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SEAMLESS QUARTER WAVE RESONATORS FOR HIE ISOLDE

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Abstract

The HIE-ISOLDE post accelerator consists of 4 cryomodules with 5 niobium-coated Quarter Wave Resonators (QWR) each. The standard manufacturing technique was to machine the inner and outer conductor separately, to shrink-fit the 2 pieces and to apply an electron beam welding at the interface. Due to micro cracks, observed on some of the cavities around the welds, we took the decision to explore the possibility of a seamless design. First cavities became available in late 2017 and were then cold-tested in the vertical cryostat. These seamless coated quarter wave resonators have shown some of the highest Q-values of all HIE-ISOLDE cavities in the acceptance tests. Furthermore, we studied the cavity performance with different compensations of the earth magnetic field and different temperature gradients upon cool down. These tests have demonstrated record-breaking RF surface fields for the Nb/Cu technology. This paper reviews the design and fabrication, and reports on the cold tests results of seamless quarter wave resonators. Possible future applications are briefly illustrated.

INTRODUCTION

The HIE-ISOLDE post accelerator is in operation at CERN since 2015, delivering a rich physics program to the community of users. The project was staged, and the high beta section of the machine was completed in spring 2018 with the addition of the fourth cryomodule. The backbone of the accelerator are the niobium sputter coated QWR,realized at CERN using copper cavity substrates done in industry. The early cavity development is documented in [1]. During the production phase, we faced performance degradations, which could be traced back to defects on the copper substrates, in proximity of the electron beam weld. In response to this issue, a seamless design was developed, as reported in [2]. In this paper we report more results, including the performance with beam. Cavities of the new design are labelled QSS, as opposed to the old QS type.

SEAMLESS QWR DESIGN

The main rationale for a seamless design was in our case to remove the possible source of defects in the copper substrates, represented by the electron beam weld, which was located close to the peak magnetic field. Small cracks on the copper substrate can trap fluids during the chemical polishing phases, which then contaminate the niobium layer. However, there are more advantages: the fabrication is simpler and cost effective with respect to the old design. Also, removing the weld allowed to greatly increasing the cross section for the heat path between the lower portion of the resonator and the heat sink in the inner conductor, with beneficial effects on the cooling, both during coating and in operation. This is because in the old design an annular gap remains above the weld, as the required mechanical tolerances for the mating pieces are more easily achieved over a short length. In Fig. 1 the seamless QWR is compared to the welded design.

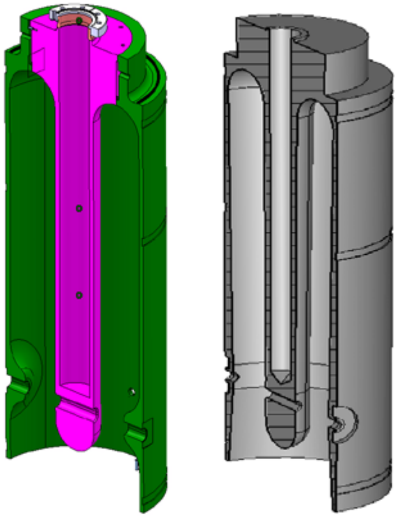

Figure 1: Welded and seamless HIE-ISOLDE QWRs.

In order to make possible the use of a lathe, and avoid milling, the cavity had to be axially symmetric. However, the removal of the cavity “noses” posed a difficulty as it severely decreased the R/Q and thinned the cavity wall, with consequent potential risk of RF leakage. We adopted a double conical shape mainly to recover R/Q.

RF leakage was suppressed by changing the beam port aperture from a racetrack to a circle with a diameter reduction of 2 mm, and by extending the cut-off length in a matching piece, which is made to support the cavity in the cryomodule, as shown in Fig. 2.

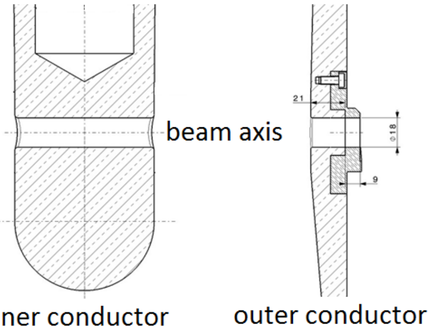

Figure 2: Beam port of the seamless HIE-ISOLDE QWR.

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RF simulations with two different codes, and laboratory measurements, demonstrated that RF leakage was under control. Beam simulations had shown that the aperture restriction was tolerable. All this has found finally confirmation in July 2018 when the first ion beam was accelerated through the full linac. Changing the shape of the beam aperture from a racetrack to a circle also had the consequence of giving up the compensation for the vertical steering. This was not expected to be a problem, as the cavity was to be installed in the high-energy section in the linac. However, the absence of compensation for the vertical beam steering limits the use of these cavities as spare units to the cryomodules after the first one on line, where steering compensation is not necessary. In addition, the optimum beta of the seamless cavities is higher than in the welded version, making the use of this cavity more favourable in the higher energy end of the linac. Table 1 shows the optimized RF parameters, compared with the welded design.

Table 1: Figures of Merit of Welded and Seamless QWR

Parameters	QS	QSS
β_{opt} [%]	10.9	12.2
R/Q [Ω]	520	502
E_{peak} /E_{acc}	5.4	5.2
B_{peak}/E_{acc} [Gauss/(MV/m)]	96	93
G= R_s.Q [Ω]	30.34	30.71
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]

Peak fields are comparable, and the loss of R/Q was maintained well below 5%.

VERTICAL TESTS

The first two seamless cavities were acceptance-tested at 4.5 K in the CERN vertical test facility and scored above all the other cavities in the series production (Fig. 3).

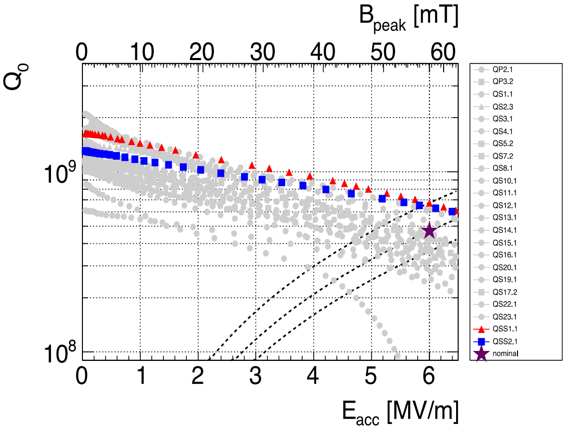

Figure 3: RF performances of welded and seamless HIE-ISOLDE QWRs in the vertical tests at 4.5 K.

The first cavity was qualified in time for installation in the fourth cryomodule, while, in order to respect the project schedule, the second had to be kept as a spare. On this second cavity, we carried out a dedicated test campaign, to understand the origin of the good performance. Full scans of Q values between 2.4 K and 4.6 K were done at several values of the RF field, as shown in Fig. 4, for different amounts of trapped flux (obtained by means of compensation coils placed outside the cryostat), and for different cool down speeds, resulting in different temperature gradients across the cavity at the superconducting transition.

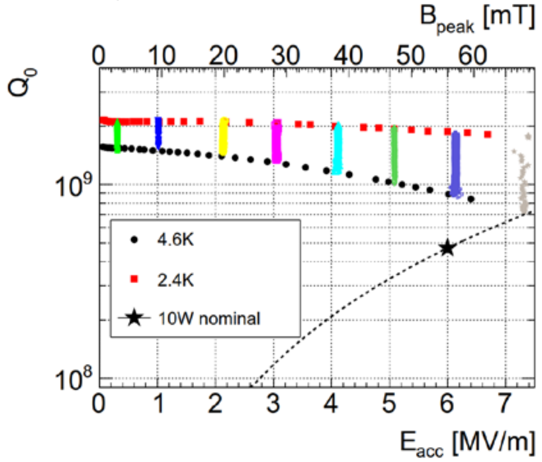

Figure 4: Q versus E and Q versus T curves of a seamless HIE-ISOLDE QWRs.

The seamless cavities were found to behave in a very different way with respect to the normal cavities. A first difference is the higher sensitivity to trapped magnetic flux. Nb/Cu cavities were known to be insensitive to flux trapping, and in all accelerators where they have been employed they operate without magnetic shielding. In contrast, this cavity shows a significantly higher sensitivity, as shown in figures 5 and 6. Still, these values are lower than in typical bulk niobium cavities by about a factor of ten.

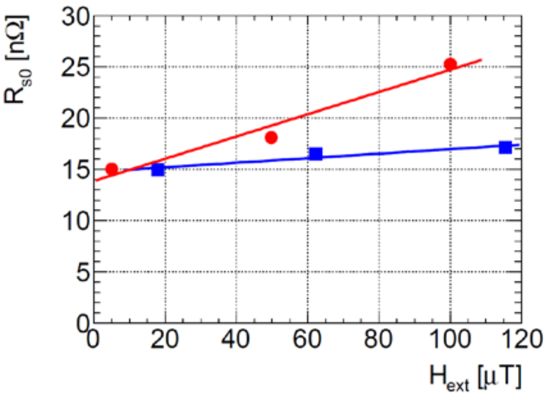

Figure 5: Dependence of the zero-field surface resistance on trapped flux (circles: QSS; squares: QS).

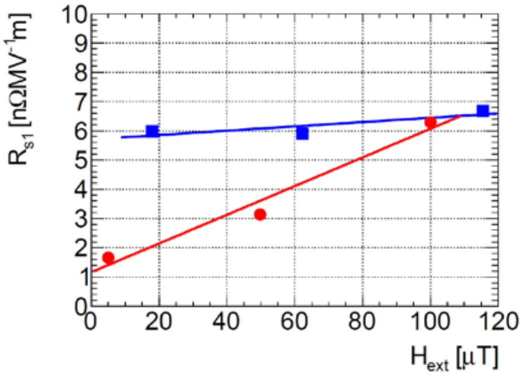

Figure 6: Dependence of the surface resistance slope on trapped flux (circles: QSS, squares: QS).

A second striking difference is that, contrary to their welded counterparts [3], these cavities show the same Q values, irrespective of the thermal gradient measured on the cavity when crossing Tc during cool down. It is possible that, due to the much higher cooling efficiency, the actual temperature gradient on the RF surface is always very small, no matter how fast the cooling is. Therefore, it is not possible to conclude that the cavity is less sensitive to the thermal gradient, as it would seem from the raw data. As a fact, the cavity performance does not depend on the modalities of cool down, and it is uncorrelated to the thermal gradient measured on the outer surface. These findings also suggest a possible interpretation for the spread in sensitivity to the thermal gradient, observed in the QS population. The weld penetration was at the beginning of the production only specified as a minimum value (2 mm), and in a second time the company was instructed to reduce it, in an attempt to mitigate the damages around the welds. This may have resulted in a variability of effective cooling cross sections at the weld in the series production, determining the actual temperature gradients on the RF surfaces. On the other hand, the insensitivity to cool down, together with a higher sensitivity to trapped flux would cast a doubt on the usual interpretation of the dependence on thermal gradient of the residual resistance, in terms of trapped thermoelectric currents.

Having realized that the cavity was sensitive to ambient magnetic fields, we have tried to test it as close as possible to zero field-cooling conditions, by making use of compensation coils placed outside the cryostat. The results were spectacular, as shown in Fig. 7. The cavity reached a peak magnetic field of 120 mT, which is the highest ever achieved with the Nb/Cu technology. At 120 mT, we observed a reversible Q switch, without quench, and decided not to push the cavity any further. The most interesting feature of this result lies in the fact that the infamous Q-slope, which has-so far-prevented the use of sputtered cavities in high gradient machines, was almost absent at low temperature. Actually, this cavity behaves as bulk niobium, as far as the Q- slope is concerned, while the residual resistance is still higher than in state of the art bulk niobium cavities in this frequency range.

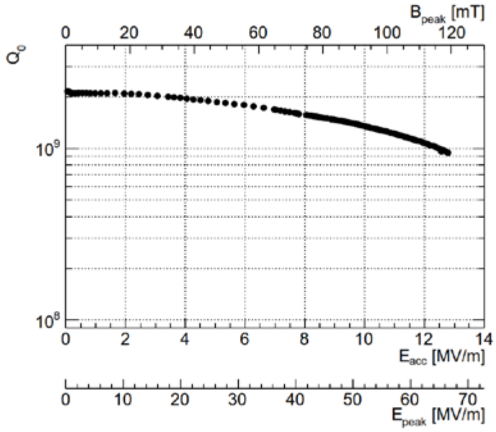

Figure 7: RF performance of a seamless QWR in reduced magnetic field at 2.5 K.

We realised that, once the linear Q slope due to magnetic flux trapping was eliminated, there remained a temperature dependent slope (non-quadratic losses), which behaved exponentially with respect to the RF field, and which can be empirically fitted by assuming a reduced superconducting gap, the reduction being proportional to the RF field. From a literature survey, it appeared that this component is common to both bulk Nb and Nb/Cu technologies, and is not usually visible in bulk niobium data just because it is strongly temperature dependent and prominent at 4.5 K, while most published bulk niobium data are at superfluid temperatures. This topic will be the subject of a dedicated paper.

PERFORMANCE IN HIE-ISOLDE LINAC

All HIE-ISOLDE cavities of the QS type, once installed in the linac, have shown a remarkable improvement in performance with respect to the vertical tests (see Table 2). Although the reason for this performance gain is not completely clear, we believe it is due to more homogenous cooling conditions: indeed the Q values in the linac are close to a zero gradient extrapolation from the vertical tests carried out at different temperature gradients.

The insensitivity to the cool down conditions of the seamless cavity made us expect no performance improvement from the vertical tests to the cryomodule. This was confirmed in the 2018 campaign. The QS cavities had their Q values changed due to slightly different cooling conditions, while the QSS cavity displayed the same results as in the vertical test, within the calibration uncertainty.

The absence of magnetic shielding in the HIE-ISOLDE cryomodules also favours the insensitive welded cavities in the comparison with the QSS. In spite of that, the seamless cavity is still well above specification in the linac and it has the advantage of a reproducible performance after thermal cycles, which might be caused by outages of the cryoplant, or by the normal annual operation schedule.

In Fig. 8, we show the RF performance of the HIE-ISOLDE cavities on line during the 2018 commissioning campaign. One of the cavities developed an RF connection fault and we decided not to use it for this year.

In Table 2, we report the Q values at nominal field for each cavity, at the vertical test and in the linac over the years. The suffixes in the legend refer to the substrate serial number and the coating number, respectively. QP are prototype cavities of the welded type.

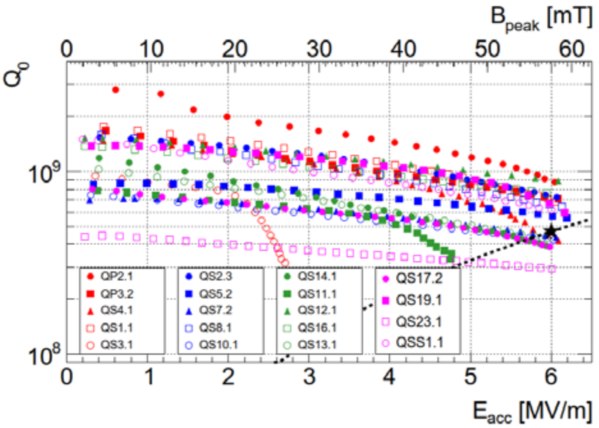

Figure 8: RF performance in 2018 of HIE ISOLDE linac cavities.

Table 2: $Q/10^8$ values of the HIE ISOLDE cavities at 6 MV/m in vertical tests (VT) and before each physics run. The HIE-ISOLDE specification is 4.7 (10 W at 4.5 K). Where field emission limited the operational gradient, the onset field is indicated.

Cavity	VT	L2015	L2016	L2017	L2018
QP2.1	6.3	8.2	3.5MV/m	11.0	8.7
QP3.2	4.3	5.4	7.9	7.7	7.3
QS4.1	4.3	5.9	6.6	7.1	4.4
QS1.1	3.7	6.6	7.1	7.9	6.9
QS3.1	3.6	4.4	4.5MV/m	4.5MV/m	2MV/m
QS2.3	3.6	-	6.4	8.4	7.4
QS5.2	3.5	-	4.2	6.2	5.7
QS7.2	4.0	-	4.3	5.3	4.4
QS8.1	3.7	-	4.9	7.2	6.5
QS10.1	3.1	-	4.0	5.7	4.2
QS14.1	2.4	-	-	4.1	3.9
QS11.1	2.8	-	-	3.5MV/m	4MV/m
QS12.1	3.0	-	-	9.0	9.0
QS16.1	5.3	-	-	9.4	7.6
QS13.1	2.8	-	-	4.1	4.3
QS17.2	4.3	-	-	-	3.9
QS19.1	4.6	-	-	-	6.6
QS22.2	3.7	-	-	-	-
QS23.1	3.2	-	-	-	2.9
QSS1.1	6.7	-	-	-	6.2

DESIGN EVOLUTIONS AND POSSIBLE FUTURE APPLICATIONS

The first obvious extension of this design is to reintroduce a mechanism for the correction of the vertical beam steering, which is inherent to the QWR geometry [4]. This would allow having a universal spare for the HIE-ISOLDE machine. Due to the tight space constraints in the existing cryomodules, tilting of the beam ports is the favoured option to achieve this result.

A more ambitious goal is to develop seamless QWRs for higher beta acceleration, having in mind applications for high current proton machines. The production of a large series of such cavities would be quite cost effective, when compared with alternatives like for instance half wave resonators made of bulk niobium. We made some explorative steps in this direction: Fig. 9 shows the RF design of a QWR with optimum beta of 0.36. The usual figures of merit are listed in Table 3. This shape would be easy to machine out of a copper billet, and the same coating recipe used for HIE-ISOLDE would be applicable.

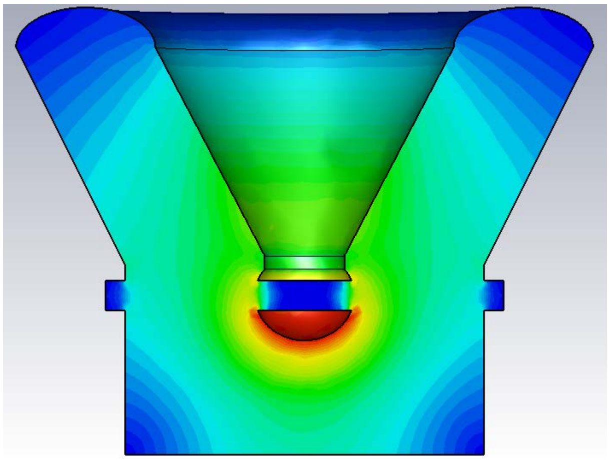

Figure 9: RF design of a seamless QWR for high beta.

Table 3: Figures of Merit of a beta=0.36 Seamless QWR

Figure of merit	Value
f [MHz]	229
Γ [Ω]	183
E_{pk}/E_0	5.6
B_{pk}/E_0 [mT/(MV/m)]	6.4
L_{cav} [mm]	360
β_{opt}	0.36
TTF(β_{opt})	0.77
R/Q(β_{opt}) [Ω]	309

Due to the large velocity acceptance, about 50 cavities of this type would be sufficient to accelerate protons between 100 MeV and 220 MeV. The total cryogenics power would be of the order of 2-3 kW at 4.5 K. The mechanical aperture for the beam was 30 mm in this simulation. If necessary, beam steering correction could be achieved by using a racetrack shaped beam aperture, and offsetting the beam. Microphonics would be utterly suppressed by the rigid copper substrate.

For a large accelerator, this solution could represent non-negligible savings on capital costs.

CONCLUSION

Seamless Quarter Wave Resonators for the HIE-ISOLDE post accelerator were designed at CERN with optimized RF parameters, fitting the existing cryomodules. The cavity substrates have been obtained in industry by machining single OFE copper billets, and then coated with niobium and tested at CERN. Two cavities have completed this process so far, while a third is about to be coated. The RF performances of these cavities were the best of the whole series production in the acceptance tests in a vertical cryostat. Moreover, the second cavity, which was extensively studied in various conditions of shielding, showed unprecedented peak fields for the Nb/Cu technology. Peculiar features of the seamless cavities are the higher sensitivity to magnetic flux trapping, and the lack of sensitivity to the cool down conditions.

This technique, while removing at the source the risk of defects around the electron beam welds, is also cost effective and provides a much better cooling of the resonator.

The validation of the QSS design was complete in summer 2018, with the first ion beam acceleration. Since then, the first seamless cavity is operating and delivering accelerated beam to the users.

Stimulated by this success, we plan to improve the design, incorporating a correction of the vertical beam steering, which would allow to install these cavities also in the low energy section of the linac.

As a possible future application, we sketched a seamless QWR, which could be apt to accelerate protons in the energy range of 100-200 MeV, with the known advantages of the Nb/Cu technology.

ACKNOWLEDGEMENTS

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S. Teixeira Lopez and T. Mikkola carried out most of the design work of the QSS cavity, M. Garlasche followed up the manufacturing in industry, and A. Sublet performed the niobium coatings at CERN.

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