THE HIE-ISOLDE SUPERCONDUCTING CAVITIES: MECHANICAL DESIGN AND FABRICATION

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Abstract

The HIE-ISOLDE superconducting linac at CERN will be based on 101.28 MHz niobium sputtered copper Quarter Wave Resonators (QWRs), which will be installed downstream of the present REX-ISOLDE linac. The current design considers two basic cavity geometries (geometric β_0 of 0.063 and 0.103). We report here on the choices for the mechanical design of the high beta cavities, as well as on the specific details of the fabrication of the first copper prototype.

INTRODUCTION

HIE-ISOLDE [1] is the name of the proposed global upgrade of the ISOLDE Radioactive Ion Beams facility at CERN. In this framework, an energy upgrade with a new superconducting linac based on QWRs is planned. Presently, the REX linac is delivering beams with mass to charge ratio of $2.5 \leq A/q \leq 4.5$ at a final energy of 3 MeV/u by means of a combination of several normal conducting structures. The energy upgrade will happen in two stages. In a first stage the final energy will be limited to 5.5 MeV/u while for the second stage the required final energy will be 10 MeV/u. The superconducting linac will also replace part of the normal conducting one so the energy span covered by the SC cavities will be between 1.2 and 10 MeV/u. In order to efficiently accelerate the beams in this velocity range two cavity geometries have been studied, one with a geometrical $\beta_0 = 0.063$ and the other with a geometrical $\beta_0 = 0.103$ (see Fig. 1). These values allow for an optimum acceleration efficiency for the heaviest A/q ratio (A/q=4.5). More details on the cavity RF design are given elsewhere in these proceedings [2, 3].

The new linac will make use of 12 low β_0 and 20 high β_0 cavities. In the first phase of the planned staged upgrade it is foreseen to install two cryomodules containing five high β_0 cavities each. The prototyping work was thus concentrated on the design and manufacturing of this cavity type. In this paper, we will describe the basic choices, as well as the key issues and findings from the fabrication of the first prototype.

CAVITY MECHANICAL DESIGN

The basic technological choice for the HIE-ISOLDE cavities lies in the use of the Nb/Cu technology [4], pioneered by CERN where a core competence exists for $\beta_0 = 1$ elliptical resonators. Much of the design work was indeed also based on the experience developed at LNL-INFN [5], where sputtered Nb/Cu QWR resonators have been in use for years. The key reason behind this choice is that, compared to bulk niobium cavities, copper ones can easily be made massive and stiff in order to reduce microphonics effects, and to prevent the deformations due to the mechanical actions of the tuning system, at a fraction of the cost. This is of course done at the expense of the added complication of the sputtering of the niobium film, a technology that has however been established for several years already. A further advantage of the thick copper substrate is that the liquid helium cooling circuits in the cryostat are simplified. The cavity can in fact be cooled only by pool boiling He-I within the inner stem and over the top part, the thick external copper wall ensuring an adequate heat transfer by conduction. A thermal analysis has been carried out with a non-linear finite element model taking into account the dependence on temperature of the copper thermal conductivity and the helium film convection coefficient (Fig. 2). With the expected power dissipation distribution the temperature does not rise above 5.1 K, the design cri-

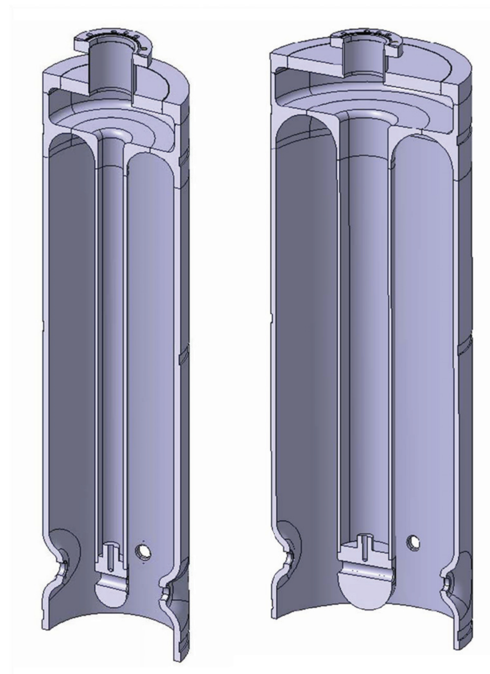

Figure 1: 3d-sketch of the two cavity types, low β_0 (left) and high β_0 (right).

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terion being that the calculated temperature should always remain below 6 K, corresponding to an expected increment of surface resistance of about 20%. The study of the natural mechanical frequencies of the cavity also led to a choice of a thick-walled structure (≥ 10 mm) in order to increase the resonant frequencies, which should be beneficial in terms of RF operation. The use of a damper in the inner stem is also envisaged, depending on the results of the first RF tests.

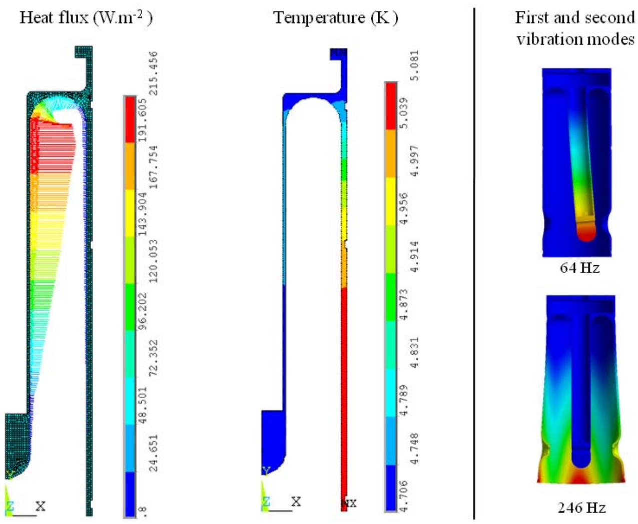

Figure 2: Heat flux input and resulting temperature distribution in the cavity, considering the thermal conductivity of RRR=100 copper and 4.5 K He-I pool boiling cooling in convection and nucleate boiling regimes (left). First and second vibration mode shapes and corresponding frequencies (right).

PROTOTYPE CAVITY MANUFACTURING

Following CERN experience, the copper used for cavity manufacturing is of Cu-OFE grade (UNS C10100), at least in the half-hard state, either in the form of rolled sheets or 3-D forged pieces, in order to minimise porosities which are harmful for the niobium film coating process. Common extruded pieces have in fact an inferior degree of compaction, with pores aligned with the extrusion direction.

A critical manufacturing choice, made in order to maximise the benefits of the cavity design, was of not performing any brazing on the main body of the cavity. Copper softening due to the high temperature treatment would hinder the mechanical stability and geometrical precision of the cavity, thus reaping the benefit of having a thick-walled structured. Moreover, experience from INFN-LNL suggests that the presence of brazing alloy in the active RF regions may also contaminate the niobium film. Manufacturing the cavity from one single copper piece by turning and/or milling of the complete shape has been considered, but discarded due to the projected cost of a 3-D forged billet of the required size and of the extremely complex operation of a 3D machining which includes the beam ports. The option of using standard metal working techniques and then joining the pieces by e-beam welding has thus been chosen, which is a common technique for SC cavities.

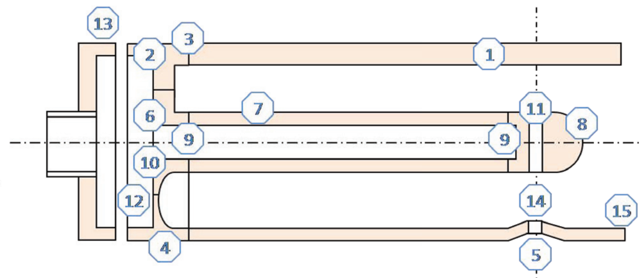

Figure 3: Schematic sequence of the different manufacturing steps of the QWR cavities. The numbering is explained in the main text.

The chosen manufacturing sequence comprises several steps, which are briefly described here with reference to Fig. 3. These comprise: 1) Rolling of the external half tubes from sheets, longitudinal welding, rough machining. 2) Machining of the outer head. 3) E-beam welding of the two parts. 4) Fine machining of the inner surface of the external conductor. 5) Deepdrawing of the beam ports and rough machining of the beam opening. 6) Manufacturing of the inner head. 7) Manufacturing of the central tube. 8) Manufacturing of the end stem of the inner conductor. 9) E-beam welding of the three parts of the inner conductor. 10) Fine machining of the inner conductor 11) Drilling of the beam line. 12) Final long-distance e-beam welding of the cavity head. 13) E-beam welding of top flange ensemble. 14) Final machining of the beam ports. 15) Straightening.

The longitudinal e-beam welding in step 1, performed over a length of almost 1 m and a thickness of 15 mm, albeit tested on several short-length prototypes, proved to be more difficult than foreseen and resulted in several porosities. These were successfully ground after welding, with the aim of preventing trapping of chemical products during surface treatment, which may clearly hinder the final RF performance. The quality of this and all other weldings has been monitored by ultrasound and X-ray testing, but these techniques do not allow resolving the smaller porosities. More testing and optimisation of the welding parameters would clearly be necessary in this respect in view of a series production.

The manufacturing of the beam ports by deepdrawing in step 5 is a critical process that has been extensively validated on several test pieces. The operation is done by progressive deformation of copper with punches of different shapes into a fixed die, under a press exerting a force of 200 kN, until the final shape is reached (Fig. 4). Development work has shown that with appropriate design of the tooling, the thickness of the wall is at all locations never reduced below 8 mm from the starting thickness of 10 mm. Executing the deepdrawing on the real cavity requires high precision in mounting and dismounting the different tools

Figure 4: Progressive formation of the beam ports by deepdrawing on a test piece. The punches and die are changed for each step. A flame annealing of the copper is performed before each step, in order to soften it and prepare it for the deepdrawing.

and extreme care in the handling. The cavity undergoes local flame annealing before each step, for softening the copper locally in order to ease the deepdrawing process, and this makes in fact all handling operations rather delicate, requiring dedicated tooling. Thermal conductivity of copper is known not to be affected by flame annealing, and the mechanical properties are partially restored by the cold working of the final deepdrawing step.

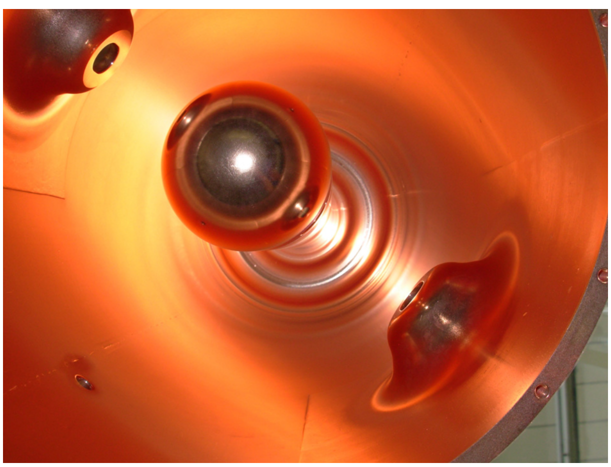

Figure 5: View of the interior of the finished prototype cavity, after chemical surface treatment.

The final e-beam welding of the top plate in step 12 needs to be done from the side of the inner surface exposed to RF, in order to minimise porosities and projections of molten material, as the LEP/LHC experience has shown. It has been demonstrated in full scale simulations on test pieces that this can be successfully achieved with the e-beam gun kept outside the cavity, at a distance of about one meter. Surface preparation prior to coating will be carried out by SUBU [4] chemical etching. The surface roughness on the welding seam after 20 μm material removal was reduced to the expected average roughness R_a of 0.8 μm, common for this type of processing. Since all other surfaces will be milled or turned with high accuracy, only this minor material removal is necessary in order to achieve an optimum surface state. More details are given elsewhere in these Proceedings [6]. It is worth mentioning that the surface treatment has been fully validated on the prototype cavity resulting in a smooth and shiny surface (see Fig. 5).

It has however been decided to look again into the possibility of machining at least the outer cylinder by 3D milling from a single copper forged billet. Although this option will probably be much more expensive that the presently considered technology, in particular since most tooling for deepdrawing have already been fabricated at CERN, it is nevertheless worth considering in view of possible series fabrication by subcontractors, who may decide autonomously of choosing this technology. As a consequence its feasibility should be validated, also because this technology would have the further advantage of avoiding any heat treatment, albeit local.

QUALITY CONTROL

The quality of the cavity has been controlled several times during fabrication with a series of RF measurement, especially comparing the variation of the resonance frequency between various manufacturing steps, and all the measurements are in line with the theoretical predictions. In order to perform these test, partial mechanical assembly of the main cavity sub components was performed (see Fig. 6).

Extensive metrology checks have also been performed at all steps of the fabrication. These were necessary in order to study deformations induced by the weldings, the accuracy of the machining of the final surface profiles, and the deepdrawing of the beam ports. For the latter in particular, the manufacturing procedure has been optimised through many iterations between metrology checks and tooling modifications, on cylindrical prototypes of short length. It is presently assumed that the procedure is fully validated and that repeated metrology controls are not needed for production, except of course for the final acceptance. It should however be mentioned that the deepdrawing process induces a slight deformation from cylindrical shape of the bottom part of the cavity, which has to be corrected by plastic deformation in a press. This in turn may induce a slight asymmetry of the beam ports distance form the cavity axis, which is corrected by the final machining of the internal surface which is required by design. The specified shape accuracy of $\pm$ 0.1 mm has finally successfully been achieved on the prototype. It should be mentioned that the construction of the prototype suffered a couple of accidents due to human errors, related to the complex sequence. This is a further demonstration of the clear need of defining detailed procedures and putting in place a strong QA plan for the series production.

Figure 6: Mechanical assembly of cavity sub components for an intermediate RF check. This operation, as well as metrology controls, are carried out in a temperature-controlled room in order to ensure the best accuracy.

CONCLUSIONS AND OUTLOOK

The design and fabrication work for the HIE-ISOLDE QWR prototype started in spring 2008 with the basic RF design. After one year of intensive study by the design, engineering and manufacturing team the cavity has successfully been delivered for surface treatment. The cavity is now ready for niobium sputtering, which has been optimised in the meantime and is scheduled for October 2009. It should be mentioned that in parallel, all the surface treatment and cavity coating facilities have also been designed and manufactured, as well as several tooling related to all the fabrication, treatment and coating operations.

Five other pre-series cavities are in the pipeline for fabrication at CERN, which will be used for equipping a full prototype cryomodule. Development of a low beta cavity prototype (mechanical design, manufacturing, coating optimisation) is also scheduled for 2010, in parallel with the optimisation of the coating of the high beta cavity.

Series production for the full HIE-ISOLDE linac could start as early as mid-2010, at the rate of 10 cavities/year, pending the official approval of the project.

ACKNOWLEDGEMENTS

This success has been made possible, in a period of hectic activity at CERN related to the LHC collider, due to the dedication and passion of a large number of people from the EN/MME and TE/VSC groups at CERN, who all gave a little share of their time and expertise in order to bring this project to completion.

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