SERIES SUPERCONDUCTING CAVITY PRODUCTION FOR THE HIE-ISOLDE PROJECT AT CERN

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Abstract

In the context of the HIE-ISOLDE linac at CERN, the phase 1 is planned to boost the energy of the machine from 3 MeV/u to 5 MeV/u. For this purpose, it is planned to install 2 cryomodules based on quarter wave resonators (QWRs) made by niobium sputtered on copper. This paper presents the different steps of the cavity series production from the reception from industry to the cavity storage before cryomodule assembly. We will describe the cavity preparation including the resonance frequency measurement, the chemical treatment, the cavity rinsing, the niobium coating and the RF test at 4.5 K.

INTRODUCITON

The HIE-ISOLDE project is the energy upgrade of the existing Isolde facility at CERN. The goal is to boost the beam energy from 3 MeV/u to 10 MeV/u for A/q=4.5 [1]. The superconducting linac will be based on quarter wave resonators (QWR), high-β and low-β, made by niobium (Nb) sputtered on copper (Cu) substrates. In phase 1, it is planned to install 2 cryomodules of 5 high-β cavities each to increase the energy of the machine from 3 MeV/u to 5 MeV/u. The QWR will have to work at 4.5 K in common vacuum (cavity vacuum and insulation vacuum are the same) at the resonant frequency of 101.28 MHz, and with a maximum of 10 W power dissipation at 6 MV/m. This paper presents the different steps of the cavity series production since the reception from the industry to the storage before cryomodule assembly.

CAVITY PRODUCTION WORKFLOW

In order to start the high-β series cavities production and to ensure the traceability and the reproducibility of the production cycle, a quality assurance plan has been implemented. The process flow is represented in Figure 1. For each step a procedure is written and all parameters are logged in a lot traveller following each cavity. The series QWR nomenclature chosen is QSX.Y, with X the cavity serial number and Y the Nb coating number.

CAVITY RECEPTION

The high-β series QWRs are produced by Research Instrument GmbH (RI) and Nb coated at CERN. The first step is the acceptance test of the copper substrate. Dimensional controls are done by RI and by the metrology service at CERN. A leak detection is done on the inner conductor, a leak rate less than 10^{-9} mbar l/s is requested. Then an optical inspection is done on the internal surface of the cavity and on all welds in order to detect any defect or material projections that can be harmful for the Nb coating. The resonant frequency is measured in standard conditions (at 20 °C, 50% humidity) before the cavity tuning.

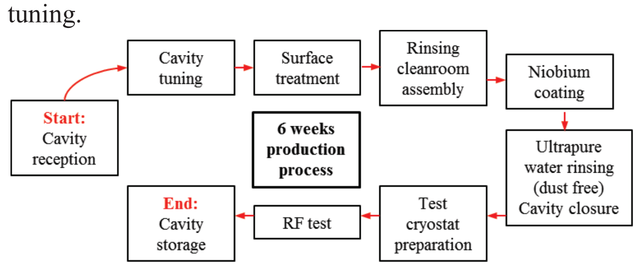

Figure 1: Summary of the 6 weeks cavity production workflow since the copper substrate reception to storage before cryomodule assembly.

CAVITY TUNING

In order to reach the operating frequency 101.28 MHz at 4.5 K under vacuum, the frequency (unperturbed) required has to be close to 100.900 MHz at 20 °C with 50% of humidity. The tip gap of the QWR is reduced by taking in account the different contributions of cavity treatments leading to a frequency shift. All contributions are presented in table 1.

Such operation is carried out in a CNC milling centre, with the QWR in horizontal position. The revolution axis is recreated by supporting the QWR by two circular slots machined close to the extremities of the outer body. This method allows achieving a perpendicularity accuracy in the order of 0.1 mm and a neat finish (Ra<1 µm). A second measurement of the frequency is done after tuning.

Table 1: Frequency Shift Contributions

Parameters	Frequency Shift (kHz)
295 K to 4.5 K and Air to vacuum (10^{-8} mbar)	+371 +/- 5
Chemical etch 40'	-27 +/- 3
Nb coating	-7 +/- 5
Tuning plate range	+/- 20

SURFACE TREATMENT

This step is done to remove the cutting fluids and the surface damaged layers before the final chemical polishing of the copper substrate. The cavity is preliminary degreased in NGL 1740 bath during 15 hours, sanded and pickled respectively with HCl solution at 50% (3 min) and H_2CrO_4 (3min) solution. The cavity is rinsed between each bath. Then two chemical etchings of 40 min are done using a mixture of sulfamic acid (H_3NO_3S, 5 g/l), hydrogen

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peroxide (H_2O_2, 5% vol), n-butanol (5% vol) and ammonium citrate (1 g/l) at 72 °C. The typical removal rate is 0.75 µm/min. The cavity is then pre-rinsed with a solution of sulfamic acid, in order to pickle the surface. A last polishing of 20 µm is done on the cavity to prepare the Nb coating. The surface presents an average roughness Ra of 0.8 µm [2].

Using the same treatment, the tuning plate made in copper OFE surface is etched of 20 µm.

RINSING AND CLEANROOM ASSEMBLY

After the chemical treatment and before the niobium coating, a low pressure (8 bars) rinsing with ultrapure water is performed on the cavity and the tuning plate to remove chemical residues and particles. The water quality is monitored for the resistivity, the total organic carbon (TOC) and the particle number. Then to dry efficiently the cavity and the tuning plate, an ultra pure alcohol (ethanol at 99.99%) rinsing is done at 5 bars. Then the cavity and the tuning plate are left to dry under laminar flow in the ISO 5 clean room.

In parallel to the cavity and the tuning plate preparation all pieces of the coating system are conditioned in an ISO 5 soft wall clean room and assembled inside an ISO 5 clean room [3]. The closed sputtering chamber with the QWR installed, is connected to the pumping system outside the clean room.

NIOBIUM COATING

Once the system is pumped, it undergoes a phase of bake-out. A first phase of 6 hours, by means of an external jacket surrounding the whole vacuum chamber, allows reaching 120 °C on the entire vacuum vessel and degases its surfaces. An internal bake-out is then performed for 48 hours with infrared (IR) lamps, allowing the cavity to be heated up to 655 °C on the external conductor and 635 °C on the internal one. This process is done to overcome the maximal temperature reached during the coating (about 635 °C), thus insuring that there is no niobium film contamination due to vacuum deterioration during the high-temperature coating. Then a Saes Getter CapaciTorr D1000 NEG cartridge is activated, allowing a local pumping inside the chamber itself, thus improving the vacuum quality [3]. The gas analysis is monitored during the bake-out, the NEG activation and the coating. The baseline coating is based on DC biased diode sputtering. The cathode is negatively polarized (≈-1000 V), the grids are grounded, and the cavity is negatively biased to -80 V. The sputtering parameters used for the coating are; 0.2 mbar Ar pressure, 8 kW power, and a substrate temperature between 315 °C and 625 °C for the internal conductor, corresponding to an external conductor temperature varying from 300 °C to 435 °C. The process is made in 14 runs of about 23 minutes each (3 min for ramp-up at 8 kW, 20 min at nominal power), alternated with pauses in between, in order to prevent the cavity temperature from exceeding the bake-out temperature. Each cycle lasts 6 hours and the total process duration is 4 days. The average film thickness after these 14 runs coating process reaches typically 7.5 µm / 2.5 µm / 1.7 µm on the internal/ top/external conductor respectively. The cavity tuning plate is also Nb sputtered in another UHV coating chamber, with a planar magnetron setup at $9{\cdot}10^{-4}$ mbar Krypton pressure, 150-200 °C temperature, and 600 W power.

CAVITY CLOSURE

The coated bottom plate is mounted on the Nb coated cavity in clean room ISO 5. The RF contact between cavity and plate is ensured by mechanical clamping with stainless steel collars housing 72 screws tightened at 5 Nm each, which push on titanium rings compensating the differential thermal contraction between copper and stainless steel at cold.

In order to prevent the cavity contamination by particles (metallic or dust) the openings (beam ports) are closed with special covers fixed on beam port supports (Figure 3). Then the cavity is wrapped with 2 antistatic plastic bags filled with N_2 gas and transported to the RF test area.

RF TEST

Preparation

The cavity is mounted in ISO 5 clean room on the test insert designed and manufactured at CERN [4]. Thermal sensors are fixed at different positions on the cavity to control the temperature gradient during the cool down and the RF test. The pick-up antenna, the RF power coupler and the tuning system are installed on the cavity.

For each test, the RF continuity (RF transmission loss from coupler to pick-up), the resonant frequency with coupler all in and almost all out with the tuning plate in flat position, the Q_0 value and the tuning range, are checked at 20 °C with 50% humidity.

The entire insert with the support is covered by an antistatic plastic bag and transported to the cryostat test area. Then the cavity is installed in the cryostat. To keep the benefit of clean room assembly and increase the general cleanliness, the cavity installation in the cryostat is done in a metallic structure closed with PVC curtains and equipped with laminar flow units installed around the cryostat opening. This place is cleaned before and after each RF test.

Cool-down

The cryostat is pumped by a mobile slow pumping unit with a 10 mbar l/s gas flow. The cavity vacuum is close to 10^{-5} mbar after 24 hours. Leak detection and a bake-out of 48 h at 340 K using IR lamps are performed before cool down. The cool down process takes 12 hours and comprises 3 parts: the purge to clean the helium line (2 h), cool down of the active thermal screen cool down at 50 K (2 h) and the cavity cool down at 4.5 K (8 h). The cool-down sequence ensures that the main part of the cryo pumping is done first by the thermal screen, to preserve the cavity surface from contamination. At 4.5 K, vacuum pressure values in the low 10^{-8} mbar range are typically reached.

All cryogenics parameters (T, P_{He}, Liquid He level) are monitored during the cool down and the RF test.

RF Test

The HIE-ISOLDE specifications call for Q_0 value of 5.10^8 at 6 MV/m without field emission and a resonant frequency of 101.28 MHz at 4.5 K.

Before each RF test all cable attenuations and power meters used are controlled.

Multipacting (MP) simulations done on the HIE-ISOLDE QWR, showed 2 barriers at low field and one at 1 MV/m. The cavity must be conditioned to process these MP levels. Conditioning is done from 200 K to 4.5 K by using pulsed power and amplitude modulation. A first RF measurement is done at 4.5 K when the cavity is well conditioned.

We experimentally observed that cavity performance could be improved by warming up the cavity above the Nb critical temperature ($T_c > 9.2$ K) followed by a new cool-down at 4.5 K without RF. This behaviour is not yet fully understood and studies are underway. The working hypothesis is that the extra losses originate from flux trapping due to thermoelectric currents, as they correlate with temperature gradients when the cavity crosses T_c.

If the Nb surface is not clean enough (Nb particles or defect), electron field emission can create X-ray radiation and limit the accelerating field (E_{acc}). As shown on Fig. 2, helium processing performed on the cavity QP2.1 can help to recover higher Q_0 and E_{acc}.

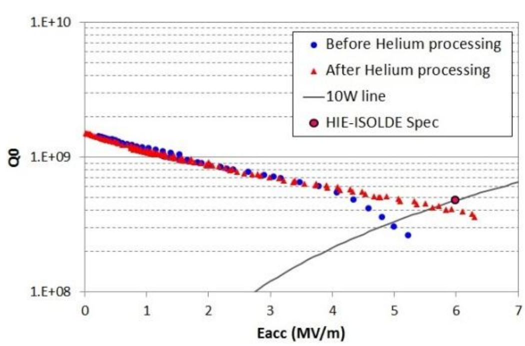

Figure 2: QS2.1 RF test before and after He processing.

When the cavity reaches the specification, the resonant frequency is adjusted using the tuning system. Measurements are done in order to validate the frequency shift range (+/-20 kHz), the reproducibility and the accuracy of the tuning mechanism (< 1 Hz).

During the warm up, after the RF test, a measurement of the frequency shift with temperature ($f(T)$) is done. The penetration of the electromagnetic field inside the conductor shifts the resonance frequency of the cavity. From the fit with a two fluid model [5] of the $f(T)$ curve, the penetration depth (λ_0) at 0 K the mean free path and thus the average RRR of the film (around 30) can be inferred.

Figure 3 shows the $Q_0(E_{acc})$ at 4.5 K and 101.28 MHz for the first three cavities accepted for the first cryomodule assembly. As we can see QP2.1 is above the specification and the other two are slightly below the required specification. The average dissipation so far is about 10 W per cavity.

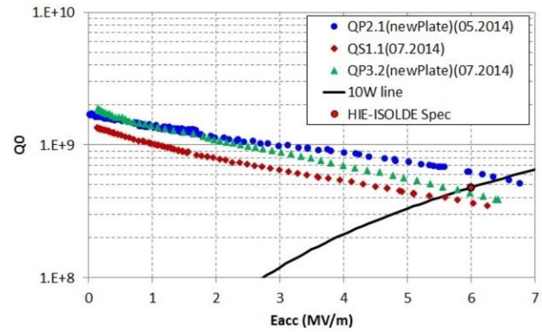

Figure 3: $Q_0(E_{acc})$ curves of the first three cavities accepted for the first cryomodule.

STORAGE

Accepted cavities are prepared for the cryomodule assembly. The RF power coupler, the pick-up and the tuning mechanism are removed from the cavity. Then beam port protections and special supports for the cryomodule assembly are mounted. All these pieces, as well as the cavity are packed with antistatic plastic bags with N_2 gas and stored in clean room ISO 5.

SUMMARY

All steps identified to produce cavities at the required performance are validated. The phase 1 of the HIE-ISOLDE project planned to install one cryomodule of five high-β cavities in April 2015. To start the cryomodule assembly, all 5 cavities have to be made for October 2014. At the moment, 3 cavities reached the specification and are stored. The fourth cavity QS3.1 will be tested soon and QS3.1 will be tested in September.

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