A COMPACT HIGH-FREQUENCY RFQ FOR MEDICAL APPLICATIONS

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Abstract

In the frame of a new program for medical applications, CERN has designed and is presently constructing a compact 750 MHz Radio Frequency Quadrupole to be used as injector for hadron therapy linacs. The RFQ reaches an energy of 5 MeV in only 2 meters; it is divided into four standardized modules of 500 mm, each equipped with 12 tuner ports and one RF input. The inner quadrant radius is 46 mm and the RFQ has an outer diameter of 134 mm; its total weight is only 220 kg. The beam dynamics and RF design have been optimized for reduced length and minimum RF power consumption; conventional construction technologies have been adopted, to favour a future industrial production. The multiple RF ports are foreseen for using either 4 solid-state units or 4 IOT's as RF power sources. Although hadron therapy requires only a low duty cycle, the RFQ has been designed for 5% duty cycle in view of other uses. This extremely compact and economical RFQ design opens several new perspectives for medical applications, in particular for PET isotopes production in hospitals with two coupled high-frequency RFQs reaching 10 MeV and for Technetium production for SPECT tomography with two RFQs followed by a DTL.

INTRODUCTION

The Radio Frequency Quadrupole (RFQ) is the low-energy accelerator of choice for science, but it is so far only rarely used for medical and industrial applications. In spite of the RFQ high current, excellent beam quality, loss-free operation and minimum shielding, cyclotrons are preferred outside of the scientific environment because of their lower cost and because they have been industrialised since a long time, a large expertise being available in cyclotron construction, operation and maintenance.

RFQ technology however has considerably progressed in recent years in terms of beam dynamics design, of RF design and tuning techniques, and of availability and reliability of construction techniques. Moreover, RF frequencies in the 700-800 MHz range, about twice the maximum used in existing RFQs, are now considered as reachable, with the effect of reducing RFQ dimensions and construction costs thus opening new perspectives in the applications of RFQs outside of the scientific world.

The first challenge in this respect comes from the medical field: the request for proton therapy accelerators is rapidly growing, but at the same time there is a strong push towards reducing the accelerator size and cost. Along this line, the design and prototyping of compact proton therapy linear accelerators operating at 3 GHz is rapidly progressing [1, 2].

For proton therapy linacs, cyclotrons are far from ideal injectors because of the strict requirements in terms of input beam emittance into the 3 GHz structure; the RFQ instead can easily deliver the required beam characteristics, provided that it operates at a sub-harmonic of 3 GHz. Along this line, a study published in the TERA Green Book already in 1995 included a 750 MHz RFQ as injector for a proton therapy linac [3]; this RFQ project was later abandoned because of the technological challenges well beyond the experience of the time.

RFQ DESIGN

In the frame of its new program for medical applications, CERN has started the design and construction of a compact, low-cost RFQ as injector for a proton therapy linac, adapting to the modern technologies the previous TERA design and building on the experience from the construction of the Linac4 RFQ [4]. The frequency of 750 MHz has been retained after an analysis showing that it is close to an optimum: lower frequencies increase the RFQ length, while higher frequencies make difficult the realisation of the first very short cell.

In order to keep a sufficient beam acceptance at high frequency, the aperture must remain of the same order as in lower frequency RFQs; the related advantage is that machining tolerances remain achievable with conventional tools, but disadvantages are the small cross-section (Fig. 1) and the fact that the RF efficiency cannot profit of the increase in frequency. Additionally, the high RF frequency imposes a limitation to the length of the RFQ: to adjust the RF voltage without using complex and expensive stabilising mechanisms, the RFQ must be shorter than about 5 λ, or 2 meters.

In this RFQ design, a number of innovative design solutions have been adopted to minimise cost and to favour a future industrialisation; the RFQ is highly modular, made of 4 identical segments of 500 mm length.
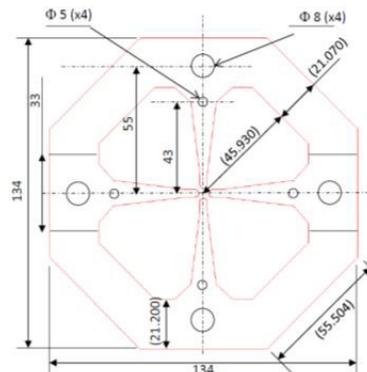

Figure 1: RFQ cross-section.

BEAM DYNAMICS DESIGN

Conventional RFQs are designed to have a high transmission efficiency, which puts restrictions on the choice of the design parameters. However, as the proton therapy requires very small average beam current [5], a compromise can be made between transmission efficiency and acceleration per unit length to design an RFQ which is significantly shorter than the conventional RFQs.

This RFQ was designed considering that the beam will be injected into a higher frequency structure (i.e. 3 GHz) and that losses at the transition of the two structures should be minimised. The synchronous phase along the RFQ has been adjusted such that only the particles that can be injected in a higher frequency structure are accelerated and the others lost at the lowest possible energy, well below the activation threshold. The transverse focusing is optimised to transport an emittance suitable for injection into a 3 GHz structure with a margin of a factor 2. The beam dynamics has been calculated with PARMTEQ [6] and TOUTATIS [7], and verified with direct tracking in a field map. The main RFQ parameters are reported in Table 1. The highest lost particle energy is 500 keV; 99.5% of the lost particles have an energy below 100 keV.

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

The RFQ accelerates the protons up to 5 MeV in less than two meters. The transmission efficiency is 30% due to the choice of limiting the longitudinal acceptance; while this limits the amount of the particles captured for acceleration, it also ensures that the particles, which are out of the acceptance, lose synchronism with the RF fields at the beginning of the RFQ, avoiding them to reach higher energies and to activate the structure. Figure 2 shows the phase space plots at the RFQ exit plane.
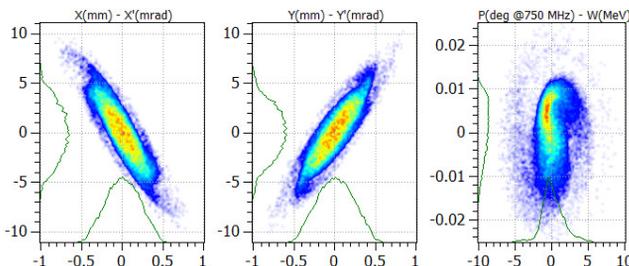

Figure 2: Output phase spaces.

RF CAVITY DESIGN

The cost of a high-frequency RFQ system being dominated by the RF, the first challenge of the RF design was to minimise the power consumption by means of a careful optimization of the transverse cross-section (Fig. 1), keeping at the same time flat surfaces required for an easy machining. Additionally, a relatively low vane voltage was chosen with the goal of further reducing the RF power. For the final shape, computed 2D values for Q-factor and capacitance per meter length are 8'240 and 104 pF/m, respectively. For the nominal vane voltage of 67.6 kV and taking a factor 1.5 as a margin for all 3D and surface effects the overall peak RF power is 399 kW.

Another challenge related to the high frequency is the high ratio between RFQ length and wavelength; in this design, a length of 2 m corresponding to 5 λ has been chosen, considered as a limit for simple field adjustment using tuners. This requires however a careful design of the tuners combining large enough tuning range and sensitivity on one hand and minimizing the RF losses on the other. A novel cone-shaped design of the tuner head has been found as the best compromise between these competing requirements. The angle of the cone is optimized to minimize the losses and improve the sensitivity. Each of the 4 modules of the RFQ (Fig. 3) has 12 holes of 36 mm diameter, 3 holes in each quadrant; 8 are used for dedicated conical tuners, while the other 4 holes are employed for either vacuum pumping ports or RF power couplers. Both can also be used for coarse tuning if necessary. RF power is coupled to the RFQ cavity by means of 4 coaxial couplers whose number can be increased if needed by replacing one or several pumping ports with couplers. The end cells design is similar to the Linac-4 RFQ; the end cell is equipped with 4 rods for detuning the dipole modes away from the operating quadrupole mode. If necessary, the frequency of the end cells can also be tuned by bending the rods. The coaxial RF coupler input is matched to the standard WR-1150 waveguide via a λ/4 transformer.
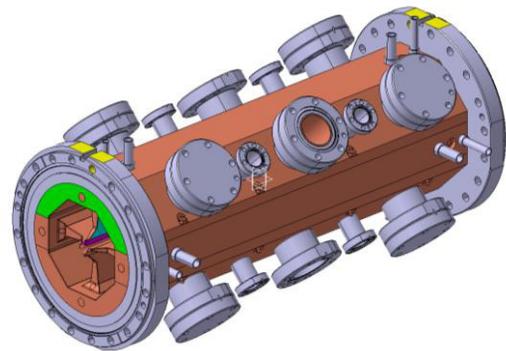

Figure 3: RFQ module.

MECHANICAL DESIGN

The mechanical design and construction procedure is based on the experience gained with the Linac4 RFQ and the brazing of other RFQs at CERN.

02 Proton and Ion Accelerators and Applications

2F Industrial and Medical Accelerators

The manufacturing procedure is similar to the one used for Linac4 [4]: constant cavity shape along RFQ modules allowing conventional two-dimensional machining, several machining steps followed by stabilisation heat treatments, final machining before first brazing with a minimum of material removed, two brazing steps (one horizontal and one vertical).

Taking advantage of the small size of this RFQ, standard forged OFE copper rods are used for the vanes, reducing by about a factor 5 the cost for the raw material with respect to the Linac4 RFQ. Module lengths have been limited to 500 mm in order to fit the standard rod size. As for the Linac4 RFQ, preliminary heat treatments of the vanes are performed at 600 °C and the final heat treatment at 800 °C. The first brazing, corresponding to the assembly of the four vanes, will be done at 820 °C with the vanes in horizontal position, i.e. with horizontal brazing surfaces. The second brazing will be at 790 °C, in vertical position, for the assembly of the flanges.

Even if this RFQ is foreseen to be used at very low duty cycle, cooling channels are machined in view of other applications requiring higher beam current. 3D thermal simulations indicate a maximum duty cycle of 5 % with a safety factor of 1.5 for the actual design.

The allowed mechanical and assembly tolerances were defined after a series of statistical error studies including mechanical errors, RF jitter and beam errors. The mechanical tolerances are ±10 μm for the cavity and ±5 μm for the tip, only a factor 2 tighter than in the Linac4 RFQ. The assembly tolerance for the four vanes is ±15 μm. The surface finishing of the cavity is Ra=0.4 μm.
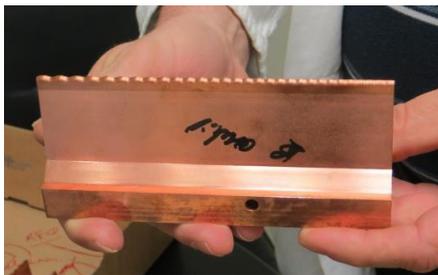

Figure 4: Modulation machining test on a minor vane.

Machining tests of the tip (Fig. 4), in the region of the minimum longitudinal curvature radius, have been performed; first attempts are in the expected tolerance.

The vanes for the two central modules are presently in the rough machining step (Fig. 5). First heat treatments have shown encouraging small deformations. The brazing of the first modules is foreseen beginning of 2015 and the assembly of the complete RFQ at the end of 2015.

Figure 5: A major vane after rough machining.

RF AMPLIFIER

The RFQ is an ideal structure to be fed by an arrangement of small RF amplifier units combined into the RFQ itself. For testing of this prototype RFQ, an arrangement of 4 IOT-based amplifiers each connected to an RF coupler has been selected, being the most economic and easiest to procure option. The IOTs will be powered with a single 'capacity charger like' power supply. The IOT amplifiers will be of the type recently acquired by CERN for 801 MHz frequency, delivering up to 60 kW in CW mode. A unit has been already tested at 750 MHz and it is expected that a peak power of >100 kW can be reached in pulsed mode. The RF power window will be based on the recent Linac4 window [8].

In parallel, RF power generation based on solid-state technology will be studied for future installations, as well as using a magnetron for feeding an RFQ or a sequence of RFQs operating in stand-alone mode for isotope production, an application where high phase stability is not required.

APPLICATIONS

Beyond proton therapy, this RFQ can become the central element of a compact light-weight system for production of radioisotopes in hospitals. In the rapidly growing market for radioisotopes there is an important demand for small accelerators installed in hospitals that can produce on request single doses of ^{18}F for PET tomography but also of other short-living isotopes for new emerging imaging techniques. Essential requirements for this application are small size, minimum weight, minimum shielding, high reliability, and low electricity consumption in operation and in stand-by, all easily met by an RFQ-based system.

An RFQ radioisotope production system can be made of 2 RFQs in cascade reaching 8 MeV energy in a length of only 3.2 m, fed by a small proton source directly coupled to the first RFQ. For a peak current of 1 mA, this system could deliver 50 μA of average current with a duty cycle of 5%. The peak current is in the range accepted by conventional targets; power consumption from the mains would be 50 kW using conventional solid-state RF sources and only 30 kW using a high-efficiency low-cost magnetron feeding both RFQs. The overall cost of such a facility would be competitive with cyclotrons that require a larger installation and much heavier shielding.

Further applications of this compact RFQ could be in the production of Technetium for SPECT tomography, by adding a Drift Tube Linac tank after two RFQs to reach an energy of about 20 MeV and increasing the peak beam current to 20 mA and the duty cycle to 10%. This would require using a more sophisticated ion source followed by a beam transport system, and developing an isotope production target matched to the beam parameters.

Production of brachytherapy isotopes, neutron production for different applications, and compact ion beam analysis are other possible applications of this RFQ.

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