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PIXE-RFQ modulation and cavity machining

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Abstract
The Proton Induced X-ray Emission (PIXE) Radio-Frequency Quadrupole (RFQ) is a transportable low energy linear accelerator working at a frequency of 750 MHz that can provide 2 MeV energy protons with only one meter in length. It can simultaneously accelerate, focus and bunch a protons beam used to analyse art and cultural artefacts on-site by the induced X-ray emission. The accelerator is composed of two modules where each was brazed from two minor and two major vanes. The vanes were manufactured from bulk rods of Oxygen-Free Electronic (OFE) copper. The process consists of wire-EDM cutting, deep drilling, heat treatments and several operations of high-precision milling machining in order to achieve the shape and position accuracies, ± 5 µm and ± 15 µm respectively, along 500 mm length and a surface quality bellow Ra < 0.4 µm. To ensure the geometrical tolerances, a special clamping fixtures were designed and manufactured, several custom-made milling tools were tested. The machining was performed in close synergy with metrological CMM measurements.

PIXE, RFQ modulation, Diamond tool, Copper OFE, Machining

1. Introduction

The PIXE-RFQ is a linear accelerator component for the MACHINA project (Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis), developed in cooperation between CERN and INFN as described in [1].
The design is based on the model of High Frequency RFQ (HF-RFQ) [2,3] but the accelerator consists of only two modules, half-meter long each. This compact construction makes it an innovative solution that tends to be easily transportable [1-3]. Each of the two modules is assembled by vacuum brazing from two major vanes and two minor vanes (see Fig. 1). The vanes are mono-block Cu OFE parts, where essential elements for the proper functioning of accelerator are the modulation and cavity surfaces (see Fig. 2). The geometrical tolerances of shape for the modulations is within ± 5 µm and ± 20 µm for the cavity. The position accuracy of modulations in respect to each other is within ± 15 µm on the final module assembly, which brings the machining precision of the brazing planes to a challenging level. Finally, to align two modules with a minimal error in reference to one another, the matching planes are re-machined based on metrology as the last operation.

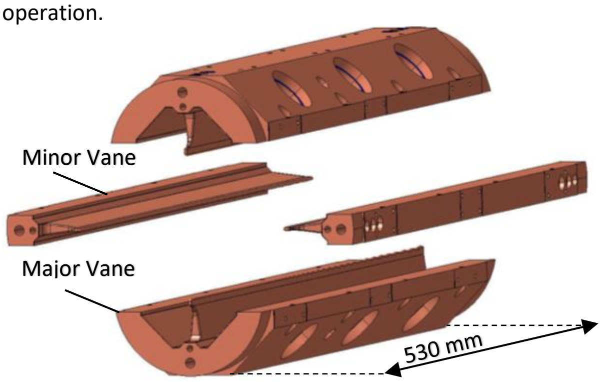


Figure 1. Explode view of PIXE-RFQ module assembly, two major vanes and two minor vanes.

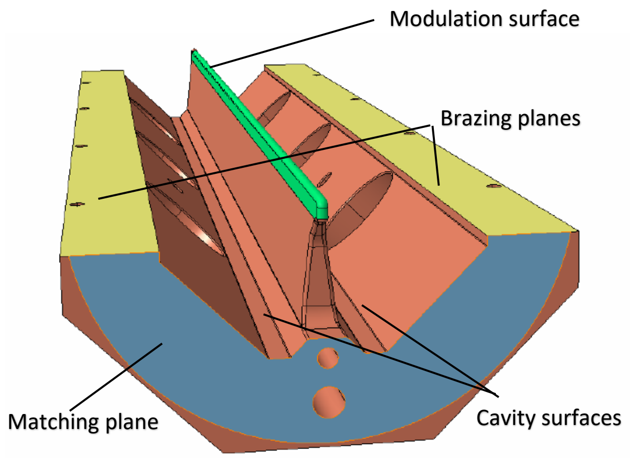


Figure 2. Essential geometry presented on the major vane.

The manufacturing process of PIXE-RFQ can be divided into over 30 separate machining operations, alternated with 4 heat-treatments, 2 vacuum brazings and 6 metrological measures. The whole process was developed based on the experience gained during manufacturing of LINAC4 RFQ in 2009-2012 and HF-RFQ in 2014-2016 [3].
This paper describes the most demanding machining steps during PIXE-RFQ manufacture as finishing of the modulations, the brazing planes, the cavity surfaces and matching planes.

2. Raw material and methods

The stock material for the vanes are three OFE copper bars (C10100 alloy), which initially measure 152 mm in diameter and 567 mm of length each. The material dimensions are selected to obtain four major vanes from two bars and all minor vanes from a half of the remaining bar, as presented on the axial view (see Fig. 3).

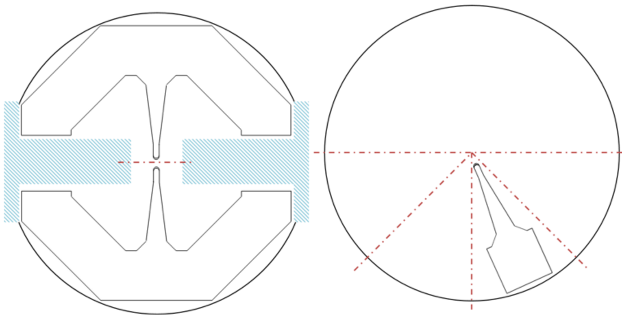


Figure 3. Raw material axial view, illustrating the position of vanes in the stock material.

The pre-roughing process is optimized in order to economize the material and reduce cutting time. The striped field areas on the figure above represent the material removed in the first machining step using the Hermle C42U. It is a 5-axis milling machine, equipped with the swivelling-rotary table (A-axis and C-axis), which is used during all operations of RFQ milling. Then the bars are cut following the dashed lines, using the Agie Charmilles FI640ccS electrical discharge wire cutting machine, with the wire diameter of 0.25 mm. Afterwards the external surfaces are machined with the allowance of 1 mm.

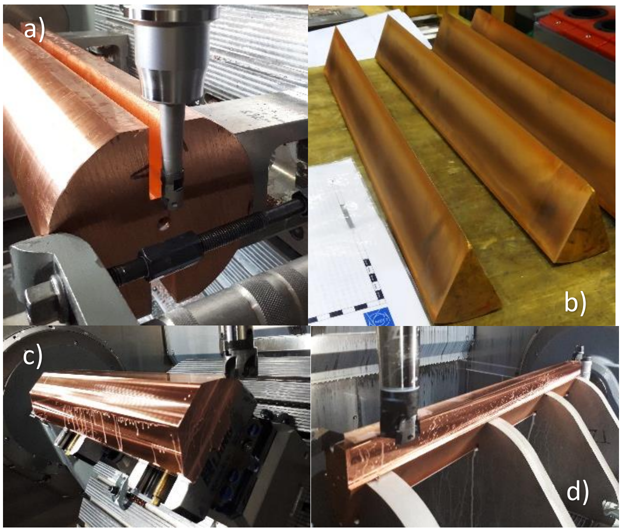


Figure 4. Different phases of pre-roughing process; a) First milling in massive bars; b) Material after wire cutting; c,d) Machining of external surfaces with 1 mm allowance.

3. Machining

The roughing process of PIXE-RFQ consists of two successive machining of internal cavity on 3 and 1 mm of allowance. After each of these operations, annealing at 600°C is performed to remove the residual stresses in the material. A multiple heat-treatment process is necessary to avoid further deformations caused by constraints added during milling, as shows by the previous experience with LINAC4 RFQ [4]. Then the external surfaces of the vanes are finished, excluding the matching planes, where 1 mm of allowance is kept for the last trimming.

3.1. Cavity finishing

During the semi-finishing process, the vanes are milled with the allowance of 0.15 mm on the modulations and the brazing planes, and 0.75 mm on the matching planes. The internal cavity, which has a shape tolerance of ±20 µm and maximal roughness Ra 0.4 µm is finished on this stage. Taking into consideration the limited tool access to the internal area, the machining of major vanes is more complex than in case of minor vanes. The solution of roll and face milling with cylindrical milling tools was chosen among ball-nose or form tool milling. In comparison to other techniques the finishing time is reduced and the cutting speed over whole tool cutting edge remains constant. Those advantages play the role in more precise and laminar surface finishing over whole surface. Based on the major vane cavity shape two geometries of milling tools were designed (see Fig. 5).

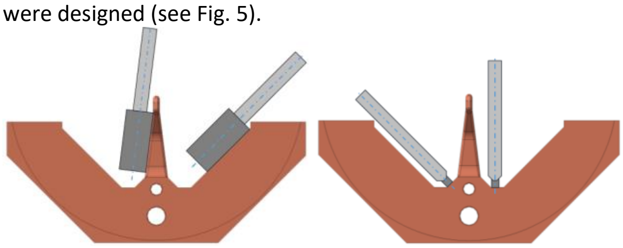


Figure 5. Tools/vane configurations during internal cavity form finishing

Several finishing tools have been manufactured by Tivoly Corporate and Groupe Boudon Favre in France and JMD Affûtage in Switzerland. The tools are tested in the small Cu OFE samples to compare surface roughness and approve the geometry of a cutting corner radius. Among all tools, two milling tools are chosen, and the roughness tests are repeated on the real shape prototype. The picture below illustrates the finishing of a cavity (see Fig. 6). The cavity semi-finishing process finishes by the third annealing at 800°C and following first metrology.

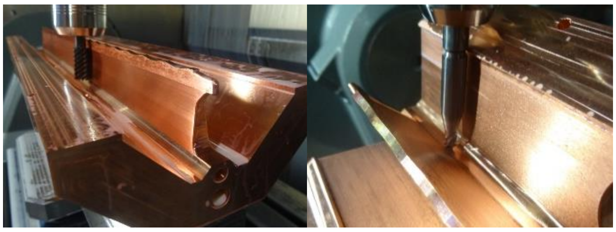


Figure 6. Finishing of the internal cavity surfaces of the major vane.

3.2. Modulation finishing

For the modulation finishing purposes, the custom form milling tool (see Fig. 7) is designed at CERN and manufactured by Masnada Diamant Industrie SAS in France.

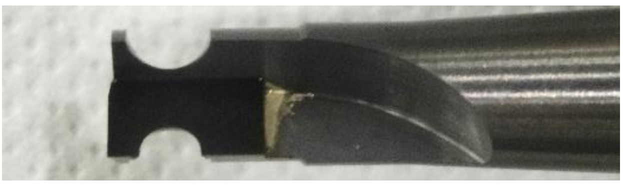


Figure 7. Form milling tool with the polycrystalline diamond insert

The core of the tool is made from carbon steel with the polycrystalline diamond (PCD) insert brazed on it. The insert shape corresponds to the axial profile of the modulation and was manufactured by laser within the tolerance of ± 2 µm.

The finishing is done by roll-milling. The advantage of this method is the finest surface quality, reduced cutting time and increased accuracy in reference to ball-nose planar milling.

During machining, a vane is attached to the stainless-steel fixture using twelve M5 bolds. The tool performs simultaneous movement in X and Y machine axis, following a modulation shape. The other machine axes are in indexed position. By this method a vane rests in fixed position during the whole finishing process, eliminating the errors of eventual re-positioning of axes.

The fixture allows to install a small sample on the face, in the modulation axis (see Fig 8).

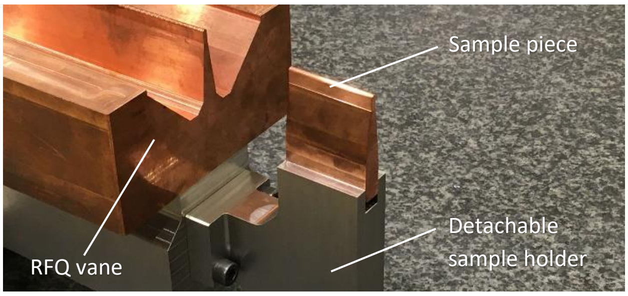


Figure 8. Sample piece installed for tool calibration purposes.

The sample is used for calibrating the tool length before machining the vane. This calibration is crucial in precise centring of modulation in reference to the previously finished cavity surfaces. The milling tool performs a straight cut on the sample, which is then removed and measured on the coordinate measuring machine (CMM). Based on the profile measurements the tool offset is compensated and the test is repeated 3-5 times for each vane to minimize the errors. Afterwards, the finishing pass is executed on a vane.
Once all the modulations are finished, their exact positions according to theoretical beam axis are measured on the CMM. The allowances on the brazing surfaces are re-machined based on metrological reports in order to minimize positioning error of modulations in respect to each other.
The vanes are assembled to be measured and then the frontal and lateral references are milled (see Fig. 9), they will be used for precision assembling once the piece will be cleaned for the first brazing.

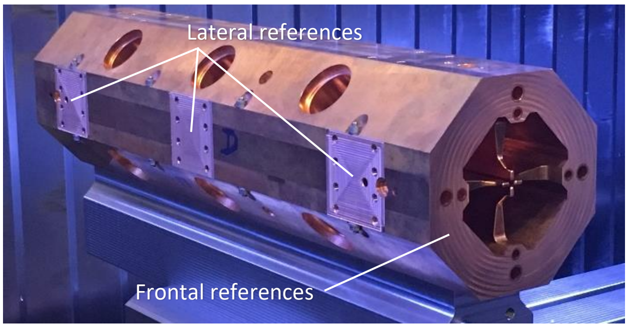


Figure 9. Machining of references on assembled vanes before the first brazing.

To assure the minimum positioning error in longitudinal direction between modulations of two modules in the final assembly, the matching planes and stainless-steel flanges are re-machined in the last step of the manufacturing process, after the final metrology. At this step the components are already clean, use of cutting cooling fluid is forbidden during the processing. The tools changing is done manually to avoid the contamination of the piece with the oil from machine tool magazine.
Each matching plane is treated separately, based on the measures done on the inner cavity and the modulations. The reports indicate the allowances to be taken in several points on the surface. A module is pre-positioned by the swivelling-rotary machine table and the digital indicator with micron resolution. Once the correct position of a plan is found, the axis remains indexed as in the case of modulation finishing. Then the reference point in Z-axis is taken on the flange surface which will not be machined, to verify initial position during machining, and in need to re-adjust it. The machining itself is done in three steps: the semi-finishing; the compensation of tool offsets, based on the measures between the semi-finished surface and the reference fixed point, and finishing (Fig 10).

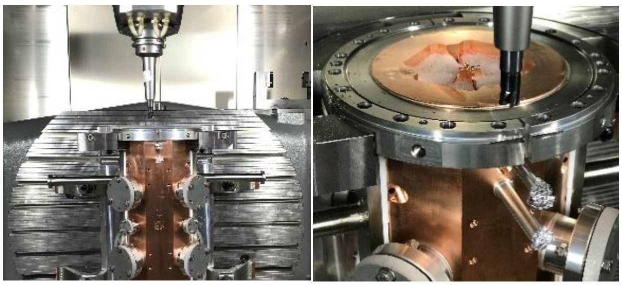


Figure 10. Module in final trimming configuration.

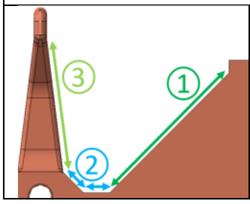
4. Results

The intermediary and final metrological measurements are done with Zeiss Prismo Ultra 12/18/10 CMM with the probing precision of 1.2 µm and the probing pressure force of 5 Nm.

4.1. Cavity metrology

The surface roughness is measured using Mitutoyo S-3000 stationary instrument on the multiple Cu OFE massive samples in longitudinal and transversal directions. In the first phase the results vary from Ra 0.1 – 1.16 µm for 18 different tools. Then two milling tools are selected, and the test is repeated in a sample with geometry corresponding to the major vane. The measured areas are presented in the table 1.

Table 1 Surface roughness - cavity.

Measured area		Tool supplier	Ra [µm]
	1	JMD Affûtage	0.19 – 0.22
	2	Boudon-Favre	0.34 – 0.39
	3	Tivoly Corporate	0.23 – 0.34

The internal cavity transversal profiles of the major and minor vanes are measured on the CMM machine in six different positions on each piece. The shape tolerance of 40 µm is successfully achieved (see Fig. 11).

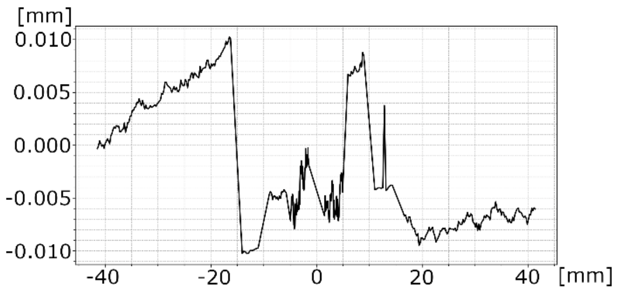


Figure 11. Deviation between nominal shape and measured transversal profile of a major vane.

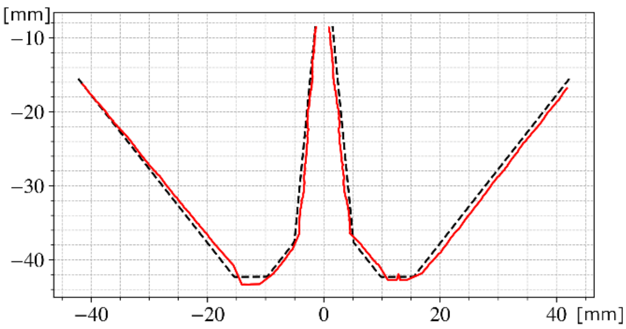


Figure 12. Exaggerated measured profile (continuous red line) superposed on the nominal profile (striped line).

4.2. Modulation metrology

The roughness test of the machined surface with the diamond tool gives the results varying between Ra 0.09 µm and Ra 0.23 µm in the longitudinal and transversal direction.
The geometrical CMM measures of modulation of each vane are done in longitudinal direction over the whole profile length (see Fig. 13). The shape of all of modulations is preserved in the tolerance of ± 5 µm.

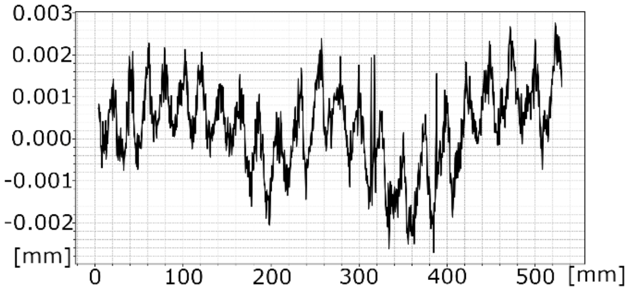


Figure 13. Deviation measured over the whole modulation profile.

The transversal measures are done on each piece in 6 different positions. Thanks to developed machining procedures and fixtures, the shape is centred during each finishing, giving the geometry as presented below (see. Fig 14)

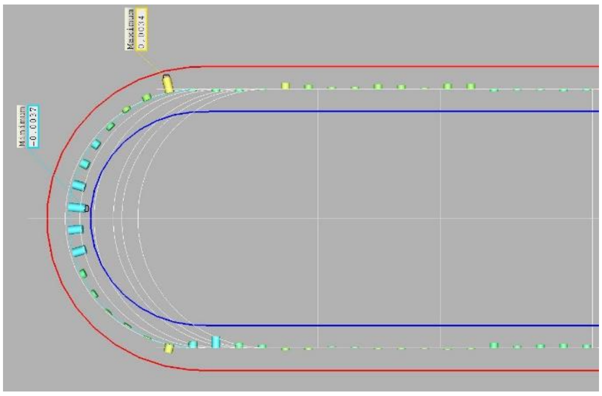


Figure 14. Transversal profile deviation (10 µm between blue and red solid lines).

5. Conclusions

The synergy of machining, stress-releasing heat treatments, vacuum brazing, metrology and precise assembling results in successful manufacture of the PIXE-RFQ for the end of 2019. The modules are planned to be installed together with the proton source in the beginning of 2020, and the first beam test will be performed at CERN. Later on, the accelerator will be tested at INFN-LABEC and then the fully functional system will be transported to Opificio delle Pietre Dure (OPD) in Italy for the first measures performed on artworks.

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