BEAM DYNAMICS OF THE IFMIF-EVEDA RFQ

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Abstract

The IFMIF project is aimed at the realization of an intense neutron beam facility for testing the irradiation of the materials to be used for fusion reactors. EVEDA (Engineering Validation Engineering Design Activities) is a first step towards the implementation of this challenging project and consists of the construction of prototypes of the main units. In particular INFN-LNL is in charge of the construction of a 5 MeV, 125 mA, deuteron RFQ at 175 MHz. In this article the main aspects of the beam dynamics design of this RFQ are described, namely the optimization of the length and the transmission issues, the main outcomes and comparison of the PARMTEQM and TOUTATIS codes used for the simulations and the basic aspects of the errors studies.

INTRODUCTION

The RFQ of IFMIF-EVEDA project is characterized by very challenging specifications, with 125 mA of deuteron CW accelerated up to 5 MeV. After the long period of conceptual and comprehensive design of IFMIF accelerator [1], 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 objectives of EVEDA are to produce the detailed design of the entire IFMIF facility, as well as to build and test a number of prototypes, including the high-intensity CW deuteron RFQ, that it will be design and build in Italy by INFN and then assembled and operated at Rokkasho in Japan.

RFQ DESIGN

The RFQ design specifications (reported below) come from the Conceptual Design Report [1]. The ambitious goal of the design was to reduce the length as well as the beam losses, the beam power loss and the RF power needed.

Tab. 1: design specifications.

Particles	D+	
Frequency	175	MHz
Input Current	130	mA
RMS Input emittance	0.25	Norm. mm mrad
Input Energy	0.1	MeV (β_{in}=0.0103)
Output Energy	5	MeV (β_{out}=0.0730)

The proposed RFQ is composed of RMS, Shaper, Gentle Buncher about 3 m long and Accelerator about 7 m long.

The main points of this new design are the following:

- Use of the standard LANL chain of RFQ Codes, Ver. 3.05: Curli→RFQuick→Pari→Parmteqm→Vanes, to have a very fast feedback on full multiparticles response for every RFQ studied [2].
- Use of an analytic law on voltage shape able to increase the voltage in a smooth way in the accelerator part. The average aperture "R0" follows the same law to keep the surface field under control.
- The Acceptance on the accelerator part has been increased from 2.6 at end of Gentle Buncher up to 4.2 mm mrad to reduce losses at high energy.
- Use of the small "a" to almost diaphragm the beam at the GB end, to stop almost all the losses at this point.
- Use of a high value of focusing factor B, around 7, to keep the beam in the linear part of focusing fields.

The voltage law used only in the accelerator part from z_1 to z_2, is the following:

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

$$with \quad \Delta z = \frac{\pi}{6} - \frac{\pi(z - z_1)}{3z_2}$$

where V_1 and V_2 are the initial and the final voltage, z_1 is the longitudinal coordinate at end of GB, and z_2 is about at half of the accelerator part. The plot of voltage is shown in Fig.1. This law allows to increase the voltage and keeps the second derivative quite smooth to match the RF frequency design. Most of the design optimization was made on the accelerator part, due to its length and importance for beam power loss. The focusing force is reduced in the Accelerator part, by varying R0 with the same law as the voltage. The consequence is a decrease of the radial focusing which, coupled to an increase of modulation m, permits to raise the acceleration factor A. The final value of B, around 4, has been checked with the matching line for the Linac.

RFQ PARAMETERS

The main parameters are reported in Tab. 2. The RFQ is almost at constant R0 for 5/9 of its length. This permits to reduce the full 3D machining modulated part and consequently to decrease the construction time. The maximum surface field is at about 5 meter in the accelerator part with a value of 1.76 kp from PARI and 1.82 kp from a direct calculation cell by cell from a FEM code (ANSYS).

Tab. 2: RFQ Main Parameters.

Length	9.78	m (5.7 λ)
Total Cell number	490	
Voltage Min/Max	79.29/132	kV
Max modulation m	1.8	
Min aperture "a"	3.48	mm
R0 min/Max	4.135 / 7.102	mm
Ratio ρ/R0 (constant)	0.75	
Final Syncronous phase	-33.5	Deg
Total RF Power+Beam power	1.6	MW
Transmission (WaterBag)	98.9	%
Longitudinal Emittance RMS	0.27	MeV deg
Output Tr. Emittance RMS	0.3	mm mrad
Beam Power Loss (WaterBag)	522	Watts
Max Surface Field (1.76 Kp)	24.7	MV/m

The geometry type chosen for this RFQ is the "2TERM" in order to reduce the multipoles contents all along the RFQ. This fact, together with a high B, produces extremely linear transverse fields around the beam.

The most important RFQ parameters are reported in Fig. 1. In the last 3 meters, all parameters were left almost unchanged, thus avoiding losses at high energy. The abrupt change of modulation and "a" at end of GB was made to create a "collimator zone" able to scrape the particles that were not well bunched and close to the vane tips. The input RMS section is composed of 6 cells.

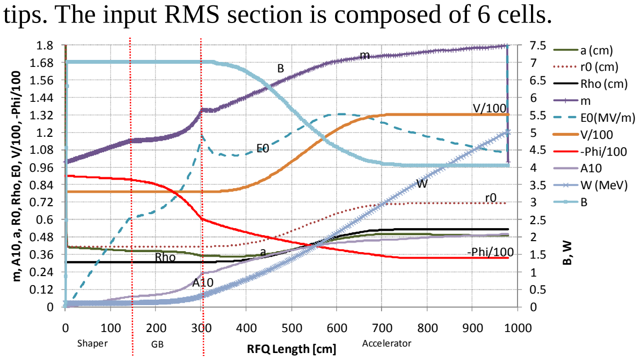

Fig. 1: Main RFQ parameters as function of length.

RFQ BEAM DYNAMICS

The full check on beam dynamics results has been done by using PARMTEQM ver. 3.05 [2] and Toutatis ver. 2008 [3]. In both codes the space charge is fully implemented, 2D (r-z) by "Scheff" routines on PAMTEQM and 3D by Finite Difference Method on Toutatis. FDM on Toutatis calculates also the multipoles effects and the image charge, which are calculated instead as fields expansion close to beam axis by PARMTEQM.

In Fig. 2 the envelopes results coming from Toutatis are reported, upon assuming a WaterBag as the input beam distribution.

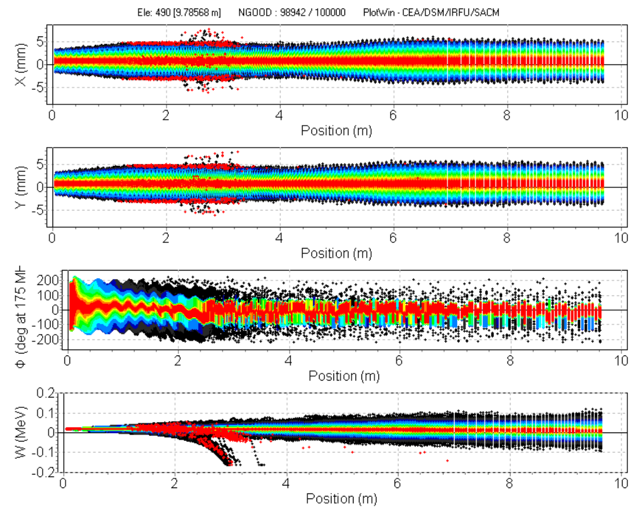

Fig. 2: X (mm), Y (mm), Phase (deg) and Energy (MeV) envelopes along the RFQ.

The Phase space output as obtained by Toutatis is reported in Fig. 3, using 1 million macroparticles at 130 mA and 0.25 mm mrad RMS emittance. A fringe fields cell of 20 mm was put at the end of the RFQ. This cell permits a smooth field variation up to RFQ exit. The final phase advance per meter is 200 deg/m transverse in order to assure a good matching with the linac.

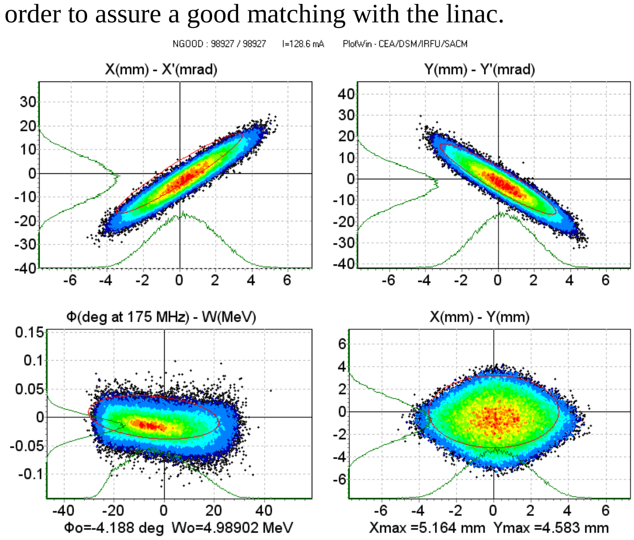

Fig. 3: Phase Space at RFQ output, only accelerated particles with input beam distribution WaterBag.

The PARMTEQM program, a space code, as been used as reference and the Toutatis program, a time code, as final check. In Fig. 4 the transmission along the RFQ is reported as obtained from PARMTEQM and Toutatis. The Toutatis runs were made with 1 million macro-particles. In this case the 3D Finite Difference Poisson solver multigrid in Toutatis was "65x65x65 and 17x17x17". The PARMTEQM runs were made with 1 million macroparticles as well. The 2D (r-z) Scheff grid was "20x40" for the Space charge solver with Image charge on, multipoles on and 5 nearest bunches.

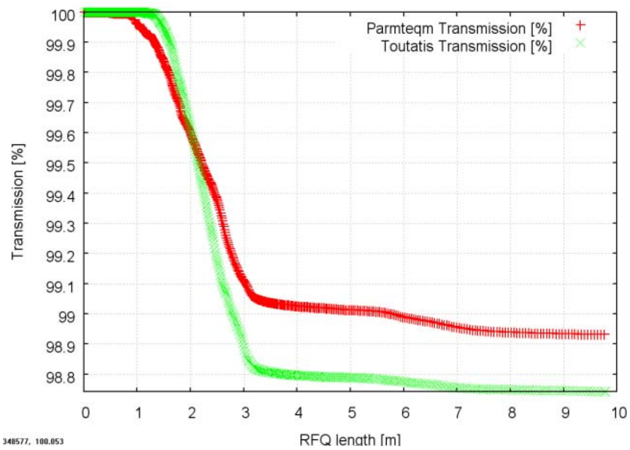

Fig. 4: RFQ Transmission from PARMTEQM and Toutatis as function of length, the difference amount between the codes is 0.2%.

PARMTEQM and Toutatis show very similar results in terms of transmission and power loss: 522 vs. 441 Watts. The RMS longitudinal emittance calculated was respectively 0.27 and 0.23 MeV deg. The small difference can be easily explained by taking into account the different positions along the structure where the quantities are calculated for an s-code respect to a t-code, and considering the different input beam distribution generation. It is mandatory to use a high number of particles for Toutatis to get the same results as PARMTEQM, due to high number of 3D cells to populate.

RFQ PARAMETERS SENSITIVITY

Up to now only some preliminary error studies on this RFQ have been performed. The program used for this purpose is Toutatis with TraceWin as Frontend. The calculations have been distributed on several computers via a client/server architecture (multi-parameters scheme) in a Linux cluster configuration with about 20-30 processors.

The effects of input emittance with different beam distributions, WaterBag and Gaussian (cut at 4 sigma) have been studied. As a result, the choice of the input beam distribution has a great influence upon the RFQ performance, as reported in Fig.5.

The Gaussian distribution has the biggest impact on beam transmission due to the larger total transverse emittance: in fact, for such a distribution, the total emittance turns out to be 16 times the RMS emittance, with respect to the 6 times of the RMS emittance for the WaterBag distribution. The emittance at the RFQ output is almost constant with respect to the input emittance. On the contrary, for lower values of input emittance an increase of a few percent of the emittance at the RFQ output is obtained.

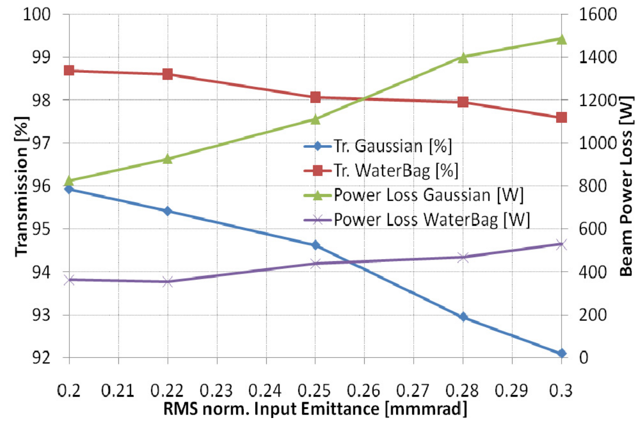

Fig. 5: RFQ Transmission and power loss as function of input emittance and input beam distributions.

The runs were made at 130 mA and 100'000 macroparticles. The reference point at 0.25 mm mrad has a 0.8% lower transmission due to the low number of particles and poor 3D mesh. From 0.2 to 0.3 mm mrad RMS normalized emittance the transmission has a 1% change if the beam input distribution is WaterBag and 4% if the input beam distribution is Gaussian.

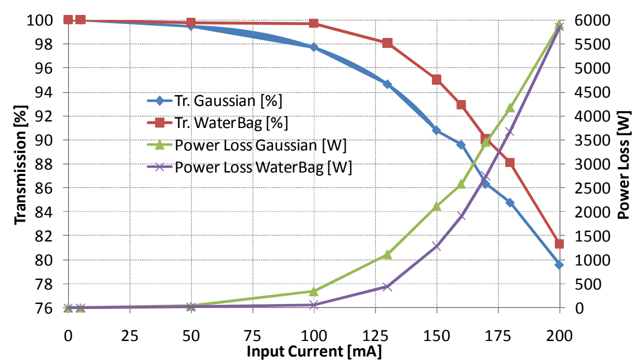

Fig. 6: RFQ Transmission and power loss as function of input current and input beam distributions.

The effects of input beam current on transmission and power loss, for WaterBag and Gaussian input beam distributions, were studied also as reported in Fig. 6. Runs were made at 0.25 mm mrad of RMS transverse emittance norm. and with 100k macroparticles. The transmission remains at more than 90% up to 160 mA for Gaussian and WaterBag input beam distributions. The transmission is almost 100% up to 50 mA. The sensitivity to the input beam distribution is lower at the highest values of current.

REFERENCES

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[2] K.R.Crandall et.al., "PARMTEQ-A beam dynamics code for the RFQ linear accelerator, LA-UR-88-1546.

[3] R. Duperrier, "TOUTATIS: A radio frequency quadrupole code", Phys. Rev. Vol.3, 124201(200).