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A SEAMLESS QUARTER-WAVE RESONATOR FOR HIE-ISOLDE

S. Teixeira López*, M. A. Fraser, M. Garlasché, T. Mikkola,
A. Miyazaki, A. Sublet, W. Venturini Delsolaro
CERN, Geneva, Switzerland

Abstract

The superconducting linac booster for the HIE-ISOLDE project, in operation at CERN, is based on Nb/Cu coated Quarter Wave Resonators (QWR) [1]. The performance of the series cavities has been presumably limited by defects in the copper substrates close to the electron beam (EB) weld. A novel cavity design has been developed and prototyped in order to allow the manufacturing of the resonators by machining them from the bulk, without any weld. The RF design was optimized for the customary figures of merit and fully integrated in the HIE-ISOLDE cryomodule. Mechanical tolerances were assessed in relation to the available range of pre-tuning and demonstrated on a dummy prototype. Beam dynamics simulations were carried out to check the effects on the beam when the new cavities will be installed in the high energy end of the linac. This document covers the design and the experimental results of the first Nb/Cu seamless QWR for HIE-ISOLDE.

INTRODUCTION

In the context of the HIE-ISOLDE project, a post accelerator is being built at CERN for the radioactive ions beams produced at the ISOLDE facility. The linac relies on superconducting Quarter Wave Resonators, based on the Nb/Cu technology. In the baseline design of this RF cavity substrate [2] , the QWR is made out of two 3D forged OFE copper parts which are joined together by EB welding. The location of the EB weld is close to the shorting section of the QWR, i.e. on the high magnetic field region and the two parts have to be carefully prepared and matched by shrink fitting. The manufacturing process was developed and successfully tested at CERN (three prototypes were done prior to launching the series production, and two more recently). Regrettably, many cavities produced in industry were subject to defects, mostly located close to the EB weld (projections, inclusions, etc.). The most critical defects, shown in Figure 1, were in the form of cracks going deep into the material, predominantly along grain boundaries.

The origin of these imperfections was thoroughly investigated but a full understanding could not be reached. The relative degradation of the Q values in the series cavities as compared to the prototypes has been correlated to the amount of defects observed. This degradation can be observed in Figure 2.

The purpose of the work described in this document was to modify the design of the copper substrates with the aim of making it possible to machine them from a single copper billet, thus avoiding completely the EB weld. The inspiration came from the experience done with a smaller QWR for the ALPI linac in INFN [3]. The main modification required was to reduce the protuberances of the RF surface at the beam ports (cavity noses). This was considered possible and even favourable in the high energy section of the HIE ISOLDE Linac [4]. Removing the weld from the high magnetic field region would eliminate the main source of potential imperfections in the location where the sensitivity to RF losses is highest. The cross section for conduction cooling of the cavity is also very much increased in the new design. For these two reasons the final cavity performance was expected to improve.

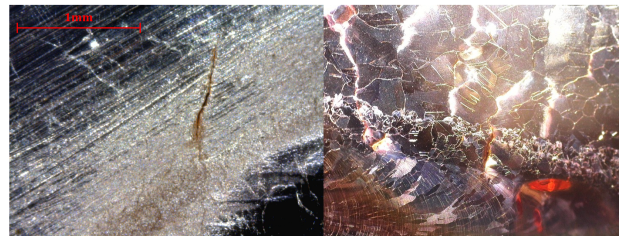

Figure 1: Defects on the welding area of the QS series cavities.

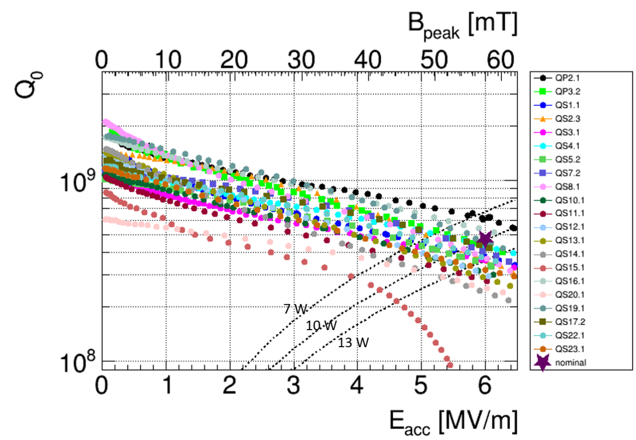

Figure 2: Performance of the QS cavities.

RF DESIGN

This study presents a comparison of a new seamless conical cavity (QSS) and the nominal design (QS) that is currently installed in the first, second and third cryomodules (CM1, CM2 and CM3). All the simulation results presented in this work have been performed with CST Microwave Studio 2016 [5] and bench-marked using ANSYS HFSS [6].

The new RF design started as a perturbative expansion of the already existing series production (QS) cavity, which

* silvia.teixeira@cern.ch

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was used as a reference along the process of the new cavity design (QSS), both cavities are shown in Figure 3. This approach of a new seamless cavity consists of a rotational symmetric cavity with a double conical shape. This shape, with respect to a cylindrical one without asymmetries, will help reducing possible leakage through the beam ports, recovering the accelerating efficiency in terms of the shunt impedance over quality factor (R/Q), and staying within the required mechanical constrains for the cavity outer shape.

Some other changes have been applied in order to optimize the efficiency, such as the diameter of the inner conductor and the beam port size and shape.

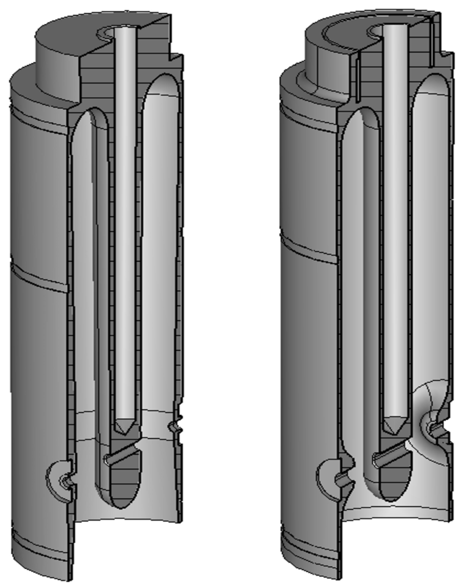

Figure 3: QSS (left) and QS (right) cavities.

The main constraint for the design of a seamless cavity was the need of having a rotational symmetric geometry that could be machined from a copper billet, using a lathe machine. The beam port protuberances break this symmetry in the nominal design, so they could not be maintained.

The first simplification for the new design was, therefore, keeping the original geometry but removing the curvature on the beam ports. This simple approach showed a dramatic reduction on acceleration efficiency (R/Q) from the previous design and an increase of the currents on the RF contact at the bottom plate.

The decision to go for a conical shape came together with the need of recovering the R/Q and avoiding the field leakage through the beam ports. Maximizing the cone angle would be beneficial for both effects, however some mechanical constrains limited the maximum possible angle (mainly the tolerances at the cavity top and the limited size of the machining rod).

The changes in geometry include the introduction of a certain conicity in both outer and inner conductors. In the area where the magnetic field is higher, the diameter of the inner conductor has been augmented from 90 mm to 95 mm. This way, the magnetic surface currents are distributed along a greater surface and therefore, the ratio B_{peak}/E_{acc} decreases. The decrease on the lower part from 90 mm to 85 mm was chosen in order to optimize the R/Q value. These changes increased the cavity frequency which was compensated by the elongation of the inner conductor. In figure 4 the distributions of the E and H-fields are presented.

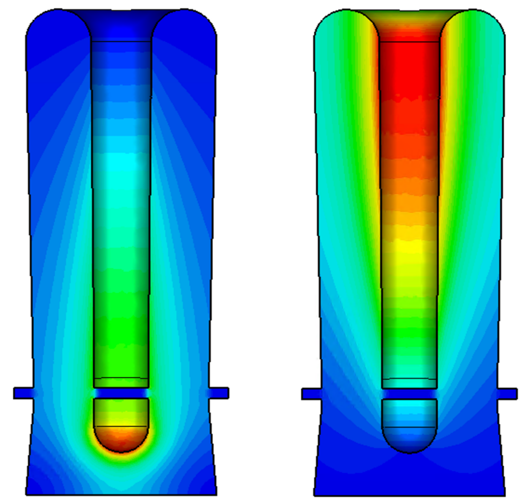

Figure 4: E-Field (left) and H-Field (right) patterns for the seamless cavity.

In addition, the modification of the design increased both the gap lengths and the separation of their electric centers. This can be seen in Figure 5 which shows the electric field profile comparison for QS and QSS models. Since the RF field in QSS is broader, we find the cross-over of TTF(β) at β=0.17, which makes this kind of cavities good to be used in CM4, as seen in Figure 6. This last cryomodule will be installed at the later stage of the linac where the particles have higher energy. For β values below that, the reduction in efficiency is less than 8 %. Figure 7 shows the R/Q curves for both models in a range of β from 0.1 to 0.15. The value of the particle velocity for A/q = 4.5 (worst case) at the entry of CM4 is β=0.135, where the difference in R/Q is about 4 %.

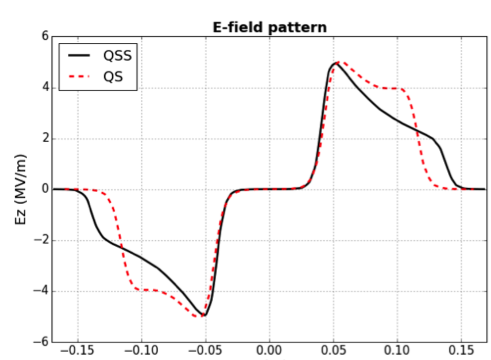

Figure 5: E-Field pattern for both QS and QSS cavities.

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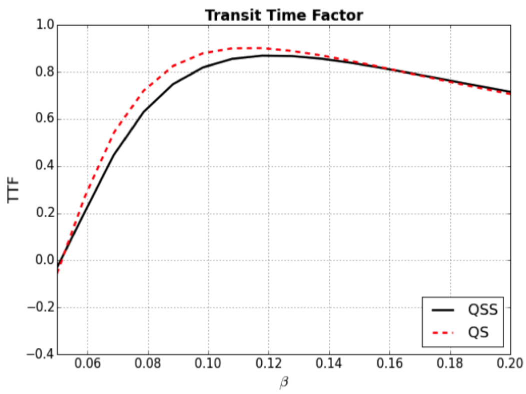

Figure 6: Transit Time Factor comparison.

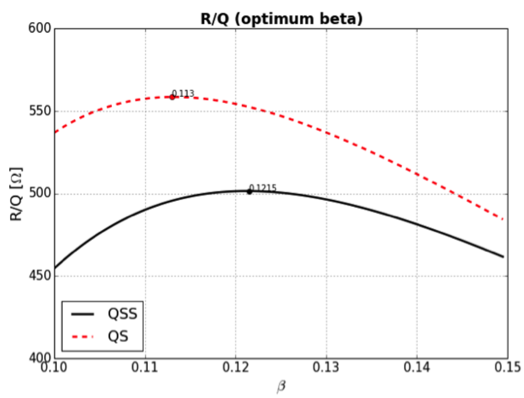

Figure 7: R/Q comparison.

The parameters of the seamless high-β cavity design are compared to the nominal design in Table 1. The accelerating field E_{acc} is defined as

$$E_{acc} = \frac{V_{acc}}{L}, \tag{1}$$

where L is the reference length that in our case is defined as the diameter of the outer cavity conductor, $L = 0.3$ m and the maximum accelerating voltage is defined in the following formula:

$$V_{acc} = \int_{-\infty}^{\infty} |E_z(z)| dz. \tag{2}$$

The Transit Time Factor (TTF) is the ratio between the actual accelerating voltage along the beam trajectory and the maximum voltage V_{acc} [7]. For the case of our QWR in the frame of HIE-ISOLDE project, there is a large variety of β values that has to be accommodated, so this ratio is defined as

$$T(\beta) = \frac{1}{V_{acc}} \int_{-\infty}^{\infty} E_z(z) \cos\left(\frac{2\pi z}{\beta\lambda}\right) dz, \tag{3}$$

and the definition of the effective accelerating voltage including TTF can be approximated as

Table 1: Comparison of QS and QSS Cavities

Parameters	QS	QSS
β_{opt} [%]	10.9	12.2
R/Q [Ω]	553	502
E_{peak}/E_{acc}	5.0	5.3
B_{peak}/E_{acc} [Gauss/(MV/m)]	96	93
$G = R_s.Q$ [Ω]	30.3	30.1
U/E_{acc}^2 [J/(MV/m)^2]	0.207	0.214
P_c at 6 MV/m [W]*	7.7	7.9

* calculated assuming R_s = 50 n[Ω]

$$V_{eff}(\beta) \approx T(\beta) V_{acc}. \tag{4}$$

We also introduce the ratio of shunt impedance and quality factor (R/Q) with β dependence. The following formula is applied to obtain the results in Figure 7:

$$\frac{R(\beta)}{Q} = \frac{V_{eff}^2(\beta)}{\omega U} = \frac{T^2(\beta) V_{acc}^2}{\omega U}. \tag{5}$$

MECHANICAL DESIGN

The new seamless cavity mechanical design is based on the old seamed cavity. The changes to outer dimensions and interfaces were kept to minimum, or done in the limits set by the size and shape of the old cavity. This allows the use of the new design in existing cryomodules and minimizes the changes in machinery and tooling used during production.

The RF surface was however modified and has now a conical shape on the inner and outer conductors. The removal of the weld seams will also improve heat conduction in the cavity. Table 2 shows the sensitivity and tolerances that needed to be respected by the machining, calculated using both Monte Carlo and Error Propagation methods. Figure 8 describes the parameters used in the study.

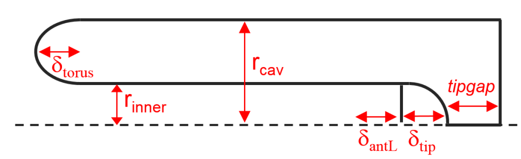

Figure 8: Description of the parameters used for the sensitivity study using a simplified cavity model.

Due to the conical shape and the disappearance of the gap at the cavity top, the weight of the cavity increased by ~45 kg, meaning a total of 186 kg + peripherals. Due to the large increase in weight from the QP cavity (first prototype), which weighted 111 kg, the different transport, handling, lifting, sputtering and chemistry equipment were rechecked to verify that they can withstand the increased loading.

The machining technique used sets a limit on the maximum depth of the RF cavity. Other limits include the max-

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Table 2: Study of the Sensitivity and the Mechanical Tolerances

Parameters	**Sensitivity [kHz/mm]**	σ**[mm]**
δ_{antL}	155	±0.1
$tipgap$	16	±0.7
δ_{torus}	105	±0.2
r_{inner}	28	±0.3
r_{cav}	47	±0.2
δ_{tip}	106	±0.2

imum diameter, cavity length and positioning of the interface points with regards to the beam axis, the interfaces for sensors and heaters, the tuning plate, pick up and coupler antennas and the He-line flange.

A new mounting flange and shutter were designed to compensate for the lost material around the beam port in order to avoid some possible RF leakage or cavity cross-talk. Their design was limited by the space inside of the cryomodule, especially during the different assembly steps. The cavity assembly in the CM were successfully simulated and tested as shown in Figures 9 and 10.

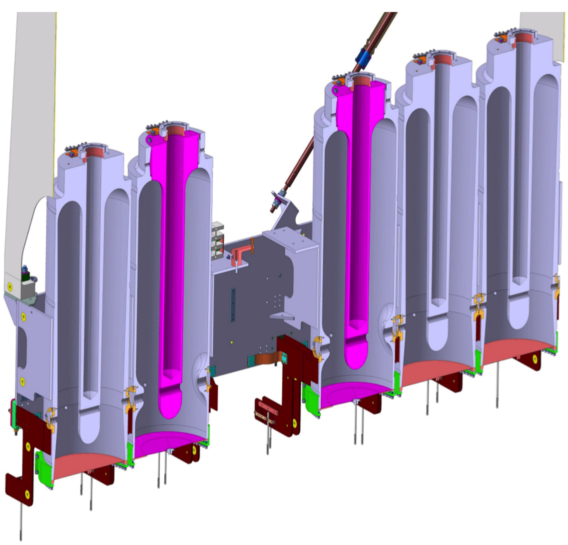

Figure 9: Mechanical simulation of a possible cavity configuration in the cryomodule.

BEAM DYNAMICS

Vertical Steering

The beam through the QWR is kicked by the RF magnetic field and by the dipole electric field inevitably existing in the accelerating gap. On the QS design, this vertical steering effect was corrected by a racetrack shape beam port and a displacement of the beam axis from the center of the beam port by 2.5 mm [4]. This offset kicks up the beam, which sees an additional RF electric field near the beam hole. However, for the seamless design this correction is not needed, since it will be installed in the high β section of the linac. Taken

Figure 10: Test blank assembly on the CM.

this into account and in order to reduce the beam port to avoid RF leakage, it was chosen to be a smaller pure circle of 9 mm radius.

Multi-particle Tracking

According to a full numerical multi-particle tracking through the whole linac consisting of 20 cavities in 4 cryomodules, without misalignment errors, the decrease of the transmission and the beam emittance growth caused by the steering effect of the QSS cavities installed in the high β section (CM3 or CM4) is negligibly small as summarized in Table 3. Two cases were checked with respect to the reference case; (1) 6 QSS-type cavities located in the final 2 cryomodules (in locations not adjacent to the solenoid) and (2) 20 QSS-type cavities at all locations, as shown in Figure 11. The cavity voltages were normalized to V_{acc} = 1.8 MV so that a comparison of the transit time efficiency can be made by comparing the output energy of the linac.

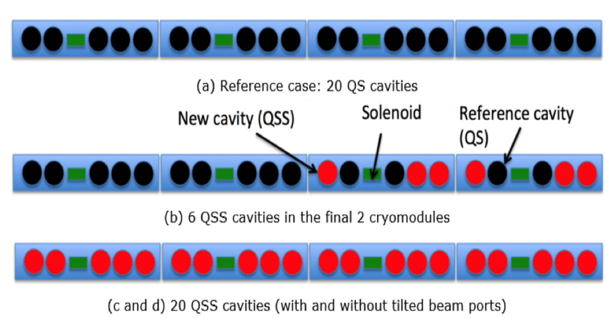

Figure 11: The cases studied in the multi-particle linac tracking simulations.

The full study can be found detailed in [8]. It was decided not to correct the steering effect because it is small enough in CM4, which is the highest β section.

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Table 3: Comparison of Transmission and Emittance Growth (A/q = 2.5)

Cavity	Output Energy [MeV/u]	Transmission [%]	*RMS [%]
(a)	14.17	100	0.0
(b)	14.20	100	-0.3
(c)	13.86	85	21.2
(d)	13.81	100	4.6

* Transverse RMS Emittance Growth
(a) Original, (b) Seamless in final 2 high β cryomodules, (c) Seamless in all high β cryomodules, (d) Tilted beam port in all sections

For future application, if the seamless cavity is used as a spare of some of the cavities in upstream cryomodules, tilting the angle of the beam port can be an option. This technique gives a smaller vertical steering at low β [9].

Reducing the beam port aperture to mitigate the field leakage from the cavities will restrict the phase-space acceptance of the linac, with potential consequences on beam transmission. The effect will be negligible for high-energy beams, accelerated throughout the linac. However, for lower energy beams where the emittance is not adiabatically damped, the emittance is larger and less margin will be available in the aperture for steering and misalignment errors. For this reason it is preferable to locate the QSS cavities away from the solenoid where the beta envelope function is large, as shown in case (b) of Figure 11.

Impact of Beam Port Aperture Reduction on LINAC Acceptance

The reduction in acceptance was also calculated for the transport of a low-energy beam from the RFQ at 300 keV/u for a conservative geometric total emittance of 20 mm mrad. The beta function at the cavities located next to the solenoids is matched at approximately 2.2 m, which gives for a nominal aperture of ±10 mm at the cavity beam port an acceptance of 45 mm mrad, roughly twice the assumed beam emittance at this energy. A 1 mm reduction in the beam port radius reduces this acceptance to 37 mm mrad, i.e. a reduction in acceptance of ≈ 20%. However, if the QSS cavities are not installed next to the solenoid but elsewhere in the cryomodule the acceptance will not be restricted.

RF MEASUREMENTS

Preparation

After the cavity went through the conventional process of frequency tuning, chemical treatment (SUBU) and coating, in Figure 12, the cavity was mounted on a test insert inside of an ISO 5 clean room [10]. Then the thermal sensors were fixed and the pick-up antenna, the RF power coupler and the tuning system installed.

Figure 12: QSS before and after coating.

Cool-down and Measurement

First, the low-field multipacting (MP) starting at 20 kV/m was conditioned at warm, with the power coupler fully inserted for optimum efficiency. When the cavity was at its nominal operation temperature, 4.5 K, a new MP barrier at 1.2 MV/m was conditioned and the cavity reached its nominal operation accelerating field of 6 MV/m. Figure 13 shows the results of this test and the performance comparison of QSS1 cavity and the other QS cavities measured in the vertical test stand. Due to the increase of the cavity cross section at the top, where the gaps for shrink fitting were suppressed, the thermal conductivity seems were optimized. Shown in Figure 13 is the data about the thermal cycle: this cavity seems to be insensitive to it, contrary to the series cavities [11].

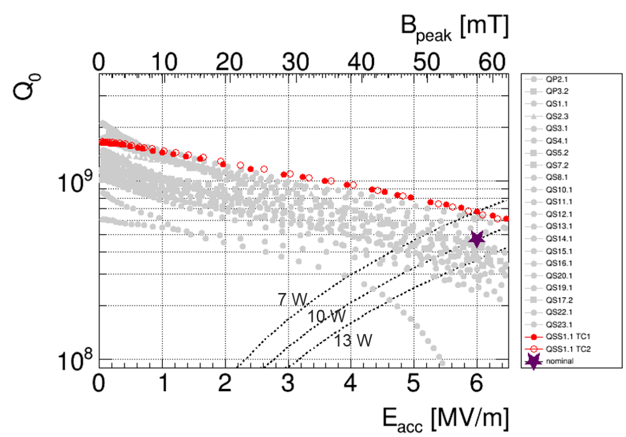

Figure 13: Performance of QSS1 among previously measured cavities.

CONCLUSION

An in-depth study of a new seamless cavity design has been developed, motivated by the wish of avoiding the EB welding process on the high magnetic field region of the HIE-ISOLDE QWR.

The RF performance has been studied and compared with the nominal design values. The figures of merit show a slight improvement in terms of magnetic peak field and a β_{opt} value that is also higher, which indicates better performance for its usage in CM4. However, if these cavities were

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to be used at a low energy end of the linac, the beam steering would have to be corrected (i.e. tilting the antenna and the beam ports). Since the removal of the weld eliminates the main source of potential imperfections, the surface resistance was expected to be improved, lowering the cryo power needed to keep the cavity in superconducting state. This is also supported by the fact that the cooling by conduction will be enhanced on the new QSS design, which will lead to intrinsically lower thermal gradients across the cavity during cool down. As shown in the RF measurements, these assumptions were indeed correct, showing an improvement of the Q value and a power dissipation of only 7 W at nominal field, 6 MV/m.

Mechanical studies and assembly tests have also taken place and the geometry and kinematics were thoroughly checked to ensure that there are no interface issues throughout the preparation processes and the integration in the cryomodule.

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REFERENCES

[1] I. Ben-Zvi and J.M.Brennan, "The Quarter Wave Resonator as a superconducting LINAC element", *Nuclear Instruments and Methods* 212 (1983), 73-79.

[2] L. Alberty, G. Anrau, I. Aviles, S. Calatroni, O. Capatina, G. Foffano, Y. Kadi, P. Moyret, K.-M. Schrim, T. Tardy, W. Venturini Delsolaro, and A. D'Elia, "The Copper Substrate Developments for the HIE-ISOLDE High-Beta Quarter-Wave Resonators", in *Proc. SRF2013*, Paris, France, 2013.

[3] A. M. Porcellato, S. Stark, V. Palmieri, and F. Stivanello, "Niobium Sputtered QWRs", in *Proceedings of the 12th International Workshop on RF Superconductivity*, Cornell University, Ithaca, New York, USA, (2005).

[4] M. A. Fraser, "Beam Dynamics Studies of the ISOLDE Post-Accelerator for the High Intensity and Energy Upgrade", 2012, *EuCARD Series on Accelerator Science and Technology*, Vol.13, EuCARD-BOO-2012-002", https://cds.cern.ch/record/1473438

[5] CST Microwave Studio, 2016. [Online]. Available: www.cst.com [Accessed 01 12 2016].

[6] ANSYS, 2014. [Online]. Available: www.ansys.com [Accessed 12 01 2017].

[7] J. K. T. H. H. Padamsee, "RF Superconductivity for Accelerators", New York, John Wiley & Sons, 1998.

[8] M. A. Fraser and A. Miyazaki, "HIE-ISOLDE beam dynamics study. New conical cavity variants: effect of beam steering", 2016. [Online]. Available: www.edms.cern.ch [Accessed 2017].

[9] A. Facco and V. Zvyagintsev, "Beam steering in superconducting quarter-wave resonators: An analytical approach", *Physical Review Special Topics - Accelerators and Beams*, 2011.

[10] M. Therasse, L. Alberty, K. Artoos, S. Calatroni, O. Capatina, A. D'Elia, N. Jecklin, Y. Kadi, I. Mondino, K. Schirm, A. Sublet, W. Venturini Delsolaro, and P. Zhang, "Series superconducting cavity production for the HIE-ISOLDE project at CERN," in *Proceedings of LINAC 2014*, Geneva, Switzerland, paper THPP131.

[11] P. Zhang , G. Rosaz, A. Sublet, M. Therasse, and W. Venturini Delsolaro, "The influence of cooldown conditions at transition temperature on the quality factor of the niobium sputtered quarter-wave resonators for HIE-ISOLDE", in *Proceedings of SRF2015*, Whistler, BC, Canada, https://doi.org/10.18429/JACoW-SRF2015-TUBA01

[12] "Internal Review on HIE-ISOLDE seamless cavities", April 2016. [Online]. Available: https://indico.cern.ch/event/525522/. Accessed [11 07 2017]