MANUFACTURING THE LINAC4 PI-MODE STRUCTURE PROTOTYPE AT CERN

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Abstract

The PI-Mode Structure (PIMS) of Linac4 consists of 7-cell cavities made from alternating OFE copper discs and rings welded together with electron beam (EB) welding. A full-scale prototype cavity of almost 1.5 m in length has been manufactured, assembled, and tested at CERN to prepare the series production of 12 PIMS cavities as part of an international collaboration. This paper reports on the construction experience including machining operations, EB welding, vacuum brazing, and metrological measurements results.

INTRODUCTION

For the high-energy section of Linac4, 12 PIMS cavities will be used to accelerate the H^- beam from 102 MeV to 160 MeV. Each 7-cell cavity is made of 15 components: 8 discs (2 end discs, 4 symmetrical discs, and 2 asymmetrical discs at the centre) and 7 rings (4 rings with tuner ports, 2 rings with tuner, and RF ports and 1 central ring with tuner, RF and waveguide port) as shown in Fig. 1. EB welding technology has been selected for the assembly of cells and ports (with the exception of the central ring) since it limits the shrinkage effect and preserves the properties of the copper used.

The PIMS cavities are tuned for a flat field distribution at the desired resonant frequency of 352.2 MHz by re-machining the tuning islands (see Fig. 1) of each disc before welding the discs and rings together. After the welding, the cavity is re-tuned by piston tuners inserted into the tuner ports of each ring to compensate the variations due to weld shrinkage and change in Q-value of each cell.

A prototype cavity has been designed, manufactured, assembled, and tested at CERN [1] [2] to develop the construction procedures and gain experience for the series production of the PIMS cavities.

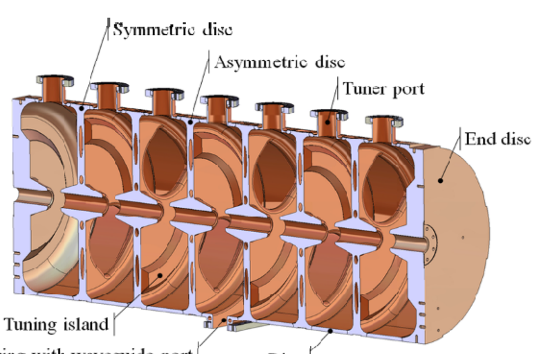

Figure 1: 3D-view of the full prototype PIMS cavity.

MATERIAL

High quality 3D-forged OFE copper (99.99 % min Cu) in half-hard temper was used, having a fine (max 90 μm) and homogeneous grain size, low oxygen content (5 ppm) and specific limits in ppm for sixteen additional elements. The main benefits compared to standard copper are improved weldability (limited risk of porosity inducing so-called virtual leaks in the vacuum system), better mechanical stability, and increased yield strength thanks to the half-hard temper.

The raw material delivered (multidirectionally forged with some components finished by ring rolling) complies with the stringent requirements of CERN's specification in terms of composition, microstructure, tensile properties, hardness, and ultrasonic examination criteria.

MANUFACTURING OF COMPONENTS

The manufacturing procedure has been developed to minimize the distortions and to reach a machining precision to the order of 20 μm with a Ra surface roughness of 0.8 μm.

The use of forged copper combined with a particular geometry (a large diameter of almost 540 mm with respect to its thickness of 10 mm) makes the components sensitive to machining distortions. A minimum of two rough machining steps was systematically implemented before the final machining step in order to minimize these distortions. For the same purposes, the machining parameters (tools, cutting speed, feed, and depth of cut) have been optimized. Furthermore, specific aluminium clamping jaws were used for the final machining in order to minimize the clamping stresses (see Fig. 2).

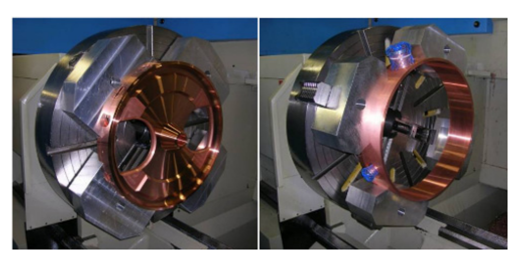

Figure 2: Machining of the discs and rings using aluminium clamping jaws.

Between 6 and 8 CNC milling and turning operations were implemented for each component machining.

For the discs, special attention has been paid to avoid connection defects in the area of the noses and coupling slots since defects such as steps and sharp edges are detrimental to the Radio Frequency (RF) performance.

For the standard rings, a calibration was sometimes implemented after the first step of rough machining in order to correct the roundness of these components which are very sensitive to machining distortions. EB technology was selected for tuner ports welding since it limits the shrinkage effect. To make the welding operations easier, the tuner ports were welded from the outside (see Fig. 3). The use of special flanges made from two removable half rings allowed the electron beam to be parallel to the joint effectively ensuring high quality welds. Additionally, a temporary backing support was used to protect the rings against spatter and guarantee a smooth inner surface, free from defects after removing the backing support by machining (eliminating the weld root where volume defects can occur) (see Fig. 4). The quality of the welds was controlled by X-ray and leak tests.

Figure 3: EB welding of ports from the outside.

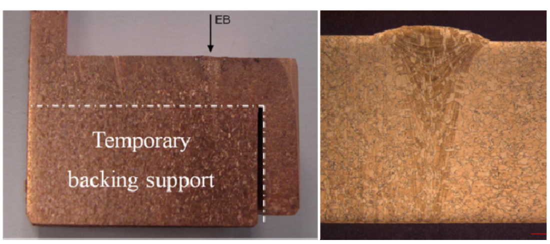

Figure 4: Cross-section of the weld before (left) and after (right) removing the backing support.

Due to the complex 3D-shape of the waveguide port opening it has been decided to machine the waveguide port together with the central ring out of the bulk copper of a "thick" ring and to braze the rectangular stainless steel flange directly onto the port opening without EB welding. This technical choice implies that the central ring is the only component subjected to heat treatments. To avoid any deformation during the brazing operation, the central ring undergoes two annealing heat treatments at 600°C during 3 h under vacuum after the rough machining steps. In the same way, the stainless steel flanges have been heat-treated at 950°C before the final machining. The standard palladium-based alloy PD106 according to EN1044 (Ag68.5%-Cu26.5%-Pd5%, melting range 807°C-810°C) was then used to braze the two CF flanges onto the tuning ports. As for the rectangular flange and the water-cooling circuit fittings they were brazed in a second operation with a silver-copper eutectic alloy AG401 according to EN1044 (Ag72%-Cu28%, melting temperature 778°C) (see Fig. 5). All brazed joints were visually inspected to check the continuous filling of the joints (no remaining gap) without accumulation or excessive flow of the brazing alloy.

Figure 5: Vacuum brazing of ports on the central ring.

All of the components were subject to metrological checks. In order to overcome temperature variations in the workshop (1ºC corresponds to almost 10 μm of thermal expansion for the largest dimension of this component in OFE Cu), multiple metrological controls were performed at several steps of the construction. This particular attentiveness allowed the required level of machining precision (up to 20 μm) to be obtained on most pieces.

ASSEMBLY

Before the final welding, the cavity was pre-assembled (simple clamping) for frequency tuning, achieved by re-machining the tuning islands on the discs walls. The assembly was facilitated by a joint clearance comprised between 0.05 mm and 0.1 mm that enables the components to be connected and disconnected without seizing. To define the final height of the tuning rings, the cavity was connected to the waveguide coupler (see Fig. 6) and bead-pull RF measurements were performed. Taking into account the expected weld shrinkage and frequency change due to the air/vacuum transition, one could then define the final height of the tuning islands on each disc, such that a flat field can be achieved within the tuning range of the piston tuners (5 fixed tuners plus 2 movable tuners).

Figure 6: The first tuning step: bead-pull measurements on the clamped PIMS prototype before welding.

The final assembly consisted in EB welding of adjacent discs and rings. High-quality welding (according to ISO 13919-2 level B) was obtained owing to three main reasons: using OFE copper, careful preparing joints (degreasing and mechanical scraping just before welding) and welding qualification on several representative samples. This qualification showed an average weld shrinkage of 0.20 mm with a maximum value of 0.30 mm in the overlapping areas of the weld. The welding parameters were defined to obtain a constant welding penetration of 7 mm all around the circumference with pores located in the backing support below the joint plan to avoid out-gassing into the cavity (see Fig. 7). A constant penetration was essential to ensure an equal shrinkage and to avoid any degradation of the inner wall of the cavity which would occur in case of full penetration, i.e. complete melting of the backing support with spatter.

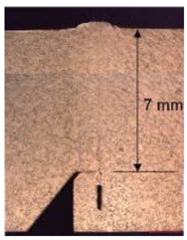

Figure 7: Cross-section of a junction ring to disc EB weld.

The beam axis straightness has to be within ± 0.3 mm on the whole length of a cavity and cannot be achieved by simply fitting the rings and discs since the clearance for each connexion is up to 0.1 mm. The alignment precision was obtained thanks to a specific tool that ensuring the coaxiality of reference diameters machined on the outside of each component with a tolerance of ± 10 μm.

Subsets made up of one ring and one disc were first assembled (six subsets in total). A careful and well-defined tack welding is crucial to ensure final weld quality. The subset parts were tack welded using the alignment tool (see Fig. 8). This operation guaranteed perfect contact between the edges, without gap, over 360° which is essential for a constant welding penetration. In addition, it prevents the ring being distorted during welding, since the different masses of the disc and ring lead to dissimilar thermal expansion.

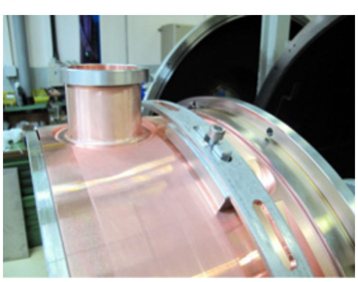
Figure 8: Alignment tooling in contact with the reference diameters of the disc and ring.

The subsets were then welded together in progressive order using the same welding procedure (see Fig. 9). Rotating the position of each weld overlap area by 180° from weld to weld prevents a "banana" deformation of the complete cavity.


Figure 9: Final assembly.

The weld shrinkage measured for each cell after EB welding of the complete cavity is shown in Table 1. It is close to 0.2 mm as measured during the welding qualification, symmetrical with respect to the central cell, and slightly higher for the central cell (n° 4) and outer cells (n° 1 and n° 7) respectively. RF measurements confirmed these values.

Table 1: Weld Shrinkage per Weld for Each Cell

cell n°	1	2	3	4	5	6	7
shrinkage [µm]	200	192	196	246	180	197	212

A final metrology control was carried out via external reference surfaces allowing the beam axis of the cavity to be reconstructed. Excellent results confirmed that functional requirements (beam axis ± 0.3 mm) were fully attained.

During the high-power RF tests [2] the prototype performed better than expected and, therefore, it was decided to use it directly as the first PIMS module in Linac4.

CONCLUSION

The challenging functional requirements of Linac4 PI-Mode Structure required the development of a mechanical design with very strict tolerances. For the construction of a full-scale prototype stringent procedures have been developed including material selection, machining, welding, brazing, and metrology. This first PIMS cavity provided fully satisfactory RF performances thus confirming the high construction quality achieved and the feasibility of the design concept.

The gained experience led to a successful technology transfer to industry for the series production of 12 cavities started mid-2011.

REFERENCES

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