Nb COATED HIE-ISOLDE QWR SUPERCONDUCTING ACCELERATING CAVITIES: FROM PROCESS DEVELOPMENT TO SERIES PRODUCTION

A. Sublet#, I. Aviles Santillana, B. Bartova, S. Calatroni, N. Jecklin, I. Mondino, M. Therasse, W. Venturini Delsolaro, and P. Zhang, CERN, Geneva, Switzerland; Marco Cantoni, EPFL, Lausanne

Abstract

The new HIE-ISOLDE accelerator at CERN requires the production of 32 superconducting cavities (20 high- β and 12 low- β) in order to increase the energy of the rare isotope beam delivered to the experiments. The Quarter Wave Resonators (QWR) cavities (0.3m diameter and 0.9m height for the high- β) are made of OFE 3D-forged copper and are coated by DC-bias diode sputtering with a thin superconducting layer of niobium. Following a preliminary process development phase, the series production of the high-beta cavities has started.

A summary of the production process is presented, with a focus on the coating recipe developed to meet the HIE-ISOLDE specifications (operation at 4.5 K with an accelerating field of 6 MV/m at 10W RF losses, Q_0=4.7x10^8 and an average surface resistance of 65 nΩ) and on the niobium layer characteristics. The RF performances of cavities produced with the coating baseline recipe are reviewed.

INTRODUCTION

The technology of Nb sputtering on copper was selected for the Quarter Wave Resonators (QWR) of the HIE ISOLDE upgrade project at CERN [1-4]. The reason of this choice is to combine the superconducting characteristics of niobium with the stiffness, high thermal conductivity and low cost of the thick Cu substrate, offering a valid alternative to bulk Nb resonators [2-4].

The construction of the new superconducting linear accelerator (linac) for the energy increase of the radioactive ion beams (from 3MeV/u to 10MeV/u for A/q of 4.5) requires the production of superconducting accelerating QWR operating at 101MHz of two geometries, 12 with a geometrical β=0.063 (“low-β”) and 20 with a geometrical β=0.103 (“high-β”).

In a first phase two cryomodules of 5 high-β cavities each are scheduled. The assembly of the first cryomodule is foreseen for the end of 2014.

BASELINE PROCESS

The process flow for the series production of the cavities is summarized in Fig. 1 and detailed in [7]. The number of steps and their complexity justify an accurate follow-up and monitoring. For each step a procedure is written and the key parameters are logged in a lot traveller following each cavity. This ensures the traceability and reproducibility of the production cycle.

A detailed explanation of the development steps to improve the layer properties has been given in [8].

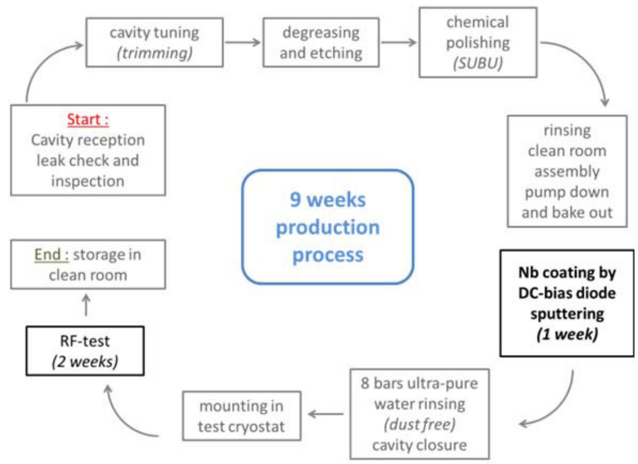

Figure 1: Summary of the 9 weeks process for the production of a cavity, from reception of the copper substrate to storage.

In summary, the main steps undertaken to match the HIE-ISOLDE specifications were:

1. changing the working gases,
2. increasing substrate and coating temperatures,
3. increasing deposition rate and coating steps,
4. increasing the global thickness,
5. increasing the local deposition rate on cavity top.

In parallel some hardware changes were made to fix peel-off issues on the antenna tip and bottom cavity edge.

To conduct this development phase prototype cavities were coated for RF-test purpose. The cavities are named Qx.y where x is the serial number of the copper substrate and y is the progressive number of Nb coating.

The adopted DC-bias sputtering baseline parameters are: 0.2mbar Ar pressure, 8kW power, and a substrate temperature rising from 300°C up to 620°C (below the bake out temperature of 650°C) on the inner conductor during a coating step. The whole coating process lasts 4 days and is done in 14 steps of 25’ coating + 5h35’ cool down to 300°C each, leading to a net coating time of 6h.

NIOBIUM FILM CHARACTERISTICS

In addition to the prototype cavities, a dummy copper cavity (Q4) had been designed as a sample holder to characterize the niobium layer: film thickness profile along the cavity inner and outer conductors, film quality based on RRR and film morphology [9].

Though the film thickness is not uniform along the cavity (fig. 2) and especially between the inner and outer conductor, the layer is thick enough and its quality is good enough to match RF needs. This is critical in particular at the top of the cavity where the largest surface magnetic field is applied (fig. 2).

#alban.sublet@cern.ch

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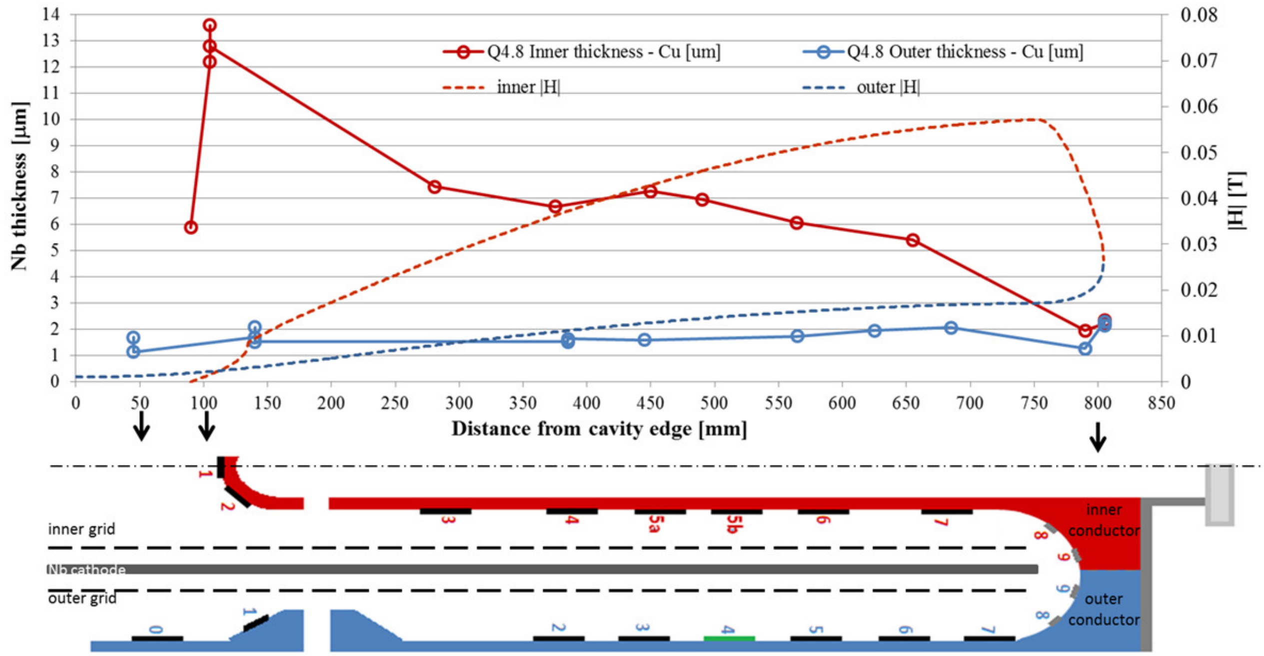

Figure 2: Niobium film thickness profile along the cavity inner (red line) and outer (blue line) conductors together with calculated surface magnetic field distribution on inner (dotted red line) and outer (dotted blue line) conductors. The sketch below represents the Q4 half cavity section with inner conductor (red), outer conductor (blue), and schematic position of cathode, bias grids and samples on the cavity walls.

If they are sufficiently pure and ordered, Nb films can display good RF properties. A “good” microstructure is also required, with well-connected grains and no voids. High bake out temperatures reduce the level of impurities on the copper substrate, in particular hydrogen, and high coating temperatures increase the grain size of the Nb film [10].

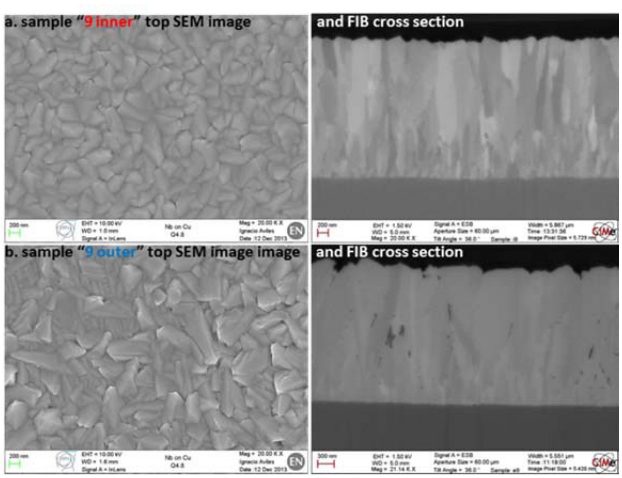

Figure 3: SEM and FIB-cross section SEM images of top cavity samples 9 inner (a.) and 9 outer.(b.).

Fig. 3 gives a closer look to the film morphology at the top of the cavity, close to the region of maximum magnetic field, and in a critical region from plasma and sputtering point of view facing the edge of the cathode. From the SEM (Scanning Electron Microscopy) images (fig. 3 left) the niobium grain size is about 200nm for the inner sample and slightly larger on the outer sample. The focused ion beam (FIB) cross section picture (fig. 3 right) shows a dense layer with a few voids for the inner sample and several small voids for the outer sample.

Although the coating is done in 14 runs with cool down in between, the film is not composed of “layers” as shown in Fig. 3. There is no interface layer observable along the coating profile that could result from the effect of residual gas in the vacuum chamber during the cool down step in between two runs or a different surface mobility with temperature. This confirms that the film grows in a continuous way along the 14 runs, with grain size growing accordingly.

At this position, the 2.1µm film thickness measured by XRF (Fig. 2) on samples 9 inner and outer is confirmed by the FIB cross section with 2.6µm.

RF TEST RESULTS

The coating baseline recipe was used 6 times to coat prototypes cavities. The RF test results of these 6 cavities are presented in fig. 4.

The HIE-ISOLDE specifications have been reached and overtaken by three cavities (Q2.8, QP1.4 and QP2.1). The best cavities offer up to 30% margin on cryogenic power, being 7W dissipation at 6MV/m.

Three cavities are below the specifications; however the causes of their lower performances have been investigated and understood.

The first cavity (Q3.4) was coated with a larger cathode-to-cavity-top gap, reducing locally the coating rate at this critical position, which probably explains its lower Q_0 [11]. However this cavity came extremely close to the specification as shown in Fig. 4.

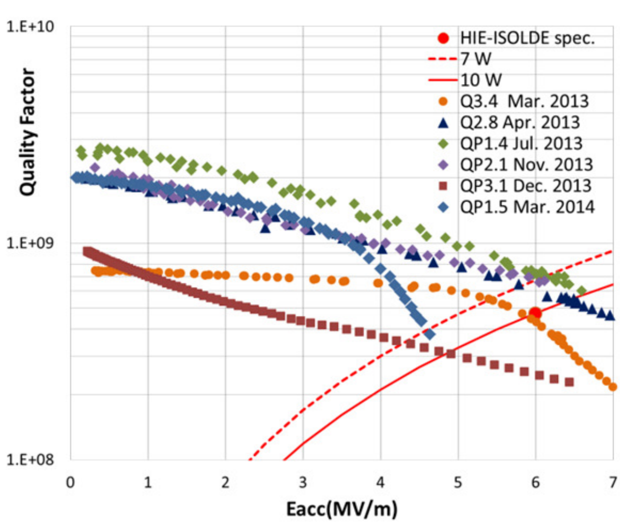

Figure 4: RF test results of cavities coated with the same baseline coating recipe.

Cavity QP3.1 has a comparable slope and behaviour as the best cavities but its Q_0 is shifted down to $1x10^9$ probably due to trapped field effect because of temperature gradient (up to 0.8K) along the cavity during the superconductive transition. The fact that the copper substrate of this cavity is from a different supplier may also had an impact on its performances.

Cavity QP1.5 has an onset of field emission around 4MV/m due to Nb particles on the cavity surface.

QP2.1 and the stripped and re-coated cavity QP3.2 (to be RF-tested) are aimed to be installed in the first cryomodule.

The change of penetration depth in the superconducting state at the transition temperature generates a shift in resonance frequency which can be fitted with a two fluid model [12]. The fit allows extracting the penetration depth (λ0) at 0K and from that the mean free path and thus to the average RRR of the film. In our case for these cavities values of λ0 ~ 50nm and RRR of about 30 have been found.

CONCLUSION

The HIE-ISOLDE cavities production process is now well established at CERN and the production has started. The first production cavity manufactured by industry will be coated at the end of June. The production rhythm is fixed to one cavity per month coated and RF-tested with target assembly of five cavities in the first cryomodule for October 2014. In parallel of the production thin film characterization and magnetron sputtering [13] development activities are underway.

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