BEAM DYNAMICS IN A HIGH FREQUENCY RFQ

A.M. Lombardi, V. A. Dimov, M. Garlasche', A. Grudiev, S. Mathot, E. Montesinos, S. Myers, M. Timmins, M. Vretenar, CERN, Geneva, Switzerland

Abstract

CERN is constructing a 750 MHz Radio Frequency Quadrupole (RFQ) which can accelerate a proton beam to 5 MeV in a length of 2 m. The beam dynamics strategic parameters have been chosen to make this RFQ a good candidate for the injector of a medical facility operating at frequency of 3 GHz . Minimising beam losses above 1 MeV, containing the RF power losses and opening the road to industrialisation have been the guidelines for an unconventional RFQ design. In this paper, the optimisation efforts, the structure design and the expected beam qualities will be detailed. The status of the construction as well as the potential for further developments will be presented.

INTRODUCTION

The office for medical application, created by the CERN director general in 2013 with the aim for CERN to become established as an important facilitator of medical physics in Europe, has -amongst others-the task of developing on-going accelerator, detector and information technologies in ways that will benefit medicine. In this framework the office has responded to the needs of several linac-based hadron-therapy projects and has created a study group for a high frequency RFQ with the aim of capitalising on the recent developments around the RFQ for the LINAC4 project, which was successfully commissioned in 2013.

Linac based proton-therapy facilities are the new generation in the field of hadron therapy machines, the main advantage with respect to the established PIMMS [1] design - being the possibility of fast energy variation (pulse-to-pulse). Typical linac-based facilities [2,3] include high-frequency, high-gradient structures resonating at the frequency of 3 GHz, equipped with Permanent Magnet Quadrupoles. Typically about 20m of accelerator are sufficient to bring the energy from 10 to 250 MeV, including a medium velocity structure up to 40 MeV and a high velocity structure up to 250 MeV. The effectiveness of accelerating non-relativistic protons with 3GHz has been demonstrated from the energy of 11 MeV [4]. It is believed that effective use from energies as low as 5 MeV is feasible. Below 5 MeV the use of 3GHz is excluded and a solution must be found for the missing link.

A HIGH FREQUENCY RFQ

The starting parameters for the RFQ design are reported in Table1. These are the working parameters used to define the layout and will be discussed in the following.

Table 1: RFQ and Source Specifications

Parameter	Value
RF Frequency	Subhar of 3GHz
Input energy	>30keV
Output Energy	5 MeV
Output Pulse Current	30 μA
Repetition frequency	200 Hz
Pulse duration	20 μsec
Transverse Emittance (100%,normalized)	0.4 (π mm-mrad)
Bunch length	±20 deg at 3 GHz
Energy spread	±35 keV
Length	Less than 2.5m

The combination of parameters as detailed in the table above calls for an unconventional RFQ design, as both the longitudinal and the transverse acceptance at 5MeV are factors smaller than the values currently obtained at this energy. Although the design of the source is outside the scope of this paper, we considered the source when defining the RFQ layout and we made sure that the challenges (emittance, extraction energy and current) were balanced between the source and the RFQ.

General Layout

In this paragraph we describe the fundamental choices that brought to the definition of the RFQ, the first one being the frequency. The choices as described here are motivated for the specific use of this RFQ in a proton therapy facility; they are not universal choices, as will be detailed in the last paragraph of this paper where other uses are proposed. The frequencies of 600, 750MHz and 1 GHz were considered: the higher the frequency the easier the frequency jump at 5 MeV but also the higher the technological jump from existing RFQs. From a purely beam-dynamics point of view the use of a higher frequency is certainly an advantage. We then compared 600 and 750 MHz on the basis of power losses consideration. The capacitance per unit length is a very weak function of the frequency, much more dependent on the ratio between the transverse radius of curvature and the average radius (ρ/r0). We can therefore assume that the capacitance is the same and we know from [5] that the power losses per meter scale like the V^2 $f^{3/2}$ where V is the vane voltage and f the frequency. For the same vane voltage the 750 MHz RFQ would use 1.4 times more power per meter, but we found out that the overall length of the RFQ would compensate for this disadvantage, and finally for the same vane voltage and same output energy the total power would be approximately the same. As the

Copyright © 2015 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-168-7

transverse dimension scale down with the frequency the power per unit volume is certainly higher the higher the frequency, so for high duty cycle and cooling consideration a lower frequency might be more suitable. Another interesting way to look at this issue is the length of the RFQ in terms of number of wavelength. If we make the comparison assuming the same output energy and a length equal to the same number of lambda (200 cm for 750Mhz and 260 cm for 600MHz) we find that actually the 750 MHz RFQ would need about 70% of the power that a 600MHz RFQ would need because the shorter length and a lower voltage would outweigh the frequency factor in the power balance. The same consideration can be used in the comparison between 750MHz and 1 GHz, but we deemed that the concurring decrease in transverse acceptance was too risky at this stage. Further consideration to this frequency should be given in the future and finally the choice was made to design the RFQ at 750MHz.

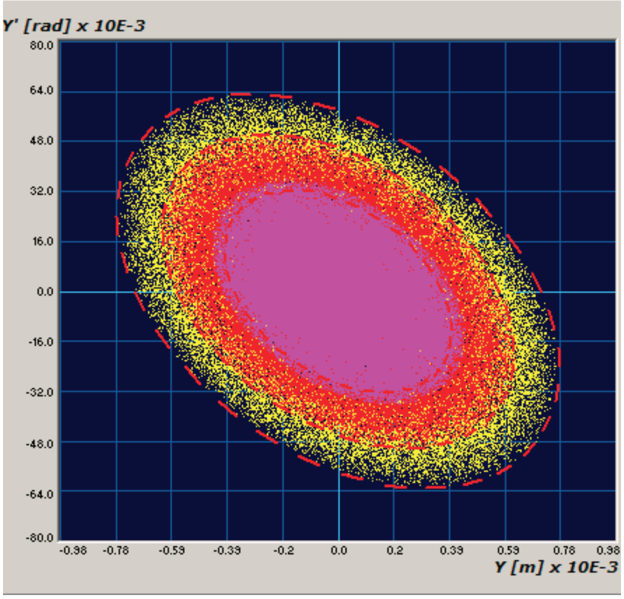

Figure 1: Comparison of the acceptance of the 3GHz structures (yellow), the RFQ design acceptance (red) and the target source emittance (pink).

The second parameter that was considered in the layout definition is the transverse brilliance and the necessary acceptance, as this is the deciding parameters for the average radius and the vane voltage, two critical parameters for shunt impedance, power needs and reliability via the maximum field on the vane-tip. The requirement of Table 1 calls for 30µA of protons in a maximum acceptance (normalised total) of 0.4 pi mm mrad and existing sources with extraction energy of 45 keV [6] deliver about 300 µA in an emittance of 0.15 pi mm mrad . We have fixed the target source emittance to 0.15 mm mrad and the RFQ acceptance to about twice that value allowing for a 20% emittance increase between the source and the injection into the 5 MeV structure. A visual comparison of acceptance and emittance is shown in Fig. 1, for a perfectly aligned system with no field errors. Once the average radius and approximate vane voltage have been identified with consideration of acceptance and source brilliance, the layout itself could be worked on starting from longitudinal consideration. The longitudinal acceptance of the 3 GHz structures, as from Table1 is rather limited with a phase acceptance of ±20deg at 3 GHz i.e. ±5deg at 750 MHz. This requirement calls for a fast longitudinal phase advance and high synchronous phase at the RFQ output. The most efficient way to transfer to 3GHz is a bunch to bucket injection without further capture or needs for re-bunching; therefore the efficiency of the RFQ is from now on quoted in the number of particles accelerated to 5 MeV that can fit into the 3 GHz bucket. It is also crucial to avoid losses at 5 MeV, energy well above the threshold of neutron production in copper. It has been therefore decided to design an RFQ which would accelerate to 5 MeV only the particles that can fit into the 3 GHz acceptance and particles that cannot be accepted should not be captured in the RFQ and lost at energies below 500keV. In order to meet this requirement we have designed a special bunching system in the RFQ where we size the stable bucket around the longitudinal acceptance at 3GHz. This design approach requires designing the RFQ backwards starting from the high energy end and iterating the global solution by forwards tracking a realistic multi-particle beam. The aim is to converge to an RFQ design where the particle outside the longitudinal acceptance have energies below few hundreds keV. The length of the RFQ is determined by the fraction of particles that we want to fit into the final longitudinal acceptance or equivalently on the number of longitudinal oscillation that we allow during the acceleration. After this phase we came up with three workable solutions, of different length and different transmission as detailed in Table 2. All solutions are assuming an acceptance of 0.3 pi mm mrad, a source extraction voltage of 40 kV, and an RFQ vane voltage of 80kV

Table 2: RFQ Options

Lenght	T eff	Comments
180 cm	30%	4-5 times the wavelength
240 cm	40%	Needs to be segmented into 2 cavities
360 cm	90%	Needs to be segmented into 3 cavities

The solutions listed above have increasing efficiency but also present a degree of increasing complexity. In fact whereas the short solution can be made out of a single RF resonator, the medium and longer solutions need to be made out of 2 and 3 separated resonators as the length will exceed the five wavelengths which is a limit for being able to tune the cavity and maintain it on frequency. The matching between two RFQs has been studied and a solution has been found to separate the cavities by 5 cm, a

Copyright © 2015 CC-BY-3.0 and by the respective authors

distance sufficient to separate electrically the cavities without compromising beam quality. It has nevertheless been deemed sufficient to accept a transmission of 30% considering the requirements of the downstream accelerators and the existing source brightness.

THE CHOSEN SOLUTION

Starting from the short option, an optimised baseline solution has been worked out on the basis of beam dynamics, RF and mechanical considerations. The guidelines for optimisation are

- a compact system but within a maximum RF peak power of 400kW, and a maximum electric field on the vane tip of 50 MV/m corresponding to 2 Kilpatrik limit;
- a two-term potential vane profile, a constant average aperture radius and a constant transverse radius of curvature for an easier tuning and the possibility of machining with a 2D cutter;
- a design robust with respect to machining and alignment errors as the use of this RFQ requires the possibility for industrialisation.

The final parameters of the RFQ are shown in Table 3.

Table 3: RFQ Parameters

Parameter	**Value**
RF Frequency	750 MHz
Input	40 keV
Output Energy	5 MeV
Length	2m
Vane voltage	68kV
Peak RF power	400kW
Duty cycle / max	0.4% /(5%max)
Input/Output Peak Current in 3GHz acceptance	100/30 µA
Transv. emittance 90%	0.1 pi mm mrad
Average aperture (r0) constant	2mm
Maximum modulation	3
Transverse radius of curvature	1.5 mm
Longitudinal radius of curvature (min)	1.9mm

The evolution of the characteristics structure parameters are shown in Fig. 2 and the beam output in the transverse and longitudinal plane is shown in Figs.3,4. In Fig.5 the histogram of the energy of the un-accelerated particles: the highest energy is 500 keV with a peak at 100 keV; this result is crucial for avoiding activation of the structure and due to its importance it has been confirmed with three independent codes [7,8,9], including direct integration in the 3D RFQ field map.

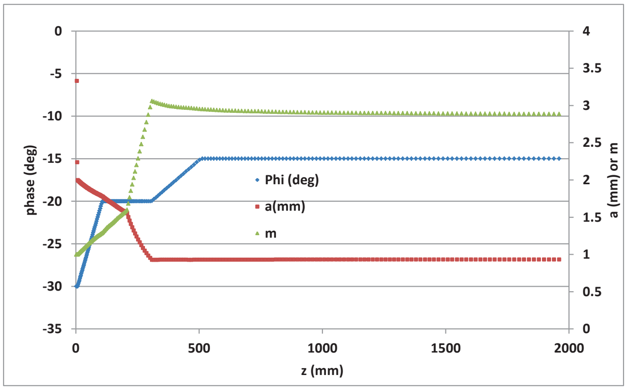

Figure 2: Phase, aperture and modulation along the RFQ.

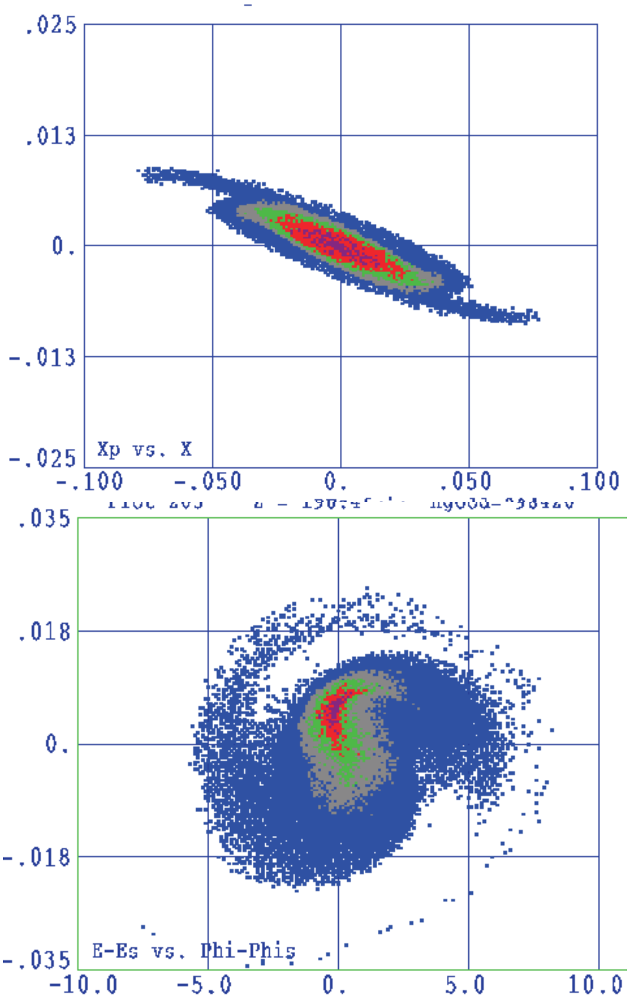

Figure 3: Transverse (top) and longitudinal phase planes at 5 MeV units of cm mrad and deg MeV respectively.

Copyright © 2015 CC-BY-3.0 and by the respective authors

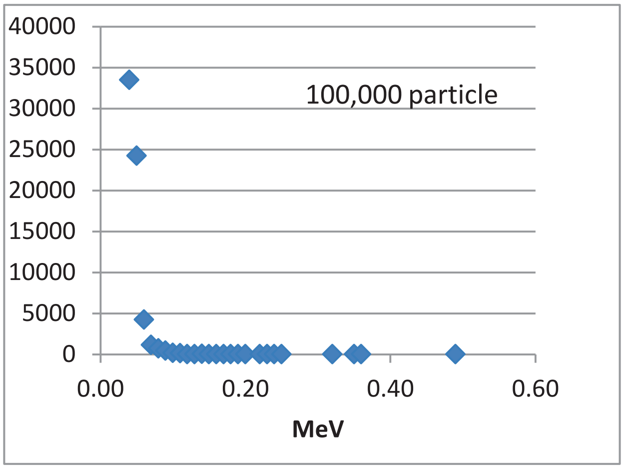

Figure 4: Energy histogram of un-accelerated particles.

RF Design, Power Source and Sensitivity to Field and Tuning Errors

RF and mechanical considerations have played an important role at the stage of the design choices for this RFQ. The design of the RF cavity has first of all been optimised on RF power consumption and tunability, two issues that need a careful balancing as increasing the number of tuners increases as well the RF power consumption. This problem has been partly overcome with an innovative tuner conical shape which maximises the effect and minimises losses and by leaving open the possibility to add an extra tuner every 50 cm of structure should it be needed. The RF power source for this RFQ is an arrangement of 4 IOT-based amplifiers each connected to an RF coupler. The IOTs will be powered with a single ‘capacity charger like’ power supply. Further details can be found in [10].

The effect of field errors has been studied in two different and complementary ways. We assumed two types of errors: static tuning errors and dynamic errors coming from RF power jitter or temperature variations. The two types of error give us different information: the needed tuning accuracy and consequently the necessary number of tuners and the necessary stability of the RF power source. We always assume a sufficient margin in the RF power source so that the average field along the RFQ is the nominal, thus implicitly applying a mitigation. We find that an uncorrelated field error of ±1% along the RFQ doesn’t have an impact on beam quality but this value is nevertheless challenging. In reality, errors on the RFQ field are generally correlated and can be expressed as a sinusoidal variation of the voltage along the electrodes. Studies to access the tolerances in this more realistic and less conservative case are going on and will be reported in the future. Preliminary results show that errors up to 2% are also acceptable

Mechanical Design and Sensitivity to Errors

The mechanical design of the RFQ is based on the successful design used for LINAC4, with a number of modifications to minimise cost and to favour a future industrialisation. The RFQ is made of 4 segments of 500 mm in length and each segment is made out of 4 poles brazed together. Each segment has a constant cross-section, slightly different for the first segment; whereas the electrode transverse radius of curvature is kept constant all along the RFQ.

In this chapter we report the results of a campaign of study on the final version of the RFQ aimed at quantifying the effects of manufacturing, alignment and field error on the beam performance. In reality the sensitivity to manufacturing error has been used as criteria for many design choices before the final stage. These results are not reported here.

The effects of manufacturing and alignment errors has been studied using the code TOUTATIS [8]. Manufacturing errors have been applied both to the transverse radius of curvature of each electrode and to the longitudinal profile. As for alignment errors we have to consider the different steps of assembling and brazing of each segment and then the assembling of the 4 segments together.

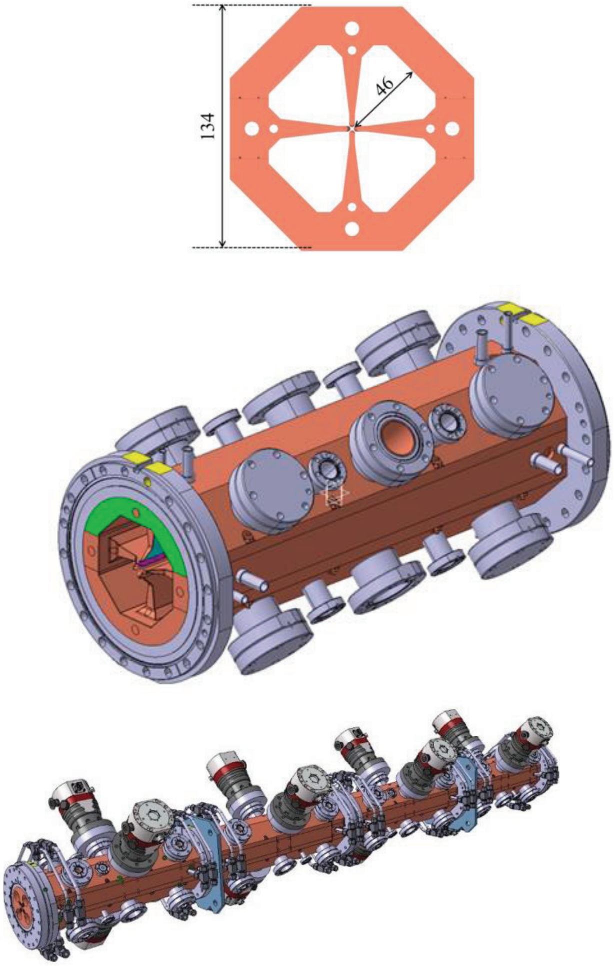

Figure 5: RFQ model showing the transverse cross-section with the 4 poles, a section and the complete RFQ made out of 4 sections.

Copyright © 2015 CC-BY-3.0 and by the respective authors

We applied an error on the shape of the modulation of up to 50 μm , an error to the alignment of the electrodes up to 50 μm , an error in the alignment between the 4 half meter long sections of up to 100 μm, corresponding to 0.2 mrad, assuming the tilt around the centre of each section. These errors exceed by far what can be expected from the CERN workshop but they give the possibility to explore the solidity of our design. The effect of the errors above will give us a limit on the machining tolerances, on the alignment before the brazing stage and on the assembly tolerances respectively. We have set as a limit a loss in transmission up to 5% and degradation in emittance up to 20% when all errors are combined. The results are shown in Table 4. The resulting tolerances are within the reach of a specialised commercial company. A sketch is shown in Fig. 6.

Table 4: Alignment Tolerances

Error	Tolerance	Part concerned
Field error(*)	±1%	Tuning
Transverse radius of curvature	±10 μm	Cutting tool
longitudinal profile	±10 μm	Machining
X and y pole displacement	±30 μm	Assembly before brazing and brazing process
Longitudinal pole displacement	±40 μm	
X and y pole tilt	±30 μm	
X and y segment tilt	±60 μm	Assembly of sections
X and y segment displacement	±20 μm	

(*) not an alignment tolerance but it has an influence on the alignment tolerance and it therefore always considered during our studies.

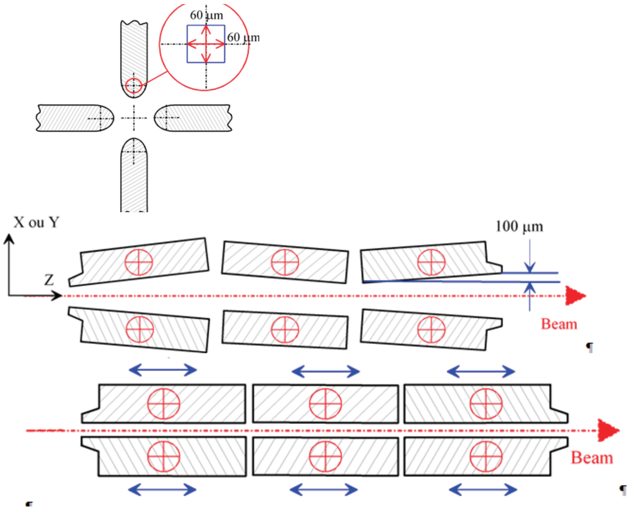

Figure 6: Sketch showing the possible alignment errors.

STATUS AND OUTLOOK

The 750 MHz RFQ is currently being machined and assembled at the CERN workshop, and then it will be tuned and subsequently will be tested with beam at the AVO/ADAM test facility at CERN during 2016. The results of the RF and beam tests will be crucial input to the design of future high-frequency RFQs. In particular we expect an improvement of our knowledge on the necessary power margin, on the maximum duty cycle, on the maximum field that we can afford to have on the vane tip and on the effect of the higher order multipoles on the transverse emittance. Further application of this design and technology are varied and include a compact linear system for the production of isotopes, based on protons at the energy of about 10 MeV and/or deuterons or alpha particles. The design of an RFQ based on the frequency of 750MHz and capable of accelerating particles with charge over mass = ½ is of high interest also for the future generation Carbon ion facility, based on using Carbon 6+ as primary ion for acceleration. For future RFQs other RF power sources will be considered and compared with the baseline solution, e.g. a magnetron or a solid state amplifier.

ACKNOWLEDGMENT

We would like to acknowledge the excellent services of the company BOUDON-FAVRE, Feillens (France) who provided the shape tools for cutting the longitudinal profile of the RFQ electrodes. .

REFERENCES

[1] P. J. Bryant, P J et al, “Proton-Ion Medical Machine Study (PIMMS), “; CERN-PS-2000-007-DR

[2] http://www.avoplc.com/Our-LIGHT-system/Product-overview

[3] . U. Amaldi and A. Degiovanni, “Proton And Carbon Linacs For Hadron Therapy”, FRIOB2, LINAC14, Geneva, Switzerland (2014)

[4] C. Ronsivalle et al. “The TOP-IMPLART project”,Eur. Phys. J. Plus (2011), 126, number 7, 68

[5] T.P. Wangler, “Lumped Circuit Model Of Four Vane RFQ Resonator”, THP0005, LINAC 84, Darmstadt, Germany (1984)

[5] J. Lettry et al , “Status and Operation of the Linac4 Ion Source Prototypes”, MonM06, ICIS 13, Chiba, Japan (2013)

[7] KR. Crandall, TP. Wangler, PARMTEQ-a beam-dynamics code for the RFQ linear accelerator, 8. AIP Conference Proceedings 11/1988; 177(1):22-28.

[8] R. Duperrier et al., Toutatis, the CEA Saclay RFQ code, Linac2000, Monterey, USA (2000).

[9] A. Perrin, J.F. Amand, “Travel v 4.06 user manual”, CERN 2003.

[10] M. Vretenar et al , “A compact high-frequency RFQ for medical applications”, THPP040, LINAC14, Geneva, Switzerland (2014)

Copyright © 2015 CC-BY-3.0 and by the respective authors