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ADVANCED MANUFACTURING TECHNIQUES FOR THE FABRICATION OF HL-LHC CRAB CAVITIES AT CERN

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Abstract

RF Crab Cavities are an essential part of the HL-LHC upgrade at CERN. Two concepts of such systems are being developed: the Double Quarter Wave (DQW) and the RF Dipole (RFD). The following paper describes the advanced manufacturing techniques developed for the fabrication of the DQW cavity prototype with an outlook on the upcoming RFD prototype production.

INTRODUCTION

In the framework of the High Luminosity upgrade project for the LHC (HL-LHC) at CERN, large sections of the accelerator will be modified [1]. One of the core enhancements are the so called crab cavities. These are novel RF cavities, aimed at reducing the crossing angle at the interaction points via the drift motion they impose to the beam bunches.

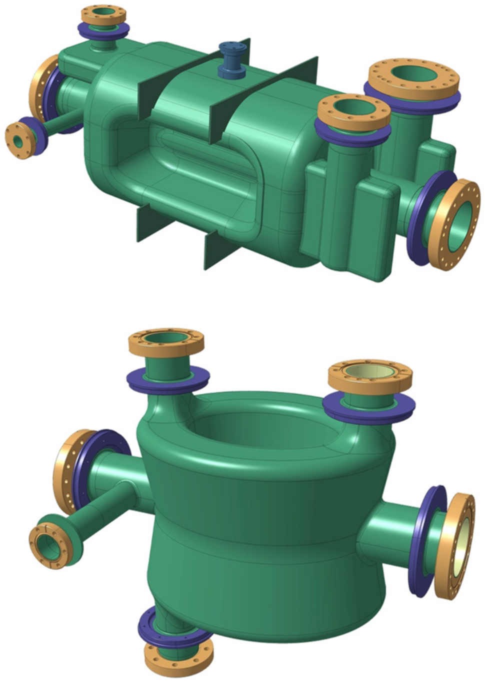

Figure 1: (Top) RFD Cavity; (Bottom) DQW Cavity.

Two different cavity designs are foreseen (see Fig.1) - one for horizontal (RF Dipole, RFD) and one for vertical (Double Quarter Wave, DQW) interaction – resulting in 16 crab cavities to be installed, two per each beam, on each side of both the ATLAS and CMS experiments [1].

In order to validate the correct operating principle, design and manufacturing of each cavity type, specific tests are foreseen in the SPS accelerator at CERN [2].

For such tests, two units of the DQW cavity have been successfully produced at the CERN Main Workshop between beginning of 2016 and first quarter of 2017; while manufacturing of two RFD units is to be launched in the second quarter of 2017.

This paper describes the manufacturing approach and advanced techniques implemented for the challenging DQW fabrication.

DQW MANUFACTURING

DQW Cut-out

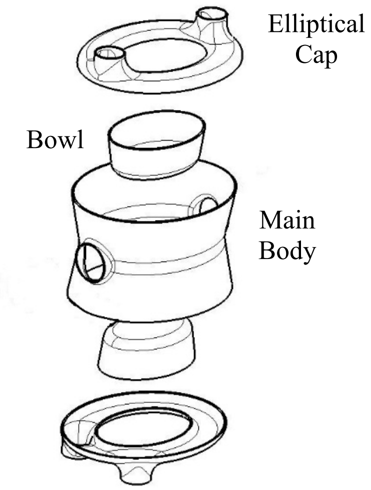

Figure 2: Scheme of exploded subcomponents.

Figure 2 shows the exploded scheme of subcomponents opted for the manufacturing of the DQW cavity. The three main subcomponents (SbC) are the Main Body, the Elliptical Caps, and the Bowls. Missing from the image are the extremities of the cavity, which connect the latter to the beam line on the main body, and to its power coupling systems on the top and bottom elliptical caps.

The rationale behind the cut-out can be resumed in the following points:

- Electron Beam (EB) welds need to comply with stringent RF, tightness and pressure equipment specifications; this leads to tight requirements on maximum acceptable weld defects (e.g. shrinkage, sagging, excessive penetration ranging in the few tenths of mm). Moreover the last joining welds are performed on components pertaining high added value and cannot be easily repaired. Cavity subdivision must thus firstly aim at allowing for the easiest weld configurations. Furthermore, wherever possible, welds must be kept away from high-field regions.

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- Number of subcomponents should be minimized, while still aiming at the easiest and lowest number of manufacturing steps on each SbC prior to final joining.
- Rough frequency tuning is performed via trimming of SbCs prior to their final welding stage. Cut-out should allow a quick and easy procedure. For the DQW cavity, such additional trimming volume has been reserved by raising the outer edge of the elliptical caps. Material allowance in such area can be more easily shaped and milled with respect to its counter-surface on the oblique wall of the main body; the latter being the most difficult part for machining (see chapter. 'Main Body Manufacturing').

Manufacturing Approach

As can be seen in Figure 1, with respect to elliptical RF cavities, the DQW (as much as the RFD) cavity pertains a complex – non-axisymmetric – geometry. This feature not only prevents from exploiting typical manufacturing processes such as spinning and turning; it also calls for the use of bulk niobium, as Nb-coating of a copper substrate would be highly challenging with such design.

The specified cavity wall thickness is 4 mm, while the cavity envelope covers a 400 mm x 500 mm x 650 mm volume. Forming of niobium sheets has thus been chosen as the process for obtaining the main SbC shapes. Such choice has been driven both by material cost optimization and by the minimum grain size achievable in sheets with respect to rods/plates: small, constant grain size being preferred for leak tightness, formability and internal surface smoothness after shaping (orange peel-like effects) [3].

In general, the following manufacturing chronology has been followed: (i) shaping of SbCs with length allowance on the edges, (ii) machining of edges to obtain interfaces compliant with profile and thickness requirements for welding, (iii) EB welding of SbCs.
Nevertheless, the exotic cavity shape together with the profile tolerances specified for the final cavity (ranging in the ±0.4 mm, down to ±0.15 mm for the capacitive plates on the Bowl) called for a more synergistic, concurrent approach among workshop entities and metrology.

For what concerns forming, the main challenge is posed by mastering the differential deformation which occurs while obtaining the elliptical shapes. Furthermore, all SbCs of the DQW cavity require extremely large elongation/compression of the fibres in order to obtain the final shapes. Such high forming ratios have shown to lead material near to local failure, excessive thinning and local buckling respectively.

An initial campaign of straight and circular tests was thus launched in order to determine forming limits via different forming methods. The campaign also allowed to quickly rule out non-viable options in terms of tool cost and process complexity. For such tests, fully annealed copper has been used in place of niobium, as its mechanical characteristics resemble those of the more expensive material in terms of yield onset and plastic limit. These preliminary tests allowed to set up the baseline processes and tools for elliptical shaping.

Finite elements simulations with the explicit code LS-DYNA® have been performed in parallel with the shaping campaign. Simulations have allowed to gain insight on the physical phenomena involved and on the material response to shaping. This has helped to steer manufacturing choices, and has allowed a faster iteration in the design of the fabrication tools via estimation of the expected shape outcome and thickness distribution [4].

For what concerns machining and welding, *theoretical-shape clamping* tools are commonly used. These tools constrain the SbC edges to their theoretical position while being processed. Such technique yields good results especially on thin-walled, axisymmetric cavities, as it allows for less stringent profile requirements while shaping. This clamping approach counteracts springback and profile errors only while parts are fixed onto the tools. On the other hand, the inability to clamp during just one manufacturing stage is sufficient for losing the beneficial effects of having applied it in previous steps.

On a non-axisymmetric cavity as DQW, constraints on practically all the edges' perimeter would be needed for maintaining such edges near to the theoretical elliptical shapes. This would require tools which are – at times - cumbersome, costly or of difficult implementation, such as during the last steps of welding. The theoretical-shape approach has thus been ruled out, since the absence of constraints in these last joining phases would have yielded to unacceptable shaping errors and to risks in terms of weld output.

An approach nearer to *zero-stress clamping* has thus been sought. In this case, SbCs have been clamped strongly enough to rigidly maintain them in place during machining/welding operations; on the other hand, clamping regions and loads have been chosen as to avoid induced deformations near the edges to be machined.

The choice of such method greatly influences the overall production strategy. First of all the best possible profile must be shaped prior to machining of the edges: since edges are not constrained to their theoretical position by the tools, profile errors after shaping directly translate into errors on the machined profiles and the thicknesses to be welded. The shaping campaign has thus aimed at obtaining the best possible tolerances for the RF surfaces, which have been retained as referencing entities; the most stringent requirement being in correspondence of the welded interfaces, where the aim has been to near the ±0.1 mm profile error band required for welding. In order to obtain and keep such challenging tolerances throughout the entire fabrication, coining has been performed after all major shaping and welding steps. Such process foresees compressing of the SbC onto a precise mould carrying the part's theoretical shape: the high loads involved induce local deformation and flow of material, thus allowing for better final shape. In case of results not yet compliant with welding requirements, manual adjustment and calibration of the edges has been performed following metrology analysis.

Interaction with metrology has been of paramount importance during machining: since parts are not forced onto their theoretical shape, their position on the clamping tools

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is not univocal. In order to provide the correct reference for milling, all subcomponents have undergone a metrology check to determine their position once assembled on the machining tools.

Another major milestone in the development of the manufacturing approach is the choice of the geometry of the welded interface between bowl, main body and cap.

For such edges, local thickness reduction to 3 mm has been opted for. This choice adds onto the technical challenges to be faced during machining, as the attainment of the required thinned geometry calls for up to 5x axis simultaneous milling (namely on the edges of the main body, see Fig. 3), with respect to the more standard 3x axis milling which would be required in case of standard vertical trimming.

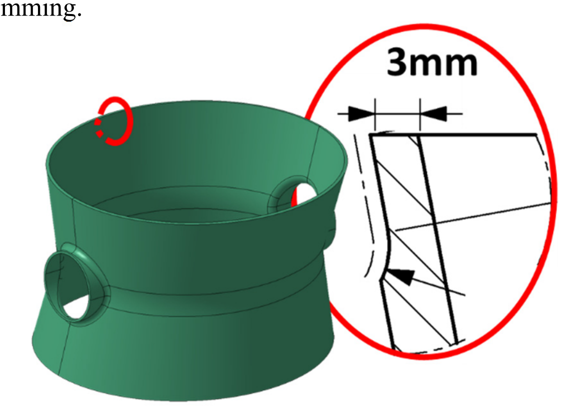

Figure 3: Main body, thickness reduction for weld.

On the other hand, this choice provides a constant thickness during the most critical steps of EB welding, thus reducing the onset of weld defects. Furthermore, the thickness reduction to 3 mm allows for a lower energy input during welding, thus lower induced deformations.

The weld configuration opted for is a butt-weld layout. Results from a test performed on a typical slot weld layout have shown that the minimal tolerances needed for insertion with clearance fit of the SbCs are large enough to cause rotational play between the SbCs and a consequent mismatch in the order of many tenths of mm: this would be unacceptable with respect to the cavity shape and weld requirements. Moreover the benefits of slotted coupling are reduced for a configuration where edges already carry low profile errors due to the choice of zero-stress clamping.

For what concerns joining procedures other than EB the stainless steel flanges at the cavity extremities have been directly brazed onto the niobium. The high-temperature brazing follows an established procedure at CERN: joining is obtained via Cu-based filler and with the use of a stainless steel ring which drives the thermal expansion of the niobium collar from the internal diameter, thus reducing the gap due to different coefficient of thermal expansion [5].

In the following paragraphs, the main SbC features and challenges encountered during DQW manufacturing are presented.

Bowl Manufacturing

The bowl shape has been obtained via the deep-drawing process schematized in Figure 4 (Top). The niobium sheet compression ratio entailed in this operation represents the largest fibre alteration amongst all of the cavity forming procedures. Such compression yields to a consistent presence of wrinkles. Their presence is inconvenient both as they directly result in geometrical nonconformities of the functional bowl surfaces and as they get stuck during sheet flow, thus hindering the smoothness of the deep drawing process. Figure 4 (middle) shows a set of copper circular samples from the initial campaign aimed at reducing presence of wrinkles; the onset of wrinkles has been mastered via permutation of process parameters such as press-pad pressure, friction coefficients, mould entry geometry and niobium sheet size.

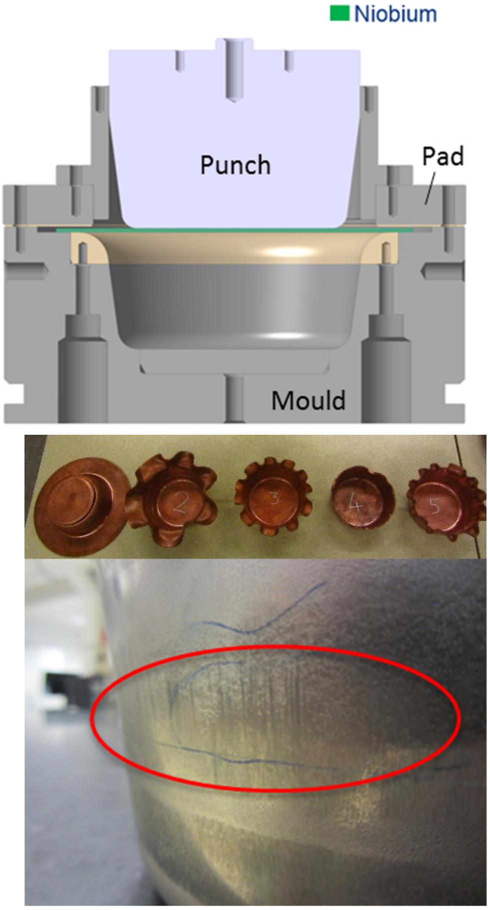

Figure 4: (Top) Bowl Deep Drawing major axis cut; (Middle) set of deep drawing trials; (Bottom) Scratches on bowl RF surface.

As the niobium sheet is being drawn to the final bowl shape, major sliding occurs between the RF surface and the tools causing tearing off of the niobium and scratches (Figure 4 bottom). Amongst the different methods tested (tool configurations, lubricants, tool materials) the most effective has been the insertion of a urethane thin film between the niobium and the mould (see Fig. 5). The large deformability of the polymer reduces shear components on the niobium surface and also provides an intermediate softer material, from which particles are preferentially torn away during sliding.

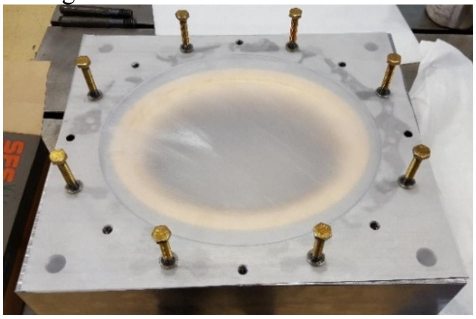

Figure 5: Bowl mould with urethane film.

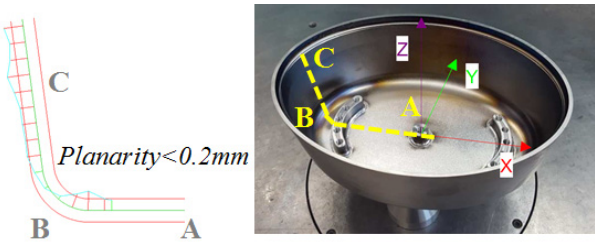

Figure 6: (Left) metrology results with specified profile band of 0.2 mm; (Right) bowl welded to tuning connections.

Metrology results for the RF profile of one of the shaped bowls are represented in Figure 6 (left). As can be seen, profile errors have been kept near the ±0.1 mm tolerance band required for welding also further away from the interfacing edge.

The tuning inserts may also be spotted on the external surface of the bowl in Figure 6 (right). These inserts provide a threaded connection for the push-pull tuning system of the cavity, and are made in NbTi due to structural requirements. The challenging heterogeneous joining of the two materials has been successfully performed via EB; Figure 7 shows the results of a qualification sample for such weld.

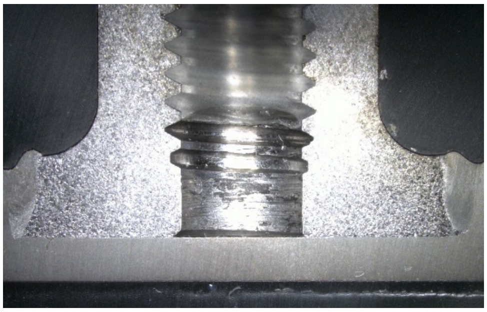

Figure 7: Cross cut of Nb/NbTi weld qualification.

Main Body Manufacturing

To form the Main Body, two sheets of niobium are initially rolled and welded to obtain a large elliptical cylinder. A punch is then pressed onto a polyurethane mould situated inside the niobium cylinder; the elastomer spreads radially the top side of the cylinder against a steel mould, into the almost-final flared shape (see Figure 8 for the main tool parts). This initial forming stage is followed by a coining step. The other side of the Main Body is then formed following the same processes. Three stages of the top main body shaping can be seen in Figure 9. In this case, finite elements analysis has allowed not only to determine the loads to be applied during forming, but also to choose the best elastomer grade and shape.

Figure 8: Tools used for main body shaping.

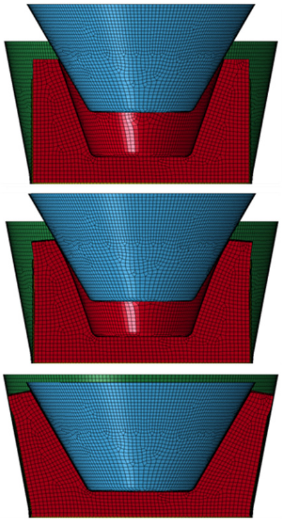

Figure 9: F.E. analysis of main body shaping via elastomer mould.

The shaping processes for the main body involve heavy tooling and loads (up to 130 tonne). The major technical challenge though rests with the machining phases of its edges: whilst the bowl and the elliptical cap possess flat surfaces - which provide at least one plane for reference and clamping- the curvy shape of the main body renders it the most difficult piece for referencing; this is even more true considering the choice of a zero-stress clamping system and the need of accessibility on practically all external surfaces for machining of the top edge, bottom and extruded beamlines.

Due to the difficult referencing, the following procedure has been followed: (i) metrology of main body and predefined markers to determine best fit to theoretical shape, (ii) assembly of SbC on tool, (iii) metrology of SbC markers and tool markers to determine position of SbC's best fit with respect to tool markers, (iv) referencing machine with respect to tool markers and applying corrections of metrology results from point (iii).

The main body assembled on its tool, together with the spheres used as markers, can be seen in Figure 10.

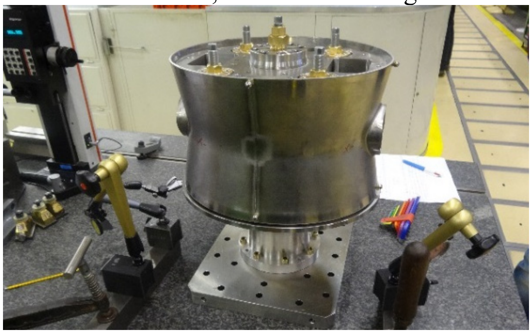

Figure 10: Main body assembled on machining tool.

Elliptical Cap Manufacturing and Cavity Welding

Figure 11 shows the bottom elliptical cap after welding with its extremities. As can be seen in the top right view, this welding configuration is most demanding due to the blind angle, which appears after welding of the first extremity. In such area, the electron beam must thus strike on a skew angle; this causes the beam to encounter material thicknesses which vary up to 1 mm during the complete welding phase. The corresponding beam travel variation has been dealt with via the addition of a backing ring (machined away at a later stage) inside which the highly focused beam dies off.

The most challenging welds have though been the elliptical ones, especially the one joining the subassembly bowl plus elliptical cap with the main body. For performing such welds, up to 5x simultaneous axes have been used (Fig. 12): vertical translation (parallel to the beam axis) allowing for constant beam focus on the welded volume, horizontal translation allowing for constant thickness normal to the beam, normal translation in order to follow the welded edge in case of inclined piece as for the bowl weld.

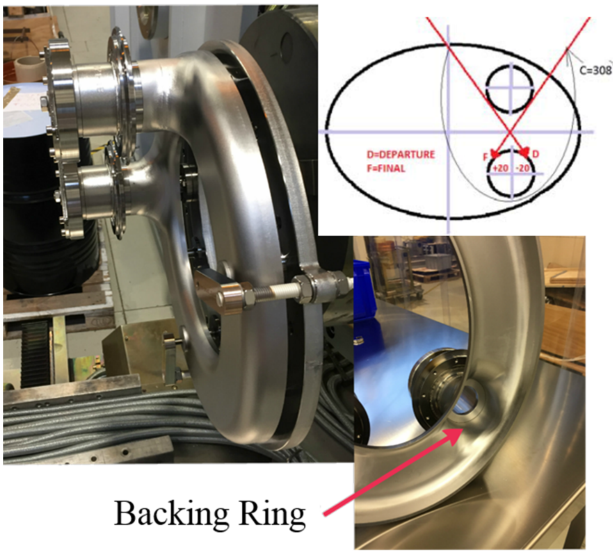

Figure 11: Welding configuration of cap with extremities.

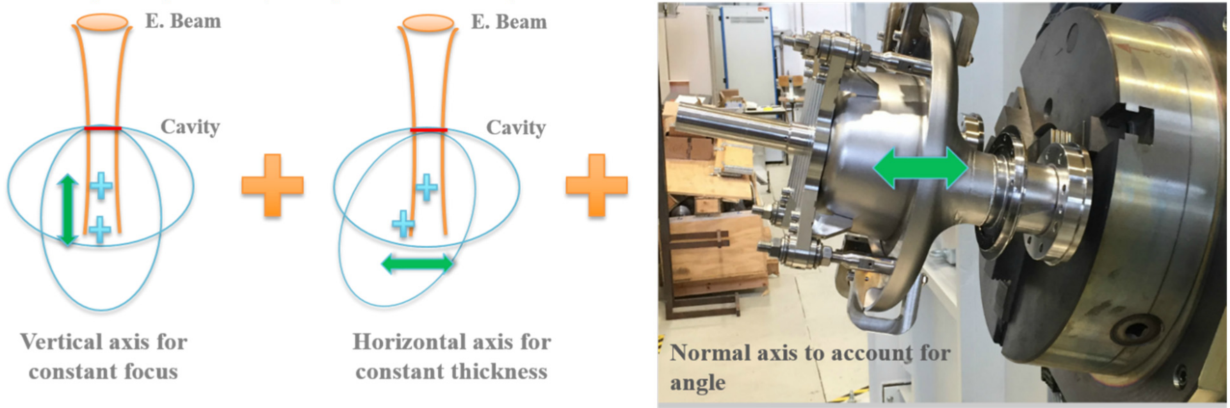

Figure 12: Simultaneous axis movement during EB welding of elliptical edges.

CONCLUSION AND FUTURE OUTLOOK

Two DQW cavities have been successfully fabricated at the CERN Main Workshop, by devising and exploiting unconventional manufacturing techniques.

The experience gained during the manufacturing of the DQW cavity is proving crucial for clearly defining the layout for the upcoming RFD cavity. For this manufacturing, cavity cut-out has been performed and technologies are currently being benchmarked for the attainment of the different subcomponents.

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REFERENCES

[1] http://hilumilhc.web.cern.ch

[2] R. Calaga "Crab Cavities for the High –luminosity LHC", THXA03, Proceedings of SRF 2017, Lanzhou (China), 2017

[3] A. Zamiri *et al*., "On mechanical properties of the superconducting niobium", (2006) Materials Science and Engineering A, 435-436, pp. 658-665.

[4] A. Amorim Carvalho *et al*., "Simulation of Niobium Sheets Forming for Accelerating Cavities" 14th LS-DYNA Forum, Bamberg (Germany) 2016

[5] N Valverde Alonso *et al*., "Electron beam Welding and Vacuum Brazing Characterization for SRF Cavities" THPP039, Proceedings of LINAC2014, Geneva (Switzerland), 2014