HIGH-FREQUENCY COMPACT RFQS FOR MEDICAL AND INDUSTRIAL APPLICATIONS

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Abstract

CERN has completed the construction of a 750 MHz RFQ reaching 5 MeV proton energy in a length of only 2 meters, to be used as injector for a compact proton therapy linac. Beyond proton therapy, this compact and lightweight design can be used for several applications, ranging from the production of radioisotopes in hospitals to ion beam analysis of industrial components or of artworks. The experience with the construction of the first unit will be presented together with the design and plans for other applications.

INTRODUCTION

In the frame of its new programme for medical applications, CERN has designed and constructed a compact 750 MHz Radio Frequency Quadrupole (RFQ) with the primary goal of providing a low beam loss alternative to cyclotrons as injector for proton therapy linacs operating at high frequency (3 GHz). While this option was already proposed in the past [1], the technical challenges of building and tuning an RFQ at a frequency about a factor of two higher than in conventional RFQs moved the proton therapy linac teams to foresee the use of an available cyclotron as injector to the high-frequency structures [2]. Although easily accessible, this option presents the drawbacks of high beam losses related to the unmatched beam transfer between accelerators operating at very different frequencies and of the need to pulse the cyclotron at the high repetition frequency of the linac.

In recent years, the experience gained at CERN in the construction of the Linac4 RFQ [3] together with the development of a new unconventional beam dynamics approach [4] and an increased confidence in the design and tuning of RFQs that are long with respect to the wavelength, meant the problem could be reconsidered on a new basis. After a preliminary analysis, a multi-disciplinary working group converged on the design of a prototype RFQ at 750 MHz reaching the energy of 5 MeV in only 2 meters [5]. While the RFQ beam optics is optimised for a specific proton therapy accelerator, its overall design is general enough to be used for a wide range of applications; construction techniques and machining tolerances are optimised for industrial production. The compactness, lightweight and standardised simplified construction of this new design open entirely new perspectives for applications of the RFQ technology outside of the scientific environment that would benefit from the RFQ qualities with respect to other low-energy accelerators: minimum beam loss with no need for dedicated accelerator shielding, excellent beam quality, very high reliability and availability, and minimum maintenance.

The construction in the CERN workshops of the prototype RFQ started in 2014 and was recently completed (Fig. 1). The main RFQ design parameters are reported in Table 1; they are based on the application as injector to the proton therapy linac of the LIGHT project [6].

Figure 1: The RFQ assembled on the tuning bench.

Table 1: Main RFQ Parameters

Input/Output Energy	40 keV / 5 MeV
Length	1.964 m
Vane voltage	67.6 kV
Min aperture radius	1 mm
Maximum modulation	3
Final synchronous phase	-15 deg
Output current (max.)	300µA
Beam transmission	30 %
Output transv. rms emit.	0.027 π.mm.mrad
Output phase spread	± 2 deg
Output energy spread	± 20 keV
RF Frequency	750 MHz
RF Power	350 kW
Operation duty cycle	0.4 %
Design duty cycle	5 %

For application in a proton therapy linac, the RFQ frequency needs to be a sub-harmonic of 3 GHz; 750 MHz has been selected because lower frequencies increase the RFQ length while higher frequencies decrease acceptance, increase power loss density and make difficult the machining of the first very short cells. However, the optimum is quite wide and for other applications the same RFQ design could be used at frequencies up to 1 GHz. In order to keep a sufficient beam acceptance at high frequency, the aperture is similar to that of lower frequency RFQs; this allows the machining tolerances to be kept in a range achievable with conventional tools, but results in a small cavity cross-section (45.9 mm inner radius) and limits the shunt impedance. To simplify the tuning, the length of this prototype RFQ has been conservatively limited to 2 m, corresponding to 5 times the wavelength.

A feature of the beam dynamics design is that particles that would be lost at the transfer into the small acceptance of the following 3 GHz structure creating activation are not captured in the RFQ and are lost at low energy (< 500 keV). This results in an RFQ transmission that is low by design but protects the components at high energy from activation.

The beam dynamics strategy developed for this prototype can be applied to reach the beam parameters required for different applications; the modular design based on identical 0.5 m units enables the realisation of different lengths and energies by adding a different number of modules. While operation for proton therapy requires only a very low duty cycle, this RFQ is designed and built for a maximum duty cycle of 5%, covering a wide range of applications. Each module is equipped with an individual RF port; in this way, the RF system can consist in an array of small RF amplifiers combined in the RFQ itself. This arrangement is particularly suited to modern solid-state RF technology.

BEAM DYNAMICS AND GENERAL DESIGN

After initial exploration on a wide set of parameters, 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 twice the Kilpatrick 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 robust design with respect to machining and alignment errors to facilitate a future industrialisation.

The evolution of the characteristic structure parameters is shown in Fig. 2 and the beam output in the transverse and longitudinal plane is shown in Fig. 3. The sensitivity to errors (mechanical and RF) as well as the beam quality at the output of the RFQ are a crucial parameter for the success of the medical facility. They have been confirmed with three independent codes [7-9], including direct integration in the 3D RFQ field map.

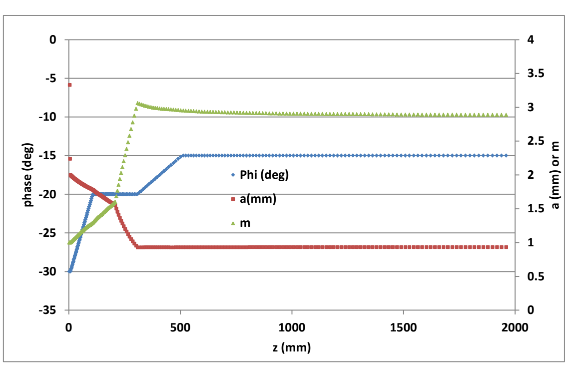

Figure 2: Phase, aperture and modulation along the RFQ.

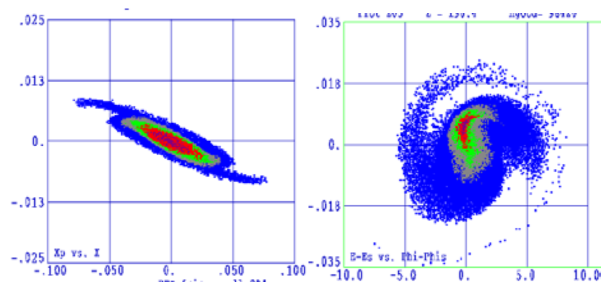

Figure 3: Transverse and longitudinal phase planes at 5 MeV (units of cm mrad and deg MeV respectively) .

MECHANICAL DESIGN AND CONSTRUCTION EXPERIENCE

The mechanical tolerances have been fixed to ±10 μm for the cavity and ±5 μm for the vane tip. This was obtained without problem using a conventional milling machine and specially manufactured shape tools for the tip, with an excellent reproducibility (Fig. 4).

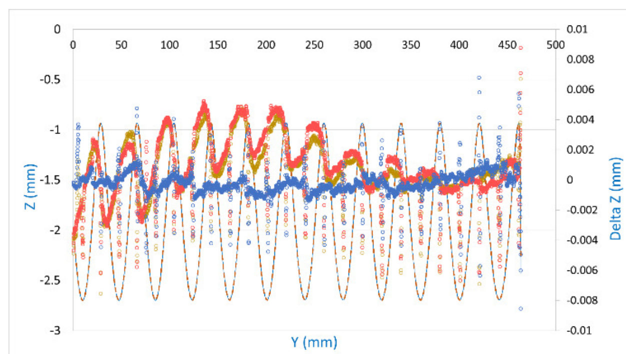

Figure 4: Metrology of the module #4 major vane tips after final machining. Z distance from the beam axis for the top and bottom vanes (dashed and full lines). Delta Z measured minus nominal position for the top and bottom vanes (red and yellow marks) and difference between the two vanes (blue marks).

Beam dynamics and RF designs have been defined to allow simple shapes that are easier to machine, including a constant transverse radius of curvature. In addition to well-defined machining steps and heat treatments, the brazing procedure based on the previous CERN experience with several RFQs allowed brazing the vanes with a minimum of deformations, respecting the assembly tolerance of ± 15 μm. As for the previous RFQs, two brazing steps with intermediate re-machining for the flange seats have been performed for each of the four modules. Figure 5 shows module 1 after the first brazing.

Before the first brazing, the vanes are aligned using points measured on the external surfaces. Mechanically held together, the four vanes are then machined to obtain flat surfaces for a perfect alignment during the brazing.

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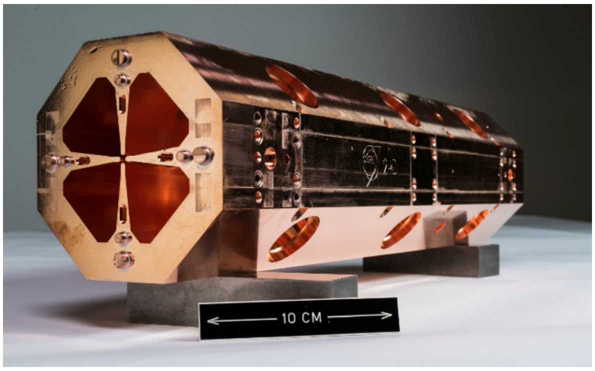

Figure 5: The RFQ module 1 after the initial brazing.

For each vane, an optimized beam axis is defined so as to reduce the errors measured on the modulation. The module alignment is done by aligning the four optimized axes of the individual vanes. After brazing, the optimized beam axis of the module is defined in the middle of the vane optimized axis. Between two modules, the axes are aligned thanks to a machining of the flanges and the use of a centering ring.

RF DESIGN AND TUNING

The RFQ consists of four modules with a length of about half a meter. The dipolar modes are detuned using dipole stabilizer rods at the end plates. In order to compensate the longitudinal field distribution the RFQ is equipped with 32 tuners of a new design aimed at minimising RF loss, as tuners are an important contribution to total loss. The RF power is fed to the cavity by four power couplers to provide an electrode voltage of 68 kV. This voltage has to be constant in longitudinal direction in order to meet the beam dynamics requirements.

The field and frequency tuning was completed in only two weeks; the goal of tuning was to find a tuner setting that provides a constant field distribution of the quadrupole mode and to compensate the dipole components simultaneously [10]. Figure 6 shows the initial longitudinal field distribution of the quadruple and the two dipole components.

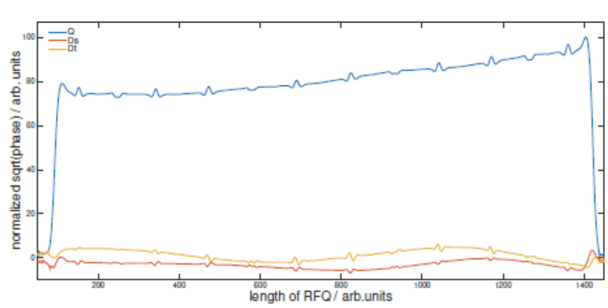

Figure 6: Measurement of the initial field distribution for the Q, Ds and Dt components.

The tuning algorithm was based on calculating a response matrix that describes the effect of every single tuner on the field components at every longitudinal position. To compensate the deviation from the actual to the desired field distribution a tuner setting was calculated using this response matrix in several steps. After six iterations, the fields were tuned to an acceptable range (Table 2). Figure 7 shows the initial and final field distribution of the quadrupole and of the two dipole components.

Table 2: Initial and Final Deviations for Quadrupole and Dipole Components

Component	Initial	Final
Quadrupole	± 10.8%	± 1.0%
Dipole-s	± 3.0%	± 1.0%
Dipole-t	± 3.6%	± 1.7%

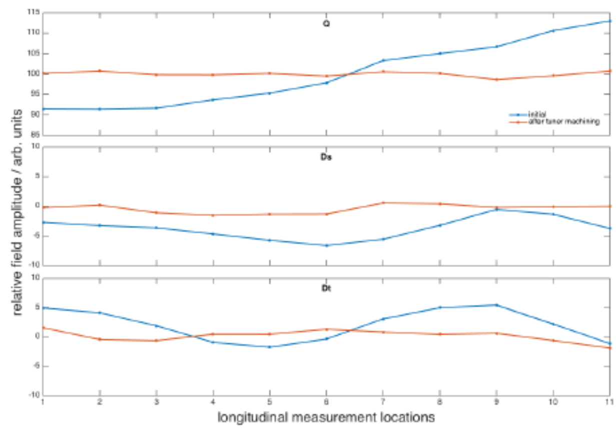

Figure 7: Initial (blue) and final (red) longitudinal field distribution of the dipole and quadrupole components.

After field tuning the frequency had to be adjusted to the operation frequency of 749.48 MHz. Therefore, all tuners had to be moved equally until the nominal frequency was reached. The tuners were then cut to their corresponding length and assembled with the final copper gasket.

Measurements of the Q-values have shown an excellent agreement with the theoretical values. The design value derived from 3D RF simulations was $Q_0 = 6440$ while measurements on all four power couplers lead to $Q_0^{meas} = 6570$.

RF SYSTEM AND COUPLERS

The RFQ is equipped with four RF ports, placed in the two central modules on opposite quadrants. The RF coupler (Fig. 8) is of coaxial type; a tapered section in vacuum provides the transition between the small diameter required to fit into the quadrant to a standard 3” 1/8 size. The RF window consists of a 10 mm thick PEEK disc with knife-edge contacts to the coaxial parts. This simple solution is well suited for low duty cycle and does not require brazing.

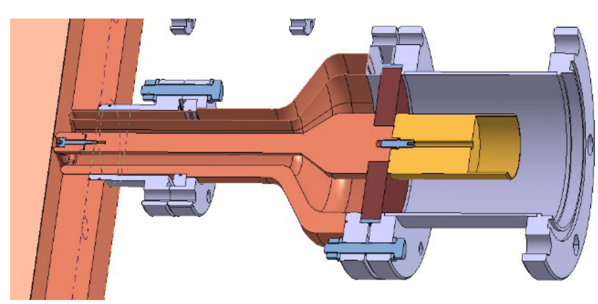

Figure 8: The RF coupler.

An individual RF amplifier feeds each of the four couplers; all amplifiers share a common power supply, accordingly to the scheme of Figure 9.

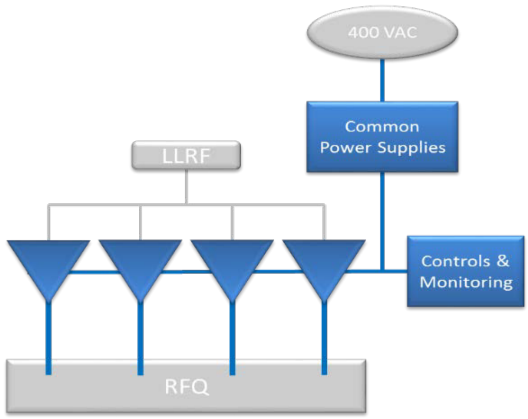

Figure 9: Layout of the RF system.

Although in the future it is foreseen to use solid-state RF unit to feed the RFQ, for the initial implementation for high-power and beam testing of the prototype a layout based on commercially available IOTs is preferred. Four TH795 units have been procured, equipped with circuits and power supplies, and installed in the test stand; they will be used for the RF and beam commissioning of the RFQ.

OVERVIEW OF APPLICATIONS

Injector for Proton Therapy Linacs

Some linac-based proton therapy facilities are under development or in the production phase; their main advantage with respect to other types of therapy accelerators is the fast cycling with easy pulse-to-pulse energy variation, which allows a more precise distribution of the dose across the tumour with the possibility of following the movement of the organ under irradiation. Using the high-frequency RFQ as injector (Fig. 10) eliminates losses at the transition to the following structure but requires lowering the transition energy from the 10-12 MeV of a cyclotron to the 5-6 MeV of an RFQ. Adding another RFQ section to reach 10 MeV is possible, as presented in the following section.

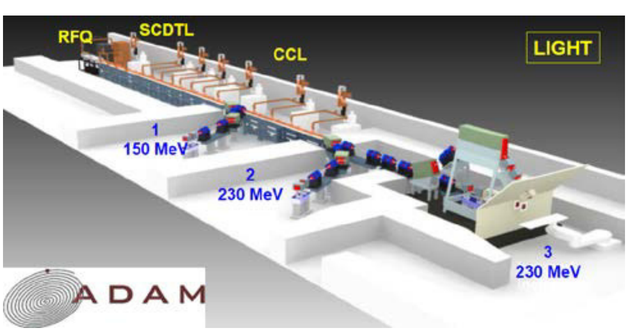

Figure 10: Layout of the LIGHT proton therapy linac by ADAM, using the high-frequency RFQ as injector [11].

PET Isotope Production in Hospitals

Medical imaging using Positron Emission Tomography (PET) is rapidly growing, leading to an increasing demand for radiopharmaceuticals containing different isotopes. Presently, most of the radioisotopes are produced by large cyclotrons in dedicated production facilities and then shipped to the hospitals; the preferred isotope is Fluorine-18 because of its relatively long half-life (110 minutes). Installing the accelerator in the hospital would shorten the supply chain allowing the production of radiopharmaceuticals on demand and paving the way for the use of isotopes with a shorter lifetime and reduced dose to the patient, such as Carbon-11 (20 minutes half-life). Although cyclotrons for PET production are small, the main factor limiting their installation in hospitals is the massive shielding required around accelerator and targets, which requires a dedicated building. Moreover, small hospitals can have difficulties affording the frequent and expensive maintenance periods required by commercial cyclotrons.

An RFQ-based PET isotope production unit (Fig. 11, Table 3) can reach the required energy (>10 MeV) with two consecutive RFQs of 2 m each; the RFQs should be separated from the RF point of view, to reduce the sensitivity to longitudinal perturbing modes, but can be mechanically coupled to minimise the transition length. The accelerator can be loss-free and does not need shielding; the entire beam goes to the target, which is contained in a shielded enclosure on which can be placed the radiopharmacy unit. A preliminary calculation of the target shielding was made assuming as maximum dose on the outside of the enclosure the value of 2 μSv/h that corresponds in most legislations to a radiation controlled area, accessible at any time wearing a film badge. A FLUKA optimisation using genetic algorithms to find an adequate compact shielding that minimizes the dose from the emerging neutrons indicates that a succession of layers of iron, polyethylene and borated (5%) polyethylene for a total radius of 1 m can limit the dose at contact to the required value [12]. Further optimisation of the shielding is still possible.

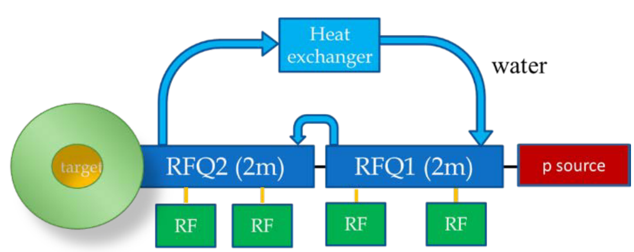

Figure 11: Scheme of the RFQ-based isotope production unit.

Table 3: RFQ Parameters for PET Production

Input/Output Energy	40 keV / 10 MeV
Length	4 m
Output peak current	500 μA
Duty cycle	4 %
Output average current	20 μA
RF Power, peak	700 kW
RF Power, average	28 kW
Footprint (RFQ, source, target)	15 m^2

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The RF amplifiers can be in an adjacent room; the resulting 3D layout is presented in Fig. 12.

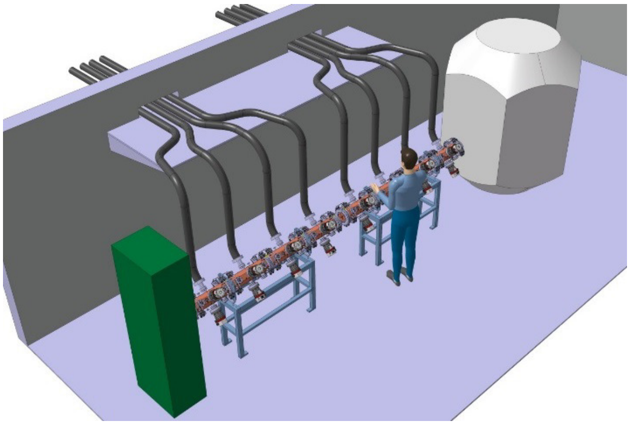

Figure 12: Layout of the PET-isotope production unit.

Ion Beam Analysis (PIXE and PIGE)

The reduced weight and dimensions of the high-frequency RFQ offer many opportunities for applications where a portable accelerator opens new perspectives. A promising direction to exploit this technology is Ion Beam Analysis (IBA) by PIXE (Proton Induced X-ray Emission) or PIGE (Proton Induced Gamma-ray Emission) with MeV proton beams. These non-destructive analytical techniques are widely used to probe the composition of the near-surface layer of solids; the applications include archeometry for the analysis of cultural artefacts, environmental science for the analysis of liquids and aerosols, and continuous quality control in industry. The usual IBA accelerators are electrostatic at the energy of 2 to 4 MeV; because of their large size and infrastructure they are installed in dedicated centres where the samples to be measured have to be transported. A transportable accelerator would open the way to in situ analysis of artwork or artefacts that are not transportable and to on-line industrial use on production lines.

Figure 13 presents the scheme of a portable RFQ-based PIXE system; its main parameters are reported in Table 4. An ion source is directly coupled to a 3 MeV RFQ of 1 m length equipped with a window for the extraction of the beam to X-ray and gamma-ray detectors for spectrometric surface analysis. Total length would be less than 2 m and weight about 150 kg; a flexible line will connect to the RFQ the air-cooled solid-state RF amplifier housed in transportable racks.

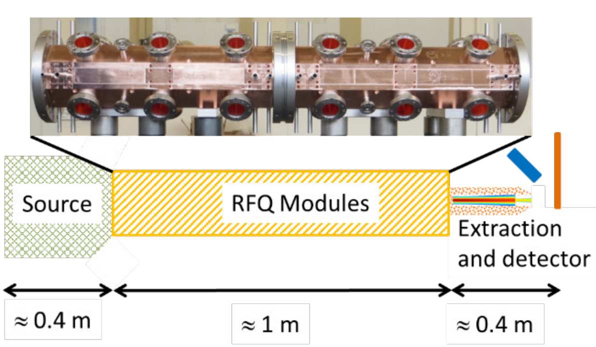

Figure 13: Layout of a portable PIXE RFQ.

Table 4: RFQ Parameters for Ion Beam Analysis

Input/Output Energy	40 keV / 3 MeV
Length	1 m
Output peak current	100 μA
Duty cycle	1 %
Output average current	1 μA
RF Power, peak	200 kW
RF Power, average	2 kW
Mains power	~ 5 kW
Weight (RFQ only)	110 kg

Acceleration of Ions at q/m=1/2

The beam dynamics of the RFQ can be designed for the acceleration of ions other than protons; of particular interest are ions species with charge to mass ration 1/2: alpha particles, deuterons, fully stripped carbon ions.

A compact RFQ for q/m=0.5 made of standard 750 MHz segments could be used for several applications:

- Acceleration of alpha particles for advanced brachytherapy (local irradiation by an alpha emitter on the tumour); for example, alpha-emitting Astatine is produced sending an alpha beam on a bismuth target. These techniques are considered to be the new frontier of nuclear medicine and if successful will require large amounts of isotopes that could be effectively produced by linear accelerators.
- Acceleration of deuterons for neutron production, with a wide range of applications including nuclear material interrogation.
- Acceleration of fully stripped Carbon ions (C6+) to inject in an advanced (linac or synchrotron) accelerator for Carbon ion therapy.

OUTLOOK AND CONCLUSIONS

The RFQ was recently installed in the ADAM/LIGHT test facility at CERN. Beam tests will start soon, including measuring the injection efficiency in a 3GHz module. The results of these tests will be an important input to further optimise the RFQ design for other uses; already now, the excellent results obtained with the Q-value and the tuning of this prototype RFQ will be used to reduce the number of tuners and to minimise the safety margin on the amplifier RF power.

The next step in the programme will be the construction of a prototype RFQ for PIXE analysis.

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