two required deposition processes: Nb (for the buffer layer) and Nb$_3$Sn. These two coatings require different power density regimes and deposition techniques: Nb sputtering employs a multilayer approach [2] with a power density approximately two orders of magnitude higher than that used for Nb$_3$Sn.

An innovative system to reach this goal has been designed and the preliminary test result results are presented in this work.

EXPERIMENTAL PLAN

A cavity made of OFHC Cu, coated with Nb$_3$Sn using DC magnetron sputtering and featuring a Nb buffer layer with a minimum thickness of 30 µm, requires several intermediate steps to be successfully fabricated:

1. Design of all components required for the cavity operation:
    (a) A vacuum system, designed to meet two simultaneous requirements: ultra-high vacuum (UHV) operability and substrate (cavity) temperatures of at least 700 °C;
    (b) A deposition system compatible with commercially available rectangular Nb$_3$Sn targets;
    (c) A cavity connection system that avoids the use of brass joints, which could compromise both the UHV conditions and the cleanliness required for the application;
2. Commissioning, testing, and construction of the complete system;
3. Scaling of the recipe with a static configuration, without involving cavity motion. The recipe must be adapted to the new magnetron, taking into account the curvature of the substrate;
4. Scaling of the recipe in dynamic mode, involving the rotational motion of the cavity;
5. Final scaling to a real cavity, followed by RF testing.

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Given the constraints related to material compatibility and system configuration, each deposition point must be validated for both Nb and Nb_3Sn layers, although only one test can be performed at a time. Since the sputtering system accommodates a single magnetron, switching materials requires physically replacing the magnetron, making careful and efficient planning essential.

RESULTS AND DISCUSSION

Vacuum System

The setup (Fig. 1, Fig. 2 and Table 1) consists of a single vertical chamber, designed such that both the process gas injection and the diagnostic measurements occur at the bottom. The chamber is housed within an ITEM rack structure. Vacuum is achieved through a combination of a primary scroll pump and a turbomolecular pump. The baking system employs DC-powered heating bands wrapped around the chamber.

Figure 1: The vacuum system.

Deposition System

The sputtering system consists of a rectangular, balanced magnetron (Fig. 3, Fig. 4 and Table 2) inserted into the cavity from the bottom of the chamber. This design allows for easy handling, particularly during installation and replacement. The baseplate supporting the target features an internal housing with a dual function: continuous water flow for cooling,

Table 1: Core 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

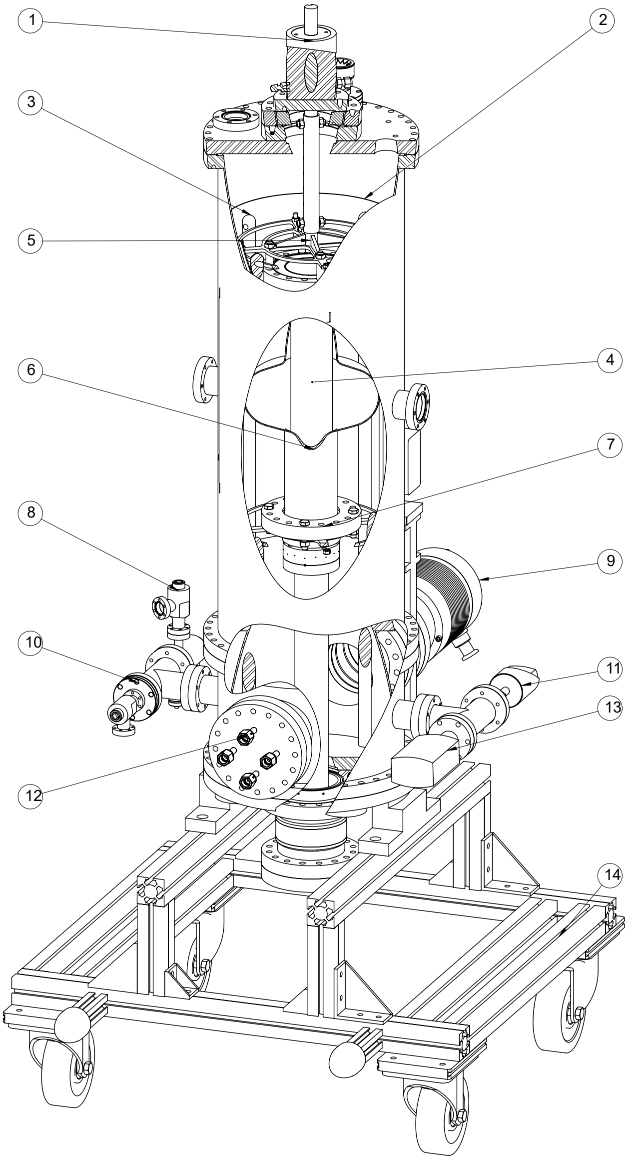

Figure 2: Exploded section of the complete system.

and accommodation of magnets, which can be configured in three different arrangements with different magnetic field intensity. Magnetic confinement can be adjusted by physically replacing the magnets, allowing for flexible composition and field control. The achievable magnetic field range, calculated based on the work of J. Goree and T.E. Sheridan [3, 4], spans from 500 to 650 Gauss at the target surface. The target has a total surface area of 120 cm^2 and a thickness of 0.5 cm.

Two main technical challenges were successfully addressed in the system design. First, the magnetron must be inserted into the cavity through the cut-offs, requiring it to fit within a diameter of 76 mm. Second, precise alignment between the cavity's rotational axis and the magnetron's symmetry axis is essential. This alignment is ensured by a 50 µm ferromagnetic UHV bearing, which enables cavity rotation, and a standard DN100CF flange, which secures the magnetron in a fixed position. Aluminum was selected as the material for the baseplate due to its excellent thermal and electrical conductivity, while also keeping the overall weight reasonably low.

Due to the size constraints and the resulting challenges in thermal management, an all-metal design was adopted for the magnetron. This approach eliminates the temperature limitations typically imposed by polymer-based seals, enabling operation at elevated temperatures. The sealing is achieved by indenting the aluminum baseplate using two custom DN50CF-profile flanges, following a mechanism similar to that of standard ConFlat flanges. In the event of disassembly, both sealing faces are re-machined to restore surface quality. Typically, the indentation depth reaches approximately 20 µm.

Figure 3: Mounted magnetron.

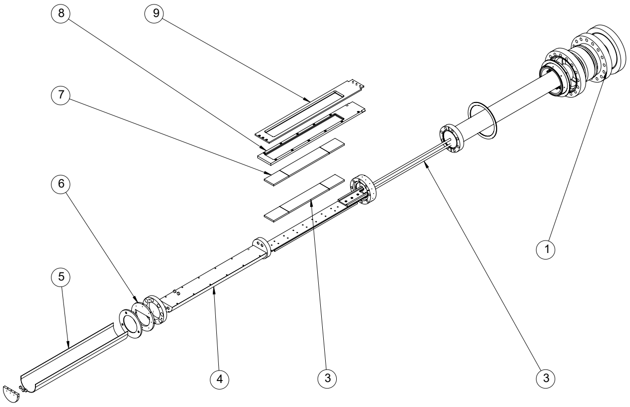

Figure 4: Exploded section of the magnetron.

Table 2: Core Components of the Magnetron

Number	Component
1	Connection flange to the system
2	Electrical and cooling feedthrough
3	Cooling channels
4	Support for the magnets
5	Permanent magnets
6	Baseplate
7	Steel screen
8	Electrical isolation flange
9	Sputtering target
10	Alignement device
11	Target mask

Cavity

The 1.3 GHz cavity is mounted on a dedicated support structure designed to ensure mechanical stability at the high temperatures required for Nb_3Sn sputtering. To ensure proper alignment of the support axis—and consequently of the cavity itself—four stainless steel rods are inserted into the chamber, serving as centering guides for the support. The cavity cut-offs feature custom connections adapted to the standard DN100CF flange. By repurposing the excess material from cavity manufacturing—whether formed by cold working or hydraulic shaping—and machining the two faces to achieve high planarity, it is possible to obtain a mechanically robust copper lip that functions effectively as a gasket. A custom star-shaped flange ensures proper indentation and sealing of the copper lip.

This configuration enhances operability throughout all phases of use of the cavity—from sputtering to RF measurement—and provides a convenient method for securing the cavity to the internal support structure within the chamber. Moreover, it avoids the typical drawbacks associated with conventional flange joining techniques, such as high costs or the complexity of selecting a suitable brazing material. Indeed, the brazing process must withstand temperatures of at least 650 °C while remaining compatible with ultra-high vacuum (UHV) conditions, which significantly limits material choices. The proposed solution circumvents these issues, offering both thermal resilience and ultra high vacuum integrity.

The cavity, acting as the substrate, is heated by four infrared lamps arranged radially around the center of the deposition system, delivering a total power up to 4 kW. Their effect is enhanced by a copper thermal shield, which helps maintain the required process temperature.

Commissioning and Tests

The components used in the system were commissioned to two companies, Mori Meccanica [5] and Cinel [6], with redundancy implemented where necessary for sensitive applications (specifically, two magnetrons were constructed). Many parts, such as connectors and gauges, were already available in the laboratory.

After the delivery of all system components, the system was tested to ensure a leak rate below the threshold of 1×10^{-12} mbarL/s. A baking test was performed to verify the proper functioning of the heating system; this also allowed to measure the minimum achievable pressure, which was on the order of 10^{-9} mbar. The infrared lamp system for substrate heating was tested and successfully reached the target temperature of 650 °C.

The innovative cavity link was provided, and a leak rate of $\leq 10^{-12}$ mbar L s^{-1} was achieved.

The magnetron was mounted and the vacuum integrity successfully verified. The measured leak rate was consistent with that obtained for the entire chamber. An ignition test was carried out, and plasma ignition was successfully achieved. The IV curve of the magnetron (Fig. 5, Fig. 6) was characterized at a pressure of 5.0×10^{-3} mbar.

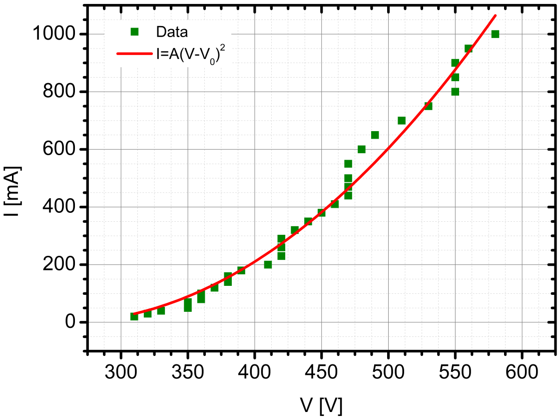

Figure 5: IV Curve.

The law utilized for the fit is $I = a(V - V_0)^2$, where $a = 0.0104 \pm 0.0005$ mA/V is a scaling parameter and $V_0 = 255 \pm 6$ V is the fitted voltage to ignite the plasma at 5.0×10^{-3} mbar.

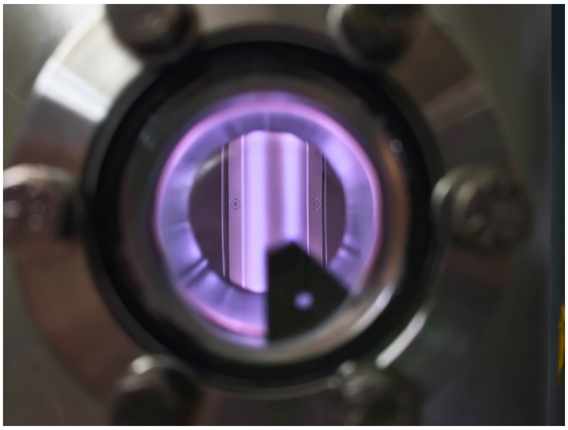

Figure 6: Magnetron ignited.

Next Steps

The first step involves conducting tests under static conditions, with the goal of fully reproducing the results obtained using previously developed recipes — particularly with respect to the critical temperature. The initial sample will consist of a dummy cavity equipped with a dedicated window located at the equator. Using custom-designed mounts, sapphire substrates will be inserted into this window during the first deposition. This setup allows for straightforward evaluation of the deposition rate and enables immediate characterization of the superconducting and morphological properties of the resulting film.

Once the desired properties have been successfully reproduced on the sapphire substrates in static mode, the dummy cavity will be set in motion to investigate the uniformity of the film and assess the impact of movement on its characteristics. The main focus in both steps will be the optimization of the critical temperature.

The final step will involve studying the coating parameters under dynamic conditions on a real OFHC cavity, validating the film from an RF performance perspective.

CONCLUSION

A complete UHV-compatible sputtering system has been successfully designed, assembled, and tested at INFN – LNL for the deposition of Nb_3Sn thin films on full-size 1.3 GHz copper cavities via DCMS. The system was conceived to reproduce the critical conditions required for high-quality Nb_3Sn growth—namely, low power density, high substrate temperatures, and strict vacuum constraints—previously demonstrated on small samples.

Different challenges were addressed, including the implementation of a compact, all-metal planar magnetron compatible with the cavity geometry, the integration of a high-efficiency heating system based on infrared lamps, and the development of a custom sealing technique ensuring mechanical robustness and vacuum integrity without resorting to brazing. The successful leak tests, plasma ignition, and bake-out validation confirm the operability of the system under the demanding process conditions.

The next phase will focus on the validation of the deposition process through a staged approach, starting with static depositions on sapphire substrates mounted on a dedicated test cavity. This will allow for fine-tuning of the deposition parameters before transitioning to dynamic deposition on the full cavity. Particular attention will be given to process reproducibility, film uniformity, and the achievement of superconducting properties in line with previous small-scale tests ($T_c \geq 17$ K).

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REFERENCES

[1] D. Fonnesu *et al.*, “Recipe optimization and SRF test of cu-compatible Nb3Sn films by DC magnetron sputtering from a stoichiometric target”, *Nature Scientific Reports*, to be published. `doi:10.21203/rs.3.rs-7516819/v1`

[2] V. Garcia, “Nb thick films for superconducting radiofrequency cavities”, Ph.D Thesis, Università degli studi di Ferrara, Ferrara, Italy, 2022.

[3] J. Goree and T. E. Sheridan, “Magnetic field dependence of sputtering magnetron efficiency”, *Appl. Phys. Lett.*, vol. 59, fasc. 9, pp. 1052–1054, Aug. 1991. `doi:10.1063/1.106342`

[4] A. Fetaj, “Design and development of an innovative system for Nb3Sn thin films for SRF elliptical cavities”, Master Thesis, Università degli studi di Padova, Padova, Italy, 2024.

[5] Mori Meccaninca Website, `http://www.morimeccanica.it`

[6] Cinel Website, `https://www.cinel.com/cinel`