IFMIF RFQ MODULE CHARACTERIZATION VIA MECHANICAL AND RF MEASUREMENTS

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Abstract

The RFQ of the IFMIF/EVEDA [1] project is a 9.9 m long cavity able to accelerate a 130 mA deuteron beam from the input energy of 100 keV to the output energy of 5 MeV. Such RFQ operates at the frequency of 175 MHz and is composed of 18 mechanical modules approximately 0.55 m long each [2]. The RFQ realization involves the INFN. Sections of Padova, Torino and Bologna, as well as the Legnaro National Laboratories (L.N.L.). The metrological measurements via CMM (Coordinate Measuring Machine) provided to be a very effective tool both for quality controls along the RFQ production phases and in the reconstruction of the cavity geometric profile for each RFQ module. The scans in the most sensitive regions with respect to RF frequency, such as modulation, tips, basevane width and vessel height provided the values of the cavity deviations from nominal geometry to be compared with design physic-driven tolerances and with RF measurements. Moreover, the comparison between mechanical and RF measurements suggests a methodology for the geometric reconstruction of the cavity axis and determines the final machining of the end surfaces of each module in view of the coupling with the adjacent ones. In this paper a description of the meteorological procedures and tests and of the RFQ along its production and assembly phases will be described.

IFMIF RFQ DESCRIPTION

One of the fundamental components of the IFMIF-EVEDA facility, being installed at the site of Rokkasho in Japan is the RFQ (radio Frequency Quadrupole) composed of 18 mechainical modules divided in 3 Supermodules, of 6 modules each. The main RFQ parameters are listed in Table 1. Due to the extremely high current value, the attainment of beam loss control is of paramount importance in such structure. Now, beam loss is determined basically by geometrical tolerances, in three different ways: vane modulation machining (± 0.02 mm), beam axis accuracy along the accelerator, and voltage law accuracy along the structure. In the following this last aspect will be taken into account. The attainment of voltage accuracy within the specified values is determined by the local cross section shape and local cut off frequency mainly depending on pole tip positioning (capacitance between electrodes) [3]. This aspect needs to be checked along both the machining and the brazing phase is the last process that can permanently affect the cross section.

Table 1: IFMIF RFQ Main Parameters

Frequency [MHz]	175
Length [m]	9.8
R_0[mm]	4.13-7.1
ρ/R_0	0.75
Beam Current [mA] (CW)	125
Beam Transmission (Gaussian)	93.7%
Beam Losses [W]	1291
V [kV]	79-132
W [MeV/u]	2.5
$\Delta V/V$ range	± 2% (target value),
Q_0	12000 (25% margin)
RF power [kW] (CW)	1250 (25% margin)

The main construction steps of each RFQ module are organized in the following phases (Fig.1):1: Deep drilling, 2: Electro Discharge Cutting3: Rough Milling 4: Finish Milling 5 Electrode brazing 6 : Corner TIG welding 7: Front face and external references final milling for module alignment.

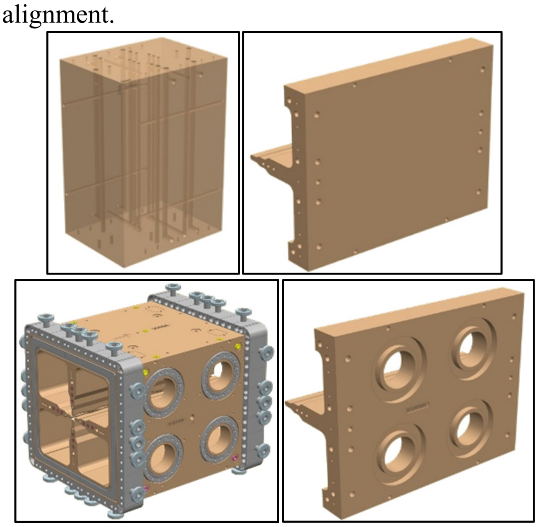

Figure 1: Component geometries along the production phases: 1 ,2, 3,7 (clockwise, from top left).

RFQ MODULE MECHANICAL METROLOGY

Metrological control and quality assurance through the production phases were performed using a Zeiss Accura CMM equipped with a VAST XT active scanning head (MPE_E=2.2+L/300[µm]). All electrodes are isostatically placed on the table and thermalized at standard ambient temperature and controlled humidity. Most of the geometry of the electrodes were inspected using continuous contact scansion to save time and increase the number of points measured for each feature, in particular for the 3D curves related to the modulation surface and the vane transversal profiles. Form and dimension tolerances were met from each electrode geometry feature, in particular with respect to modulation as partially reported on Figure 2.

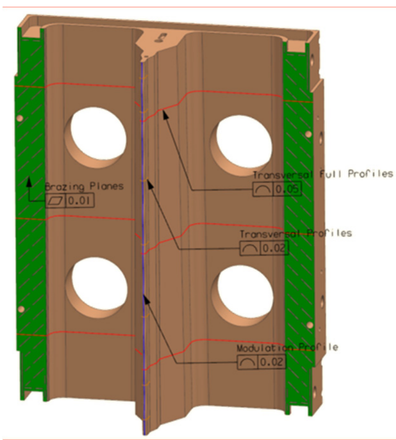

Figure 2: Form tolerances applied on curves of significant 3d-curve surfaces.

The inspection of the radiofrequency exposed surfaces (modulation, vane and vessel planes) leads to understand their position and then fixes the 6-Degrees Of Freedom with respect to an external electrode reference system coordinates (Figure 3).

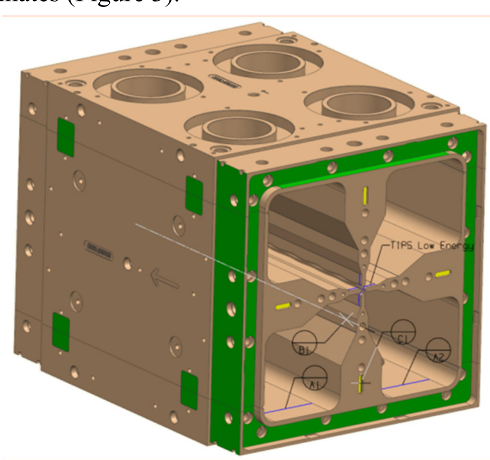

Figure 3: Dry assembly module with some element reference use for the module reference coordinate system.

Once the entire geometry of each electrode is known, in the dry assembly phase, the front grooves (yellow on Figure 3) and the extreme transversal profiles (TIPS on Figure 3) are measured with respect to the module reference system coordinate. The entire internal geometry is established respecting both geometric and radio-frequency requirement (nominal pre-braze assembly). In this phase, electrodes were moved in order to get an accuracy of the tip profile below the 0.02mm. At this condition all the electrode tips are almost at the same distance respect to the ideal Beam Axis (i.e. ΔR_0<0.01 mm). After the brazing phase almost all the modules show that the electrodes moved from the nominal position. In order to obtain the new internal geometry, tips and grooves were re-measured and a calculation of the new beam axis was performed.

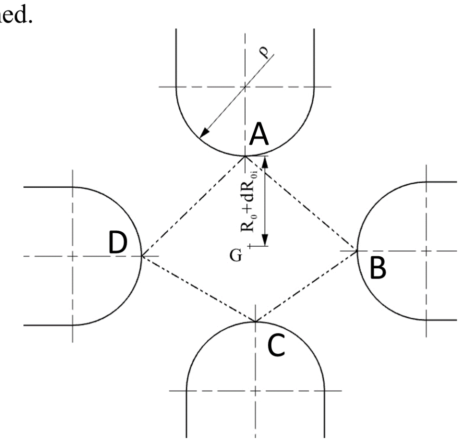

Figure 4: Beam axis point G calculated based on the transversal TIPS profile measured.

Measurements reveal that electrodes, during the brazing cycle, moved mainly in the transversal plane rather than the longitudinal direction where displacements are almost 0.05mm, much less than the minimum length of a cell ($\beta_{min}\lambda/2$=8.76 mm). So, as the electrodes were not deformed but only a solid rotation-translation occurs, the real beam axis could be calculated using the centre of the two quadrilateral areas (figure 4), at the low and high energy side of each module. In order to calculate also the mean deviation of the electrode tips, the real beam axis point G was used with the apexes A, B, C, D both forlow and high energy quadrilateral areas, and then averaged to get the measured ΔR_0 for each module. The measured real Beam Axis was used to machine coherently the front faces and the external references in the phase 7.

RF MEASUREMENTS

The alignment of the electrode is checked by RF test too. In order to perform these tests, at both ends of each module, two straight sections of waveguide (a=b=340 mm), 300 mm long and short-circuited at their ends are connected. a and b are equal to the distance between RFQ upper and lower walls. If f_0 is the “natural” resonant quadrupole frequency of each module, and f_{WG} is the resonant frequency of the same module connected with

ISBN 978-3-95450-169-4

the waveguides, a linear relationship (characteristic for each module) holds between the two above-mentioned quantities, as far as small deviations of geometrical RFQ parameters are concerned. In particular fq_0 is the resonant frequency of each module when closed with perfect H boundaries at both ends for modules 2 to 17, and when closed with E boundary at the initial (final) section for module 1 (18) and with perfect H boundary at the final (initial) section of module 1 (18). These RF tests were performed before and after each brazing step (Figure 5).

Figure 5: A RFQ module connected with the square waveguide for RF measurements

As for the determination frequency sensitivities wrt geometric parameters variation, it is evident that a key parameter is the dependence of frequency deviation Δf_0 (and consequently Δf_{WG}) on the geometric errors in the RFQ. Since these quantities depend via the Slater Theorem on the unbalance between electric and magnetic energies, the effect of geometric errors on frequency is dominated by the geometric errors related to ρ and R_0, the pole tip region being characterized of a concentration of electric energy. Therefore, it is possible to write $\Delta f_{WG} \approx \chi_{R0}\Delta R_0 + \chi_\rho \Delta\rho$. Simulations performed in both 2D (SUPERFISH) and 3D environments (HFSS v.15) showed that χ_{R0} ranges from 11 MHz/mm for the first modules up to 7 MHz/mm for the last ones and that χ_ρ is approximately equal to $\chi_{R0}\cdot R_0/\rho$ = 1.3 χ_{R0} in our case. On the other hand, it has to be observed that, while $\Delta\rho$ depends only on construction accuracy (±10 μm in our case), ΔR_0 depends on electrode positioning due to alignment and/or brazing, that are significantly higher. Therefore, above expression was furtherly simplified to $\Delta f_{WG} \approx \chi_{R0}\Delta R_0$. As for Δf_{WG} is concerned, such value is determined by difference of the f_{WG} obtained with RF measurement on each module with the f_{WG0} nominal frequency obtained with HFSS simulations. It has to be pointed out that the ΔR_0 determined in this way takes into account the average displacement on the four electrodes of the average aperture R_0 of each module. In Figure 6, the comparison between the average apertures deducted from mechanical and RF measurements is shown.

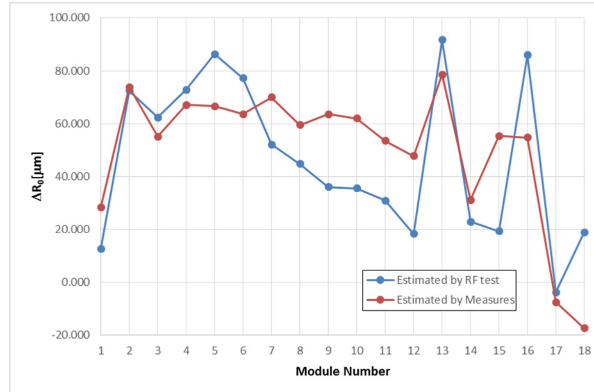

Figure 6: Average ΔR_0 estimation for each RFQ module. The red curve represents the outcome of mechanical measurements, while the blue curve represents the outcome of RF measurements.

From the graph it is possible to draw some outcomes:, first, almost all ΔR_0 values are positive: in fact, during brazing, when temperatures approach 850° C, thermal deformations of Stainless Steel are slightly less than the corresponding one of copper. After brazing, mechanical measurements show a stretching of the E-shaped electrodes on the surface where vacuum, tuner and coupler flanges are placed, with little effects on their pole tip displacements. Conversely, the T-shaped modules turn out to undergo a displacement of pole tips from beam axis. The overall effect is a decrease of inter-electrode capacitance and an increase of frequency. Second, all the measured values are such that $|\Delta R_0|$< 100 μm, with an average value on all the modules of 46 μm for the RF measured data and of 50 μm for the mechanical measurement data. For the given frequency sensitivities χ_{R0}, they correspond to a 0.35 MHz overall frequency shift and are all within the ±1 MHz tuning range established for the IFMIF RFQ: this result was confirmed by the RF measurements on the overall RFQ, in which a frequency shift of about 0.28 MHz was detected [4]. Finally, the two curves show for almost all samples a good correspondence between RF and mechanical data, both as trends and numerical values is concerned.

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