IFMIF-EVEDA RFQ DESIGN

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Abstract

The RFQ of IFMIF-EVEDA project is characterized by very challenging specifications, with 125 mA of deuteron accelerated up to 5 MeV. After the long period of conceptual and comprehensive design of IFMIF accelerator, the decision of the construction of its low energy part has implied a new analysis of the RFQ design. In particular the beam dynamics design has been optimized, with a consistent reduction of the structure length and power consumption, and improvement of the performances in terms of beam losses. The resonator, of four vanes kind, has been designed taking advantage of the theoretical background and experimental experience gained in Europe with IPHI and TRASCO projects. The mechanical design has been analysed considering different approaches, involving vacuum brazing, laser or e-beam welding.

MAIN BEAM DYNAMICS OUTCOMES AND RFQ PARAMETERS

The main RFQ parameters are listed in Table 1

Table 1: IFMIF RFQ input design parameters

Particles	D+	
Frequency	175	MHz
Input Current	130	mA
RMS Input emittance	0.25	Norm. mmmrad
Input Energy	0.1	MeV
Output Energy	5	MeV
Max Surface Field	25.2	MV/m (1.8 Kp)
Length L	9.78	m
Voltage Min/Max	79.29/132	kV
R0 min/Max	4.1 / 7.1	Mm
Transmission (WaterBag distr.)	98.9	%
Beam Power Loss	522	Watts

The IFMIF EVEDA RFQ beam dynamics study[1] was aimed at minimizing beam losses at high energy, reducing the RFQ length and power consumption. A closed-form and continuous up to the 2nd derivative voltage law V(z) was used. In this way it is possible to increase the voltage in a smooth way in the accelerator part and to have continuous cut-off frequency excursions.

FOUR VANE RFQ DESIGN

Geometry optimization

The choice of a four-vane structure with variable R_0 and voltage profile required an accurate tuning of the 2D section of the RFQ in order to compensate for local TE_{21} cut-off frequency f(z) variation due both to voltage and aperture variation. In the first case such frequency variation is related to the 2nd derivative of the voltage, while, in the second case, the cross section tuning process had to compensate the R_0 variation along the cells. The desired Cross Section Frequency is obtained by varying the Vane Base Width 2·W1 along the RFQ. The minimum W value (1 cm) was chosen in order to allow cooling channel positioning and the minimum W1 value (1.5 cm) was chosen to avoid mechanical oscillations during machining. The upper flat surfaces (9 cm) allow the positioning of tuners and RF couplers (Fig.1).

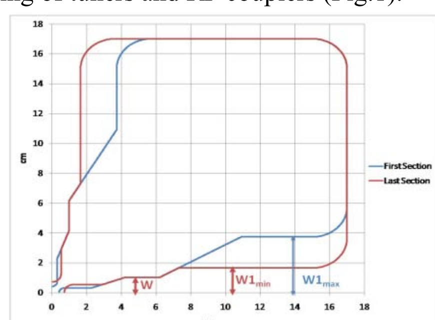

Fig. 1: Vane base width tuning for the IFMIF RFQ.

The related optimization was carried out with SUPERFISH calculations and the main results are summarized in Table 2. It has to be pointed out that the total power P_d is related to the 2D power calculated by SUPERFISH, P_{SF}, by means of the relationship

$$P_d = P_{SF}\alpha_{3D}\alpha_v + P_b$$

where α_{3D}=1.3 is a factor that takes into account the 3D losses, P_b is the beam power at Beam Current =130 mA and α_v = 1.21 (= 1.1^2) takes into account the possibility of enhancing the intra-vane voltage up to the 10 % with respect to the nominal value.

This optimized geometry was also simulated with HFSS 11.0, by creating a 3D model of the RFQ obtained by connecting the 2D section calculated by SUPERFISH and with no coupling elements in between. The results obtained upon such simulation show that the maximum error between the "ideal" field profile given by the 2D code along z and the HFSS-simulated one is within 4% and is concentrated in the first 3 meters of the structure (Fig. 2).

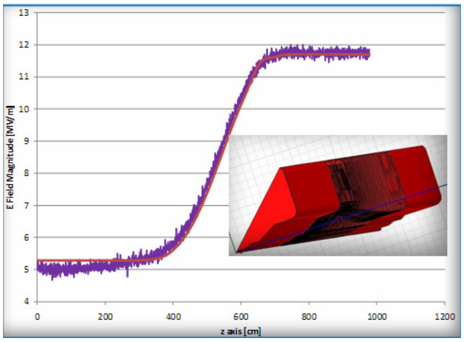

Fig. 2: comparison between 2D (red curve) and 3D blue curve electric field magnitude variation along z of the RFQ.

The sensitivity with respect to geometrical errors was addressed both numerically and analytically, and it was found that the maximum [minimum] sensitivity χ is located in the initial [final] section of the RFQ, where $\Delta f/\Delta R_0$=11.8 MHz/mm [7.5 MHz/mm].

Table 2: SUPERFISH results

Shunt Impedance	206-270	kΩm
Q_0 (SF)	15100-16700	
Copper Power (SF)	450	kW
Stored Energy	6.6	J
Max H field	3000-4500	A/m
Max. Power Density	1.6-4.1	W/cm^2
Total power	1.345	MW

Tuning range and segmentation issues

In order to cope with geometrical errors, a system of 88 slug tuners (22 tuners / quadrant) of 90 mm diameter is foreseen. The average tuner sensitivity χ_T turns out to be of about 70 kHz for Δh=1 mm penetration of all tuners. The 2D initial cut-off frequency was chosen to be equal to 174 MHz, with the aim of exploiting a tuning range well above the frequency range spanned by geometrical perturbations. For instance, if ΔR_0 = ±30 μm, the frequency shift corresponding to maximum sensitivity ($\Delta f/\Delta R_0$=11.8 MHz/mm) is equal to ±350 kHz, and the frequency tuning range is equal to ±1000 kHz. In this case it can be shown that the operational frequency can be obtained with a 14.2 mm tuner penetration, thus fixing the tuning range to be equal to Δh=[0 mm, 28.4 mm].

As an example of the effectiveness of the chosen tuning range, the effect of a 50 μm R_0 perturbation (590 kHz) located in the first half of the RFQ was considered, for both cases of uncoupled (Fig3 bottom) and coupled (Fig 3 top) RFQ with a coupling cell located at z=L/2. It is possible to notice that the tuning algorithm permits the reduction of the voltage perturbation $\Delta V(z)/V_0$ up to the design specifications without any "saturation" of the available tuning range.

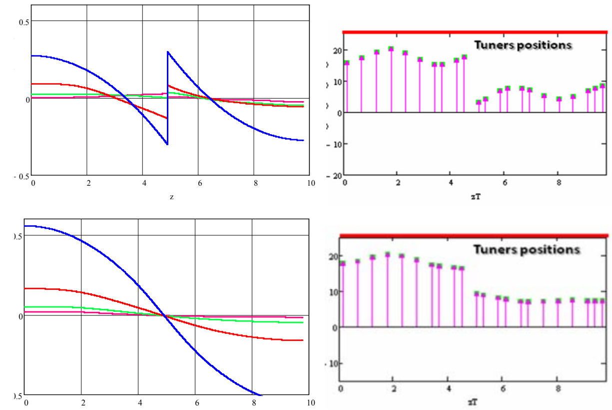

Fig. 3: (right) $\Delta V(z)/V_0$ field correction provided by tuning (three iterations, the perturbed field prior to tuning is the blue curve, red 1° iteration, green 2° iteration , magenta 3° iteration). (left) The tuners positions are below the "saturation" position (red line) .

The possibility of adopting a segmented structure by introducing a coupling cell in the middle of the RFQ is being considered and HFSS simulations in order to obtain the optimized geometrical cell parameters are in progress. However, it has to be noticed that, although the coupling cell is effective in reducing the structure sensitivity up to 40%, it is not effective with dipole mode perturbations and the chosen tuning range is effective to contrast perturbations also with an unsegmented structure.

MECHANICAL DESIGN CHOICES

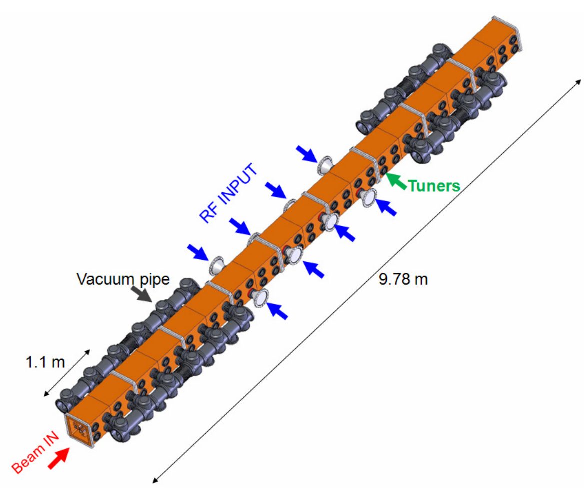

Fig. 4: RFQ schematic layout

In the base line design the accelerator tank is composed by 9 modules flanged together (Fig.4); a regular pattern of lateral CF100 flanges allows to host the dummy tuners, the aperture for vacuum pumping manifolds and the power couplers loops. These last devices will be built under the responsibility of JAEA.

Alternative technologies respect to vacuum furnace brazing for the construction of the accelerator modules have been preliminary tested; namely the welding of the four components from inside the cavity, employing the e-beam welding and laser welding, were considered. Unfortunately in both cases we found that the R&D effort required for the final result was not consistent with our time schedule. Concerning brazing instead we identify a new approach that can cope with the specific problems of IFMIF RFQ, making the maximum use of the experience gained with TRASCO construction.

Due to the relatively high transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass amount (so that for an assumed transversal shape the longitudinal one is fixed) . Staring from these constraints, the choice of the basic construction units of the RFQ was to use copper blocks of length 550 mm (Fig.5). Such blocks will undergo two brazing cycles: in the first, the four electrodes of each block will be joined in a horizontal oven, then, in the second, two of such blocks will be brazed in a vertical oven, together with Stainless Steel head flanges, in order to obtain a mechanical module of 1100 mm of (Fig. 6) for a total weight of about 700 kg. The total number of modules is equal to 9: it has to be noticed that the end caps of the RFQ will be made with 500 mm modules.

To minimize the use of Ultra-pure CUC2 and to limit the induced stresses on the raw material, a rough-cut of the shape of the sub-module components from a starting block of about 500x280x570 mm will be performed, by using a EDM.

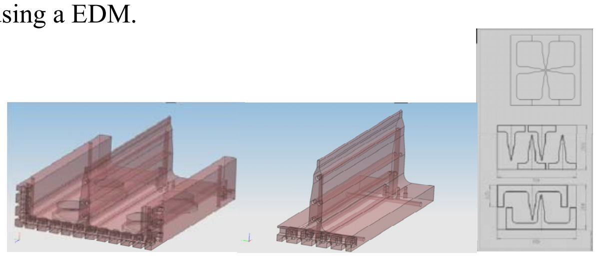

Fig. 5: sub-module components and nesting in the starting block.

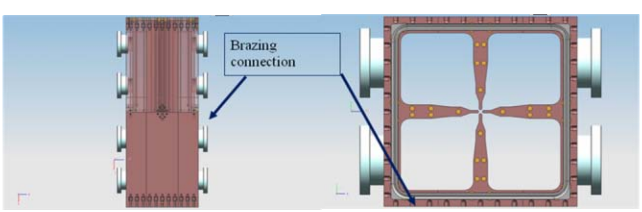

Fig. 6: the brazed 1100 mm assembly

A finishing stock of about 1 mm will be considered (to compensate the shape changes after the annealing step @600 C). This approach will also minimize the finishing milling time and the total energy transmitted to the sub-modules components during machining.

As for the cooling system, a separation of the cooling lines for vanes and cavity skin is needed in order to have the possibility of controlling the frequency via the water temperature, by acting separately on inductive and capacitive part; another constraints come from the fact that the contact surface between the cooling lines and the sensitive volume must be minimized and any water passage through ducts/brazed surfaces must be avoided. Moreover the water temperatures and velocities were chosen in order to minimize the frequency change induced to the cavity due to the RF power. Another feature of the system is the collection of all the cooling connections far from the bolted flanges

The cooling channels arrangement is being validated via thermo-structural analyses performed in ANSYS environment, making use of the power density map provided by SUPERFISH simulations. The case study considered were the sections with minimum and maximum vane thickness (A1 and A2 sections). For such simulations the vanes temperatures were assumed to be equal to 23°C [23.5°C] for the channels located in the cavity skin for section A1 [A2], 20.5°C for the channels located in the cavity vanes for both sections A1 and A2, while the convective exchange coefficient was assumed to be equal to 8000 $W/(m^2K)$

In figures 7 and 8 the temperature and deformation distribution are shown.

• A1 section: $Power = 75{,}9\frac{W}{cm}\ Peak\_Power\_Density = 1.6\frac{W}{cm^2}$

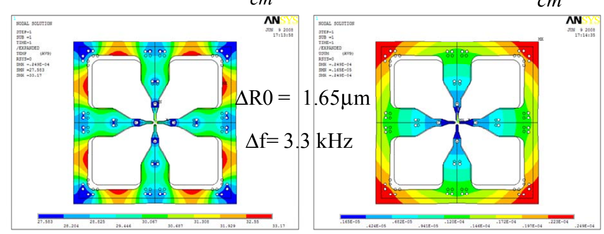

Fig. 7: ANSYS calculations of cooling channels effects at RFQ input, max copper temperature of about 33 deg.

• A2 section: $Power = 160.1\frac{W}{cm}\ Peak\_Power\_Density = 3.1\frac{W}{cm^2}$

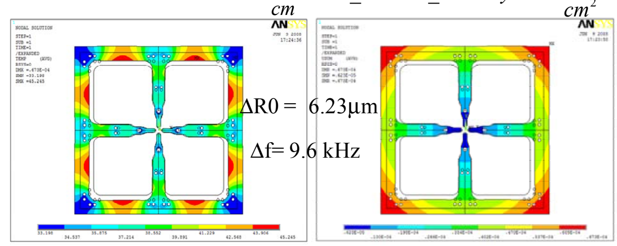

Fig. 8: ANSYS calculations of cooling channels effects at RFQ output, max copper temperature of about 44 deg.

REFERENCES

[1] M. Comunian, et. al. " Beam Dynamics of the IFMIF-EVEDA RFQ", THPP075, This conference.