THE IFMIF-EVEDA RFQ: BEAM DYNAMICS DESIGN

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Abstract

The IFMIF-EVEDA (Engineering Validation and Engineering Design Activities) project foresees the construction of a high intensity deuteron accelerator up to 9 MeV, with the characteristics required for the actual IFMIF facility. The linac will be installed in Rokkasho, and INFN is in charge of the construction of a 5 MeV, 125 mA, deuteron RFQ operating at 175 MHz. In this article the beam dynamics design of this challenging RFQ is described, namely the design, the main outcomes in terms of beam particles physics, and finally the study of mechanical and rf field error tolerances. The RFQ design method has been aimed to the optimization of the voltage and R0 law along the RFQ, the accurate tuning of the maximum surface field and the enlargement of the acceptance in the final part of the structure. As a result this RFQ is characterized by a length shorter than in all previous design, very low losses (especially at higher energy) and small RF power dissipation[1][2][3].

RFQ PARAMETERS AND DESIGN

The IFMIF EVEDA RFQ specification and the main design parameters are listed in Table 1.

Table 1: IFMIF RFQ Parameters

Particles	D+	
Frequency	175	MHz
Input Current	130	mA
RMS Input tr. emittance	0.25	N.mmmrad
Input/Output Energy	0.1/5	MeV
Max Surface Field (1.82 Kp)	25.6	MV/m
Length L	9.78	m (5.7 λ)
Voltage Min/Max	79/132	kV
Total Power with margins	1.6	MW
Mean aperture R_0(min/max)	4.1 / 7.1	mm
Trans. (WaterBag÷Gauss)*	99.1÷95.7	%
Power Loss(WaterBag÷Gauss)*	253÷1007	Watts
RMS Output Long. Emittance*	0.197	MeVdeg
RMS Output Tr. Emittance*	0.26	N.mmmrad

*Average of 10 Toutatis runs with 10^6 particles.

The design of such high current RFQ is very challenging due to the necessity to limit deuteron losses, keeping in particular extremely low the losses in the high energy part. The aim is to minimize the neutron production and the consequent activation of the RFQ structure.

Due to the high space charge effect at low energy. The value of input energy has been chosen of 0.1 MeV to maintain the value of maximum transverse current up to 200 mA until the end of Gentle Buncher;, this large margin guarantees small losses along the buncher formation process.

All the RFQ simulations here reported has been made by using the CEA code "Toutatis" [4].

Transverse Parameters Characterization

The IFMIF EVEDA RFQ beam dynamics study was aimed at minimizing beam losses at high energy, reducing the RFQ length and power consumption. The main parameters are plotted in fig. 1, the focusing force "B" at the beginning of RFQ is about 7, i.e. a very high value to compensate the high space charge force and keep the beam in a linear force fields. It is not possible to ramp the value of "B" in the shaper because we get a larger beam size and due to that same losses in the gentle buncher process. The normalized transverse acceptance of the RFQ in smooth approximation is defined by:

$$Acc = \frac{a^2\sigma_{T0}}{2\lambda}\sqrt{\left(1-\frac{B}{4\pi^2}\right)^3 \Big/ \left(1+\frac{B}{4\pi^2}\right)}$$

with λ the wavelength a small aperture, σ_{T0} phase advance at zero current and "B" the focusing factor expressed by:

$$B = \frac{qV}{mc^2}\frac{\lambda^2}{R_0^2} \quad and \quad \sigma^2_{T0} = \Delta_{RF} + \frac{B^2}{8\pi^2}$$

The variation of acceptance and "B" is therefore strictly connect to voltage and average aperture R_0 along the RFQ. For that reason a closed-form and continuous up to the 2nd derivative voltage law V(z) and R_0(z) was used.

$$V(z) = V_1 + (V_2 - V_1)\left(\frac{1}{2} + \frac{15}{8}\left(-\sin(\Delta z_{12}) - \frac{1}{3}\sin(3\Delta z_{12}) + \frac{1}{5}\sin(5\Delta z_{12})\right)\right)$$

$$R_0(z) = R_{01} + (R_{02} - R_{01})\left(\frac{1}{2} + \frac{15}{8}\left(-\sin(\Delta z_{34}) - \frac{1}{3}\sin(3\Delta z_{34}) + \frac{1}{5}\sin(5\Delta z_{34})\right)\right)$$

$$with \quad \Delta z_{12} = \frac{\pi}{6} - \frac{\pi(z-z_1)}{3(z_2-z_1)} \quad and \quad \Delta z_{34} = \frac{\pi}{6} - \frac{\pi(z-z_3)}{3(z_4-z_3)}$$

In this way it is possible to increase the voltage in a smooth way in the accelerator part and to have continuous variation of the phase advance per meter along the RFQ. The R0 and the voltage V are ramped after the Gentle Buncher, the V is increased for 4.4 meters instead the R0 are changed for 4.5 meters to reduce the surface fields and smoothing the phase advance change rate. The final value of the voltage V_2 is limited by the total available RF power, the final value of R0 allows to avoid the resonance $\sigma_T = \sigma_L$.

In the final 3 meters of accelerator almost all the parameters are kept constant. It's done to avoid small losses and to limit the part of the RFQ where the full 3D machining modulation is needed.

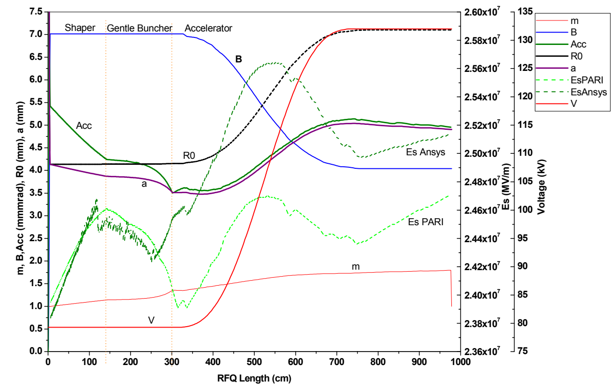

Figure 1: Modulation, Focusing factor B, Acceptance, Mean aperture "R0", minimum aperture "a", Surface Fields "Es" and voltage profile along the RFQ.

The ratio of V/R0 also is limited by the surface fields Es. The increase of R0 and "a" produce the increase of acceptance. The ratio of ρ/R0 is kept constant at 0.75 to reduce the surface fields, at the price of higher multipoles components. The modulation law chosen was the "2TERM" type, allows to manage successfully the non linearities.

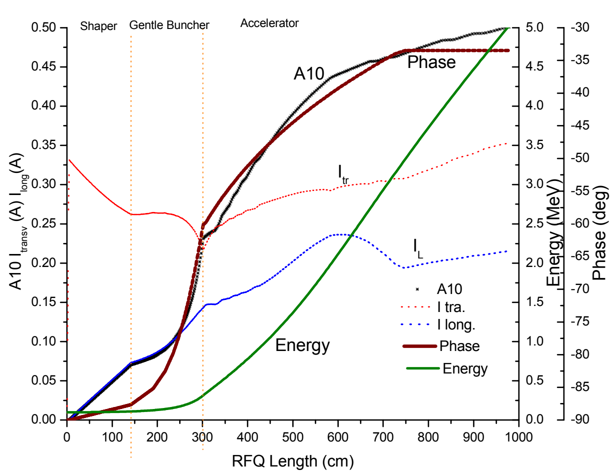

Figure 2: Energy, Acceleration coefficient A10, Synchronous phase, Current Limit Transverse and Longitudinal along the RFQ.

Longitudinal Parameters Characterization

Due to the strong longitudinal space charge phenomena during the separatrix formation, also with the presence of filamentations, the shaper section of the RFQ is very long, about 1.4 meters, this guarantees with an relative high number of cells, the high longitudinal beam capture. The bunching process is so done in as smooth as possible way to capture as much as possible particles. The particles capture indicate by RFQuick was 100% in a large range of GB energy but with the multiparticles tests the real useful zone in energy was very small, so the selected GB final energy was 0.31 MeV, and at the end of GB the synchronous phase is -60 deg, this is the maximum phase possible keeping in account the longitudinal current limit. In the accelerator part the synchronous phase is increased linearly, respect to the cell, from -60 to -33.5 deg, if it is increase more rapidly part of the beam go out of the separatrix. The energy gain per meter in the accelerator part is about 0.7 MeV/m. The plot of Fig. 3 show the final phase space with a gaussian input beam distribution, very few particles on 106 are making longitudinal halo.

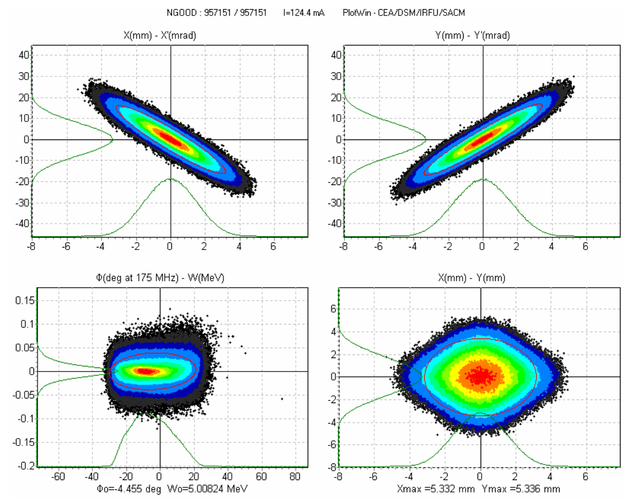

Figure 3: Phase Space at RFQ output with input Gaussian beam distribution of 130 mA, ε=0.25 RMS N. mm mrad.

ERRORS STUDIES

Alignment Between Modules

The RFQ structure will be made by fundamental elements 550 mm long; such elements are either brazed of flanged with a short longitudinal discontinuity. For that reason a study of tranverse misalignment at transition is mandatory. Vanes shape with an error on profile value $x_p(z)$ were generated, according to:

$$xp(z) = xp_0(z) \pm r\Delta X \quad with \quad -1 \leq r \leq 1$$

where ΔX is the maximum vane error amplitude considered and the random value "r" is regenerated for each element (Fig. 4). This procedure are made with 10 different RFQs, to accumulate statistics, and with a range from 0 to 100 μm of ΔX (Fig.5). It appears to be possible to handle errors on segmented RFQ in the order of ±50 μm, without a too large impact on transmission and power beam losses.

Due the huge numbers of runs to do, the errors study has been made by using Toutatis on a Linux cluster with about 20 nodes.

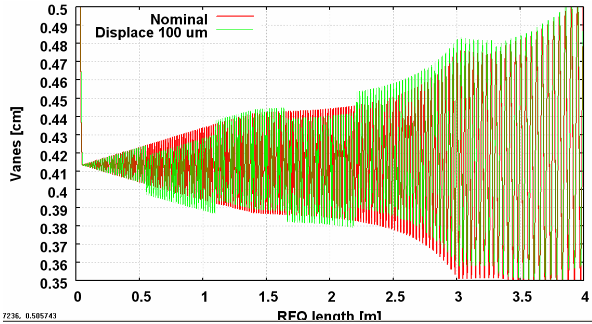

Figure 4: Vanes profile nominal and segmented in 550 mm pieces, along the first 4 meters of RFQ.

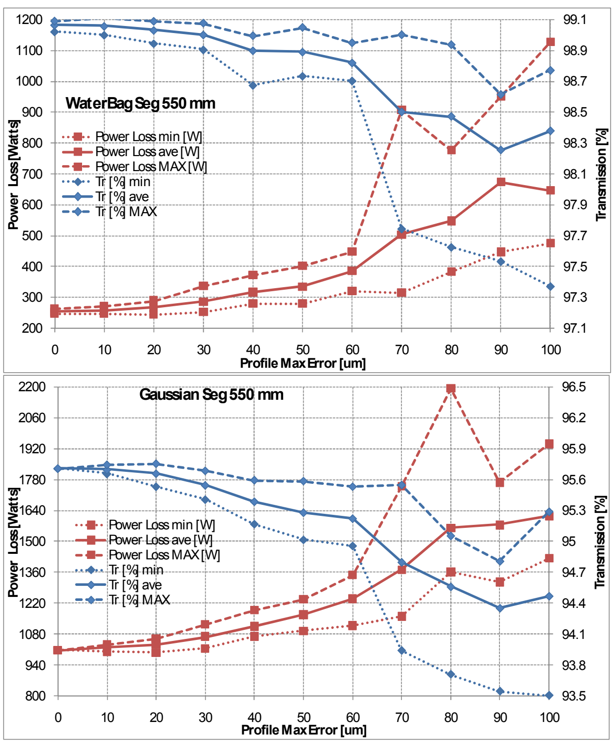

Figure 5: Transmission and Power loss due to the segmentations applied with gaussian and waterbag input beam distribution.

Voltage Tilt

To study the RF errors a tilt on voltage respect to the nominal value has been generated, (fig. 6), corresponding to a non null component of the first perturbing quadrupole.

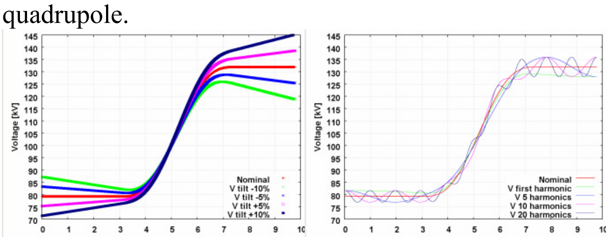

Figure 6: Tilted Voltage profile and harmonics profiled Voltage along the rfq.

The results of tilted voltage are in fig. 7, a positive tilt means a lower value of voltage at RFQ beginning. The power loss remains below 1.6 kW for very large range of values of tilted voltage.

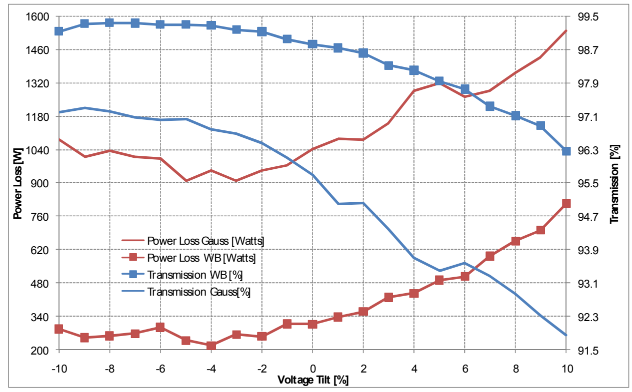

Figure 7: Voltage tilts effects on Transmission and Power loss with gaussian and waterbag input beam distribution.

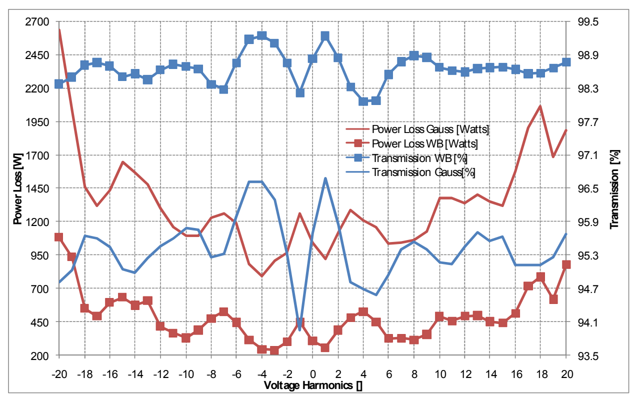

Figure 8: Voltage harmonics effects on transmission and power loss with gaussian and waterbag input beam distribution.

Residual Voltage Error

We have then simulated the residual voltage error after RFQ tuning by introducing higher order harmonics according to:

$$V_r(z) = V_0(z) + \mathrm{sgn}(n) \cdot \Delta V \cdot \cos(n \cdot \frac{\pi}{2} \cdot z / L_{rfq})$$

where n is integer and ΔV=3% of the nominal voltage (Fig. 6). The results show very little dependence from the applied voltage harmonics. From the results on tilted voltage and harmonics analysis it seems to be possible to handle a maximum error of ±3% on voltage (Fig. 8).

REFERENCES

[1] A. Mosnier, et. al. "The IFMIF-EVEDA Accelerator Activities", EPAC 2006, Genoa (Italy).

[2] A. Pisent, et. al. "IFMIF-EVEDA RFQ Design", EPAC 2006, Genoa (Italy).

[3] M. Comunian, et. al. " Beam Dynamics of the IFMIF-EVEDA RFQ", EPAC 2006, Genoa (Italy).

[4] R. Duperrier, "TOUTATIS: A radio frequency quadrupole code", Phys. Rev. Vol.3, 124201(2000).