# STATUS OF HIE-ISOLDE SC LINAC UPGRADE

A. Sublet#, L. Alberty, K. Artoos, S. Calatroni, O. Capatina, M. A. Fraser, N. Jecklin, Y. Kadi, P. Maesen, G. Rosaz, K.-M. Schirm, M. Taborelli, M. Therasse, W. Venturini Delsolaro, P. Zhang, CERN, Geneva, Switzerland

*Abstract*

The HIE-ISOLDE upgrade project at CERN [1] aims at increasing the energy of radioactive beams from 3MeV/u up to 10 MeV/u with mass-to-charge ratio in the range 2.5-4.5. The objective is obtained by replacing part of the existing normal conducting Linac with superconducting Nb/Cu cavities. The new accelerator requires the production of 32 superconducting cavities in three phases: 10 high-beta cavities for phase 1 (2016), 10 high-beta cavities for phase 2 (2017) and possibly 12 low-beta cavities for phase 3 (2020). Half of the phase 1 production is completed with 5 quarter-wave superconducting cavities ready to be installed in the first cryomodule. The status of the cavity production and the RF performance are presented. The optimal Linac working configuration to minimize cryogenic load and maximize accelerating gradient is discussed.

## INTRODUCTION

The superconducting post accelerator for the HIE-ISOLDE project [1] entered gradually the construction phase in 2013 after an R/D stage which had taken off in 2009 with the formal approval by CERN. The schedule of the project foresees to deliver beams up to 4.2 MeV/u for the heaviest species in autumn 2015 with a single high-beta cryomodule of 5 cavities. A second cryomodule will then be installed during 2016 bringing the beam energy up to 5.5 MeV/u for all the radionuclides available at ISOLDE. This will complete phase 1, making Coulomb excitation studies possible up to mass-to-charge ratio (A/q) = 4.5.

The cryomodules house five superconducting high-beta Quarter Wave Resonators (QWR) based on Nb/Cu technology [2-4], and a superconducting solenoid for beam focusing.

The QWR are installed in a common vacuum cryostat, i.e. the beam vacuum and the thermal insulation vacuum are connected. They are designed to work at 4.5 K at the resonant frequency of 101.28 MHz, and with a maximum power dissipation of 10 W at 6 MV/m.

This article presents the performance of the cavities and their assembly in first cryomodule.

## COATING, TUNING AND TESTING

### Production Scheme and Coating

The first cryomodule cavities production started end of 2013 and finished end of 2014: 5 cavities and a spare unit have been coated. The prototype and series QWR nomenclature chosen is QPX.Y and QSX.Y respectively, with X the cavity serial number and Y the Nb coating process number [5]. The copper substrates were manufactured at CERN for the two first prototypes (QP2 and QP3), the substrates for the series were manufactured by industry (QS1, QS2, QS3 and QS4) [6].

The coating process is based on DC-bias diode sputtering, the hardware setup (UHV chamber, Nb cathode, DC power supplies, etc.) and the process have been kept identical (production steps, coating recipe, etc.) for all the cavities produced as described in details in [7], except for QP2 substrate, which has seen an additional annealing prior to coating. Over the one year production period, a total of 7 coatings have been made on these 6 substrates: one cavity has been coated twice due to bad initial RF performances (QP3.2), one has been rejected due to bad initial RF performances (QS2.1) and has been stripped and re-coated (QS2.2) in February 2015. It will be used in the second cryomodule. Typically a period of about two months is necessary [8] from the copper substrate reception at CERN in order to obtain a coated cavity and verify its RF performance.

### Cavity Tuning

To match the Linac frequency of 101.28 MHz at 4.5 K under vacuum the QWR must be tuned. This process is done in two distinct steps [9, 10] that take into account and compensate:

1. the frequency shifts (about 400 kHz) induced by: the manufacturing deviations, the chemical polishing, the Nb coating, the thermal contraction at the operation temperature
2. the cumulated frequency uncertainties (~10 kHz).

The first step addresses the frequency shifts, it consists of a pre-tuning of the cavity after reception at room temperature and before coating by trimming it to a determined “tip-gap” length [9, 10]. This length is calculated depending on the foreseen duration and number of chemical polishing (SUBU) [11] to which the substrate will be submitted. The chemical polishing is used to eliminate surface defects (inclusions, spatter, etc.) from the as received substrate. The cavity frequency shift has a linear dependence to the SUBU duration and typically a 26.5 +/- 3 kHz frequency shift was observed after the initial 40 minutes SUBU. The SUBU process might reveal additional defects that must be either mechanically or chemically polished again, thus introducing a further frequency shift. The stripping of one cavity and the new coating process (including SUBU) will also induce a frequency shift.

The second step addresses the frequency uncertainties within an active tuning range of about 40 kHz at 4.5 K.

#alban.sublet@cern.ch




ISBN 978-3-95450-168-7

This is performed by a mechanically adjustable tuning plate fixed at the bottom of the cavity [10]. A shaft is actuated by a stepper motor, with a resolution down to 0.1 Hz/step, which can elastically deform the plate up to 5mm below the flat position.

To accommodate for the different surface preparation and coating scenarios, two sets of tuning plates have been designed. The so called "standard" one consists of a flat copper disk with a 0.3 mm thick deformable membrane. The "special" one consists of a similar copper disk with a 1.5 mm thicker edge, offering about 27 kHz additional compensation margin, depending on the initial "tip-gap" distance.

Table 1 summarizes the type of tuning plate used for each cavity installed in the first cryomodule.

## *RF Test and Performance*

Each cavity has been RF-tested and characterized after coating by measuring its Q-factor as a function of the accelerating field. Cavities are anti-dust rinsed a last time prior to assembly in the cryomodule.

The cavity preparation, cool-down and test procedures are described in [12]. The RF-test consists basically of three steps, illustrated for the case of QS2.2 in Fig. 1 and described below:

1. RF-conditioning: applied to process the multipacting barriers during the initial cool-down phase, using RF pulsed power and amplitude modulation. If the RF test still reveals field emission the process continues with step 2, else with step 3.
2. Helium processing: applied to mitigate field emission provoked by dust particles or defects on the Nb surface. If this process is not effective a further anti-dust rinsing of the cavity might be necessary.
3. Thermal cycle(s): applied to remove trapped magnetic flux by warming up the cavity up to 20 K, namely above the Nb thin film critical temperature (9.2 K), and cool it down back to 4.5 K. If RF test reveals field emission then the process restarts from step 2.

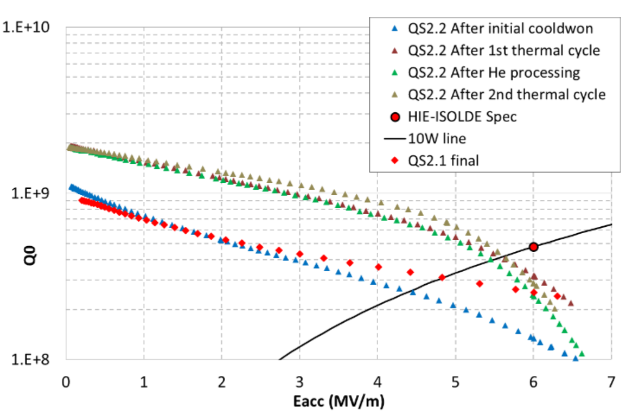


Figure 1: Results of RF test of QS2.2 and QS2.1.

In Fig. 1 we show the effect of the thermal cycles, as described in step 3 of the procedure. Thermal gradients in the cavity during the superconducting transition are source of thermoelectric currents, which result in flux trapping. It has been shown [13] that there is a clear dependence between the thermal gradient in the cavity and the residual resistance. Up to 50% reduction in *Rs* at low field (0.2 MV/m) can be gained thanks to thermal cycling.

In the case of QS2.2 the performance gain obtained thanks to the first thermal cycle is clearly visible (Fig. 1). Field emission was observed with an onset around 4 MV/m after the first thermal cycle. It was not mitigated by the helium processing. The second thermal cycle helped to gain a bit in the medium field region but the performances remain limited by field emission. This cavity will be anti-dust rinsed a second time and RF-tested again.

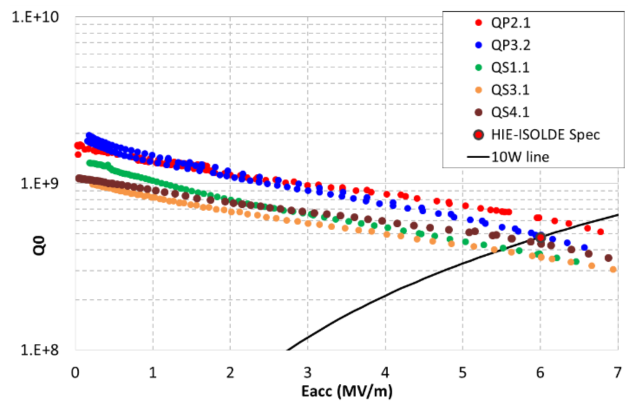


Figure 2: RF test results of the 5 cavities of the first cryomodule.

Figure 2 shows the final RF cold test results of the cavities selected to be installed in the first cryomodule. The cavities can be grouped in two families around the HIE-ISOLDE specifications:

1. slightly above: QP2.1 and QP3.2
2. slightly below: QS1.1, QS3.1 and QS4.1

The process of coating was identical for all these cavities. The differences are possibly linked to the history of the substrate as discussed below. Table 1 summarizes the performances of cavities selected for the first cryomodule. The total dissipated power remains within the cryogenics margins.

Table 1: First Cryomodule Cavities Summary Table

| Cavity name | Q00 @ 0.2 MV/m | Q0 @ 6 MV/m | Pcav (W) | Tuning plate |
|---|---|---|---|---|
| QP2.1 | 1.59E+09 | 6.23E+08 | 7.6 | Special |
| QP3.2 | 1.93E+09 | 4.91E+08 | 9.7 | Special |
| QS1.1 | 1.33E+09 | 3.78E+08 | 12.5 | Standard |
| QS3.1 | 9.96E+08 | 3.66E+08 | 13.0 | Special |
| QS4.1 | 1.12E+09 | 4.36E+08 | 10.9 | Standard |
| Total | | | 53.7 | |

## *Discussion*

At the reception at CERN some QS substrates showed welding inaccuracies (projections, defects, weld misalignments, etc.), whereas in the QP prototypes cavities no obvious defect was found by visual inspection.

These differences might be explained by the different welding parameters and setup used in industry. Their impact on the cavities performances is hard to evaluate and may not explain the RF performances differences especially in view of the strong improvement between QS2.1 and QS2.2 and its performance close to QP2.1 and QP3.2 at least at low field. A review of the welding process and of the quality control procedure is under way to improve the welding for the next cryomodules substrates.

From the prototype cavities manufactured at CERN, QP2 has seen an additional annealing (the same thermal cycle, which is applied before each standard coating) before the final chemical polishing. A second cavity, QP3, has been coated twice because of bad initial RF performance and has therefore been also annealed twice. The RF performances of these cavities are both above the HIE-ISOLDE specifications (Figure 2).

From the QS series cavities only QS2 has been re-coated and hence annealed twice The RF test results of QS2.1 (final) compared to QS2.2 after 2$^{nd}$ thermal cycle (Fig. 1), demonstrate the positive impact of a second – identical – annealing and coating on the cavity performances. QS2.2 belongs now to the best of the two families, at least at low accelerating gradient. The field emission loading appeared at high field is attributed to a contingent effect (dust contamination after coating).

Thus investigating the effect of cavity history (cavity annealed before coating or re-coated) might be the right approach to explain the performance gain. Annealing of the substrate consist of a full bake-out cycle of the cavity up to 650°C under vacuum for about 50 hours and cool down. After this step the cavity is either coated or vented to air as in the case of QP2.1. Then the standard procedure continues with a further chemical polishing (SUBU) before coating and the preparation for coating [7]. Such a treatment could lead to a purification of the bulk substrate if part of the bulk impurities segregate to the surface and are subsequently eliminated by the SUBU polishing which removes about 10 µm.

In the case of a substrate which has not sustained a previous annealing step, the impurities segregated to the surface might react with the Nb coating or even diffuse into the Nb layer. This may lead to an increased residual resistance, degrading the RF performances of the cavity.

Signs of sulphur migration to the copper surface have been observed on OFE copper samples annealed in vacuum at 400°C. This aspect is currently under investigation at CERN.

## FIRST CRYOMODULE ASSEMBLY

The selected cavities have been positioned in the first cryomodule with the best performing cavities positioned as far upstream as possible. This is to guarantee the longitudinal capture of the beam from the upstream Linac, even if the cavities experience some degradation in accelerating gradient. For future cryomodules placed downstream it is foreseen to position the worst cavities on the outside to prepare for the risk of cavity performance degradation due to contaminations from outside and thus protect the good cavities.

Figure 4 shows a picture of the cryomodule assembly with the five cavities and the solenoid. It will be mounted in its vacuum vessel and closed by the end of April. Commissioning at cold in the HIE ISOLDE Linac hall is scheduled in May-June 2015.

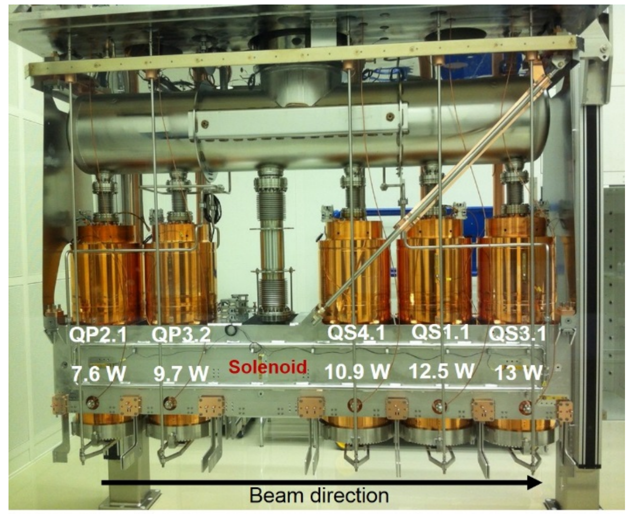


Figure 4: Picture of first cryomodule (April 2.2015).

## CONCLUSION

The first five cavities for the HIE-ISOLDE project have been successfully produced and assembled in their cryomodule. The cavity production process reached a mature point. A hypothesis of the mechanisms influencing the Nb layer properties and the cavity performances will be tested in the near future.

The experience and understanding gained during the first cryomodule production phase is already being applied to the production for the second cryomodule.

## ACKNOWLEDGMENT

We acknowledge funding from the Belgian Big Science program of the FWO (Research Foundation Flanders) and the Research Council K.U. Leuven. We would like to acknowledge as well the receipt of fellowships from the CATHI Marie Curie Initial Training Network: EU-FP7-PEOPLE-2010-ITN Project # 264330. The precious support of G. Bisoffi, E. Palmieri, A. Porcellato and S. Stark from INFN-LNL is warmly acknowledged.

## REFERENCES

[1] M. Pasini et al., “A SC upgrade for the REX-ISOLDE accelerator at CERN,” Proc. of LINAC’08, Victoria, BC, Canada
[2] C. Benvenuti, N. Circelli and M. Hauer, “Niobium films for superconducting accelerating cavities”, Appl. Phys. Lett., Vol. 45. No. 5, Sept. 1984
[3] C. Benvenuti et al., “Superconducting Niobium Sputter-coated Copper Cavity Modules for the LEP

Energy Upgrade", Proc. of PAC1991, vol. 2, pp. 1023-1025

[4] V. Palmieri, V. L. Ruzinov, S. Stark, et al., "New Results on Niobium sputtered Copper quarter wave resonators" Proc. of the Sixth Workshop on RF Superconductivity, Newport News, Virginia, 1993

[5] W. Venturini Delsolaro et al., "Nb Sputtered Quarter Wave Resonators for the HIE-ISOLDE", Proc. of SRF'13, Paris, France

[6] L. Alberty et al., "The copper substrate Developments for the HIE-ISOLDE High-Beta Quarter-Wave Resonators'', Proc. of SRF'13, Paris, France

[7] N. Jecklin et al., "Niobium Coatings for the HIE-ISOLDE QWR Superconducting Accelerating Cavities", Proc. of SRF'13, Paris, France

[8] A. Sublet et al., "Nb Coated HIE-ISOLDE QWR Superconducting Accelerating Cavities: From Process Development to Series Production", Proc. of IPAC'14, Dresden, Germany

[9] P. Zhang et al., submitted to Nuclear Physics A

[10] P. Zhang et al., "The Tuning System for the HIE-ISOLDE High-Beta Quarter Wave Resonator", Proc. of SRF'13, Paris, France

[11] S. Calatroni et al., "Influence of copper substrate treatments on properties of niobium coatings", Proceedings of the 6th workshop on SRF superconductivity, CEBAF, Newport News, Virginia, USA

[12] M. Therasse et al., "Series superconducting cavity production for the HIE-ISOLDE project at CERN", Proc. of LINAC'14, Geneva, Switzerland

[13] P. Zhang et al., "The influence of cooldown conditions at Tc on the Q0 of niobium sputtered quarter-wave resonators", 6th International Workshop on Thin Film and New Ideas for RF Superconductivity, Oct. 6-8 2014, LNL, Legnaro, Italy



ISBN 978-3-95450-168-7