THE COPPER SUBSTRATE DEVELOPMENTS FOR THE HIE-ISOLDE HIGH-BETA QUARTER-WAVE RESONATORS

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Abstract

A new Linac using superconducting Quarter-Wave Resonators (QWRs) is under construction at CERN in the framework of the HIE-ISOLDE project. The QWRs are made by niobium sputtered on a bulk copper substrate. The working frequency at 4.5 K is 101.28 MHz and they will provide 6 MV/m accelerating gradient on the beam axis with a total maximum power dissipation of 10 W. The properties of the cavity substrate have a direct impact on the final cavity performance. The copper substrate has to ensure an optimum surface for the niobium sputtered layer. It has also to fulfil the required geometrical tolerances, the mechanical stability during operation and the thermal performance to optimally extract the RF dissipated power on cavity walls. The paper presents the mechanical design of the high β cavities. The procurement process of the copper raw material is detailed, including specifications and tests. The manufacturing sequence of the complete cavity is then explained and the structural and thermo-mechanical behaviour during the tests performed on a prototype cavity.

INTRODUCTION

The High Intensity and Energy (HIE) ISOLDE project is a major upgrade of the ISOLDE and REX-ISOLDE facilities at CERN, which can currently deliver post-accelerated radioactive ion beams (RIBs) with energies up to 2.8 MeV/u via a normal conducting linear accelerator. This will be replaced by a superconducting Linac, composed ultimately of four high beta and two low beta cryo-modules, all containing superconducting RF QWRs for beam acceleration and solenoids for beam focusing. Such upgrade will allow increasing the maximum energy of the delivered RIBs up to 10 MeV/u [1]. For the first installation stage, two high-beta cryo-modules with a total of 10 QWRs are foreseen.

SUBSTRATE DESIGN

The first prototypes of the HIE-ISOLDE high-beta copper substrates were manufactured at CERN from rolled, deep drawn and electron beam welded copper sheets (Cu-OFE, UNS C10100) [2] – figure 1, left. Their manufacture was crucial for developing both fabrication strategies and sputtering techniques. At that time, design studies were being carried out in view of both reducing the manufacturing complexity of the copper substrates and increasing their stiffness, aiming for less sensitivity to the pressure fluctuations of the helium bath.

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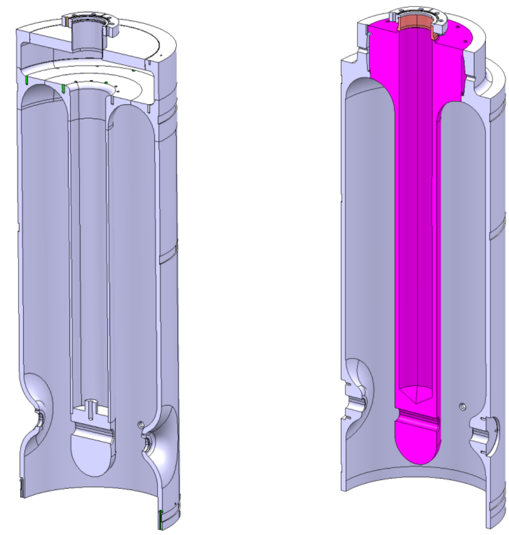

Figure 1: HIE-ISOLDE high-beta copper substrates: left) rolled and welded prototype; right) bulk machined prototype (inner conductor shown in magenta).

As very promising results were being found when increasing the sputtering temperature up to 600°C, which compromises shape accuracy, dedicated studies allowed relaxing the functional tolerances of the QWRs by a factor of five [3].

The new design – figure 1/right, consists of two parts (inner and outer conductors) machined out from copper forgings, shrink fitted and electron beam welded. Cryogenic connectivity is done through a DN63CF stainless steel flange vacuum brazed to a copper nozzle.

The number of critical RF electron beam welds was reduced to one and beam ports are no longer deep drawn but precision machined, allowing for both improved shape accuracy and repeatability. Sensitivity to pressure fluctuations is reduced by a factor of 10^2.

Supported by results, this version became the base design for the serial production of the HIE-ISOLDE high-beta copper substrates.

STRENGTH ASSESSMENT

Since 2008, the design of the HIE-ISOLDE high-beta cryo-modules has significantly progressed [1, 4]. In particular, regarding the strategy for supporting and aligning the RF cavities inside the cryomodule [5], as cavities are now simply supported by the beam ports. Specially designed supports connected to an alignment mechanism and bolted to the beam ports allow aligning the beam axis of each cavity to the theoretical axis of the linear accelerator. A Finite Element (FE) analysis was performed aiming at assessing the mechanical strength of the bulk machined copper substrates under exceptional working conditions, taking into account a pressure rise of the cryogenic system up to 4.5 bar (absolute) [6]. Results show that the beam opening, inside the inner conductor, is expected to reach a 5 µm offset with respect to the beam ports. The global sensitivity to pressure detuning is of the order of 0.074 Hz/mbar [6]. Dedicated stress analyses allowed validating the design of the high-beta quarter-wave copper substrates with comfortable safety margin. A modal analysis indicates that the first vibration mode occurs around 74 Hz.

THERMAL PERFORMANCE

As can be observed in figure 1, the inner conductor contains all the volume dedicated to the cryogenic helium bath. Thus, the outer conductor is purely cooled down by heat conduction, all heat being extracted through the two regions connecting the two conductors. In view of optimal heat extraction, these are both copper-on-copper prestressed and welded contacts. A FE analysis was performed to assess the thermal performance of such interfaces [7]. Material was Cu-OFE UNS C10100 with a minimum Residual Resistivity Ratio (RRR) of 100. A non-linear convection model was adopted for simulating the cryogenic nucleate boiling heat transfer in two-phase 4.5 K He I. Thermal conductance is force-driven, as prestress was calculated from a structural analysis simulating the shrink fitting process. The circular RF weld has a bonding penetration depth of 1.8mm. Heat loads on RF surfaces were imported from electromagnetic simulations [8], 10W in total. Results from the steady state non-linear FE analysis show a negligible temperature gradient along the outer conductor. However, the circular electron beam weld on the RF surface is critical for extracting the heat from the outer conductor, as the total power flowing through the weld is a factor of 10 higher than the amount extracted by the prestressed contact.

COPPER PROCUREMENT

The procurement of Cu-OFE UNS C10100 forged blocks started by identifying potential suppliers through a market survey. Final material specifications are resumed in table 1. Two geometries were envisaged: either a single forged cylinder, or inner plus outer conductor near net shape forgings. A first call for prototypes allowed both assessing suppliers' technical capacity and procuring material to cover immediate needs.

Table 1: Forged Copper Specifications

Material	ASTM B 170 UNS C10100 Grade 1
Forging	3-D hot forging + cold forging
Grain size (max.)	300 µm
Hardness	65-90 HB
NDT	100% UT @ 2 MHz

Figure 2: Rough copper forgings for the outer conductors (left) and inner conductors (right).

Significant scattering of both costs and delivery times was observed between different suppliers. In some cases, first production trials failed. All finished prototypes were accepted with minor derogations concerning grain size, homogeneity and controllability. Prototyping allowed confirming that fine and homogeneous microstructures are possible (despite dimensions), that defects can be expected both after hot and cold forging, and finally, that Ultrasonic Testing (UT) controllability, strongly dependent of both microstructure and dimensions, is essential for assessing the material's quality. SEM observations performed on Nb coated Cu coupons cut from the first prototype block showed that the film microstructure was comparable to coatings performed onto rolled sheets.

MANUFACTURING TECHNIQUES & SERIAL PRODUCTION

A total of three bulk machined copper substrates were produced at CERN. The first prototype was manufactured from a single round forged billet, but this approach was found to be considerably time and budget consuming, due to technical limitations. For the serial production, near net shape copper forgings were preferred – figure 2. Regarding quality control, reception tests including UT are complemented by both destructive and non-destructive tests, as full material traceability is ensured. Generally, the forged half-hard material presented good machinability, and standard metal cutting techniques were adopted. However, due to geometric constraints, a special tool had to be developed to allow machining the beam ports in a 5-axis CNC milling centre. Ball nose end mills were used for final machining – figure 3, and surface roughness better than Ra=0.8 µm was measured. Prior to assembly, the leak tightness of the inner conductor is assessed at room temperature, the maximum acceptable leak rate being 2.10^{-11} Pa.m^3/s.

The inner and the outer conductors are first assembled by shrink fit. At CERN, the strategy adopted was to heat up the outer conductor in a vacuum furnace (background pressure better than 2.10^{-3} mbar) until attaining a temperature difference of 100°C. As depicted in figure 3, the inner conductor is then inserted by gravity into the outer conductor, becoming permanently joined.

ISBN 978-3-95450-143-4

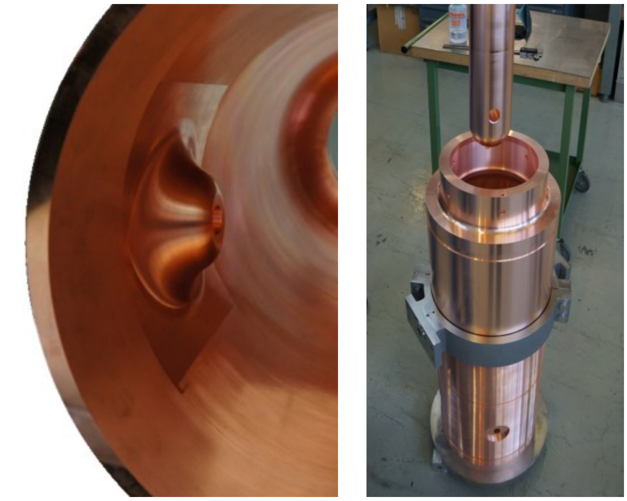

Figure 3: left) detail of beam ports finish; right) Inner and outer conductors being assembled by shrink fit.

Once shrink fitted, the inner and outer conductors are electron beam welded from the RF side, the cavity standing in vertical position. All electron beam welds are pre-qualified by extensive tests. The circular weld is performed in two runs: first, a high intensity penetration run aims achieving the desired penetration; and secondly, with a defocused beam, the smoothing run ensures a good surface quality. The result is shown in figure 4. The next step consists of electron beam welding the copper nozzle to the cryogenic opening. The assembly is then leak tested at room temperature.

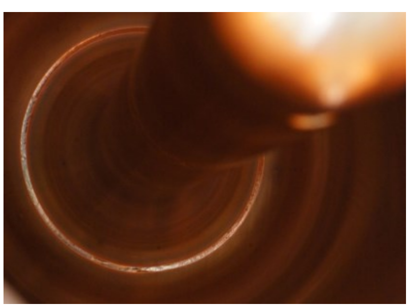

Figure 4: Circular electron beam weld on RF surface.

The final operation consists of tuning the copper substrate to a desired target frequency, by progressively trimming the free length of the outer conductor.

TEST RESULTS

The first bulk-machined prototype cavity manufactured at CERN and Nb sputtered at CERN with baseline production coating parameters was measured and for the first time RF performance exceeded the HIE-ISOLDE specification. The copper substrate was found to be able to extract all heat loads throughout conditioning and operation. The sensitivity to Helium pressure fluctuations was measured below 2.10^{-2} Hz/mbar, twice better than requirements. Preliminary characterization of microphonics show performance levels beyond expectations (stiffness of the new design).

CONCLUSIONS

The key copper substrate developments for the new HIE-ISOLDE high-beta SC QWRs were presented from design to material’s procurement, manufacturing and testing. Compared to first prototypes, which were based on plate metalworking techniques, the adoption of a bulk machined design lead to significant innovation: shape accuracy, stiffness and surface quality were significantly improved, as machining operations were minimized by adopting near net shape copper forgings. Critical RF welds were reduced to the minimum possible.

Nevertheless, special attention has to be dedicated to material’s procurement and quality control, essential throughout the whole manufacturing process. Finally, test results beyond expectations allow us to conclude that the reported aspects played a major role on the development of the SC HIE ISOLDE high-beta QWRs.

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 number 264330.

The precious support of G. Bisoffi, E. Palmieri, A. Porcellato and S. Stark from INFN-LNL is warmly acknowledged.

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