HIGH FREQUENCY RFQ DESIGN AND LEBT MATCHING FOR THE CERN TWINEBIS ION SOURCE

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Abstract

An Electron Beam Ion Source (EBIS) is being developed at CERN [1] for production of highly charged ions, for instance fully stripped ^{12}C. The focus has so far been on the electron gun design, aiming for a high current compression, which results in a rapid ionisation process and thereby high repetition rate. Initial commissioning tests of such an electron gun, the so-called MEDeGUN [2], have already been performed and we are now in the process of designing a multi-purpose ion extraction and diagnostics line. The Low Energy Beam Transport (LEBT) line will transport the ions into the downstream Radio Frequency Quadrupole (RFQ) with a nominal energy of 15 keV/u. The 750 MHz RFQ is designed to accelerate ions from 15 keV/u up to the final energy of 2.5 MeV/u. After the RFQ design was finalized and its acceptance calculated, the beam matching to the RFQ was studied, finding a set of parameters for the LEBT that maximize the transmission through the RFQ. Details of the RFQ design, of the LEBT matching procedure and its final results are illustrated in this paper.

INTRODUCTION

After the design, construction and successful commissioning of a 750 MHz Radio Frequency Quadrupole for the acceleration of protons from 40 keV to 5 MeV in the space of 2 meters, we have studied a potential extension of the beam dynamics concept from protons to ions. In the framework of the strategy paper for medical applications [3] the layout of a linac-based carbon ion accelerator for medicine is a key ingredient of a potential future study involving other partners. Besides, the availability of a fully stripped carbon ion beam at the energy of 15keV/u in the framework of MEDeGUN allowed for a perfect synergy between the endeavors on the LEBT and the RFQ design. The result of this study is two-fold. First, we have detailed an RFQ designed for fully stripped carbon and tailored to the beam characteristics of the source and LEBT of MEDeGUN that could be used as such as a pre-injector of a linac-based medical facility. Second, we have studied the variation of critical parameters, exploring the trade-off between length, RF power needs, beam throughput and machinability for a standalone RFQ that could accelerate carbon ions as well as alpha particles and could be used for other purposes.

LEBT MATCHING

The LEBT has been designed to transport the ion beam from the TwinEBIS source, set at 30 kV, to the RFQ (at the

matching plane). The ion distribution used for the matching is the result of simulations that reproduce the physics of the ion production in the source [4]. The resulting beam is extracted by a 17 kV extractor electrode and accelerated up to 6.5 keV/u. It then travels into a set of nine accelerating rings set between 27 kV and ground voltage that boost the energy up to 15 keV/u. Between the extractor and the accelerating gaps an additional 'adaptor' electrode was added to keep the beam focused. The particles at their final energy are then focused and matched to the RFQ by two gridded lenses and one Einzel lens. The aim of the matching is to maximise the number of particles that fall into the RFQ acceptance, defined as the biggest ellipse in the transverse phase space that can be accelerated and transported through the RFQ with nominal transmission. The matching technique is explained in [4] and consists of finding the optimal set of voltages applied to the focusing elements (the adaptor, the two gridded lenses and the Einzel lens).
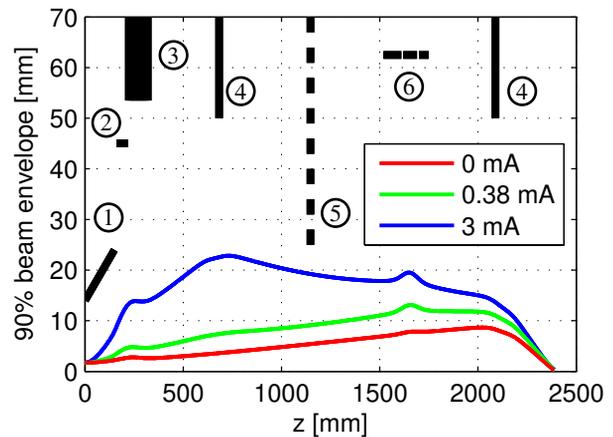

Figure 1: Plot showing the envelope of the matched beam for a current of 0 mA, 1 mA and 3 mA. The apertures of the relevant optical components are indicated: (1) Extractor, (2) adaptor, (3) accelerating gaps, (4) gridded lenses, (5) horizontal collimator, (6) Einzel lens.

The matching was performed for three input currents. 3 mA, corresponding to the maximum theoretical current that can be generated by the TwinEBIS, 0 mA, representing the case without space charge, and 0.38 mA (corresponding to $1 \cdot 10^9$ $^{12}C^{6+}$ ions in a 5 μs pulse), the current that could be extracted by the EBIS source in the present configuration. All the extracted beams are composed of 50% of $^{12}C^{6+}$ and of 50% of other charge states.

In Figure 1 a sketch of the main elements of the LEBT, together with the 90% beam envelopes are showed. The

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maximum number of particles falling into the acceptance for a 3 mA beam is 88%. By decreasing the beam current, the space charge effects are reduced and, as a consequence, on one hand the beam size is kept smaller, avoiding aberrations due to the non linear part of the electric field in the focusing elements, and on the other hand the emittance growth due to space charge is reduced. The transmission resulting from the re-matching at different currents is then 96% for the 0.38 mA beam and 99% for the zero space charge case respectively. These values refer to the particles that fall into the acceptance in both transverse planes at the same time.

RFQ DESIGN

Input Parameters

The choice of the characteristic parameters used for the design of the RFQ was driven by different constraints. The $^{12}C^{6+}$ ion beam energy is defined by the maximum accelerating voltage that the LEBT can hold, in this case 30 kV, that leads to an input energy of 15 keV/u at the entrance of the RFQ. Regarding the output energy, two different solutions at 2.5 MeV/u and 5 MeV/u are proposed. The choice of having two alternatives allows to widen the range of options in the selection of the accelerating structure following the RFQ. The minimum vane aperture (minimum distance between two opposite vanes) and the inter-vane voltage are strictly bound to the maximum surface field that can be hold by the vanes without breakdown. In order to define the maximum surface field, Kilpatrick's criterion [5] was used and the maximum surface field was chosen to be $E_{s,max} = 2 \cdot E_k$, E_k being the Kilpatrick field at 750 MHz. The constraints on the minimum required transmission of the RFQ, in the case of a medical machine for carbon therapy, comes from treatment requirements. The dose required for treatment translates to an average current of 0.8 nA [6], corresponding to $8 \cdot 10^8$ ions/s. The TwinEBIS could be able to provide $1 \cdot 10^9$ $^{12}C^{6+}$ ions in a pulse of 5 μs length, at a repetition rate of 200 Hz, resulting in an ion current of $2 \cdot 10^{11}$ ions/s. If one considers that just the 2/3 of the RF pulse are going to be conserved in the following acceleration stage (the pulse length in foreseen to be around 3 μs in the linac), a $^{12}C^{6+}$ current of $1.3 \cdot 10^{11}$ ions/s should be available, which is two order of magnitudes larger than the requirements. Therefore the transmission is not considered as a critical constraint for the design.

Design Procedure

A parametric scan of the maximum surface field as a function of the aperture and the vane voltage was performed in order to define a set of combinations that guarantees a maximum surface field below the defined limit $E_{s,t}$=50.6 MV/m (a variation within 5% is accepted considering that Kilpatrick criterion is highly conservative).

Figure 2 shows the maximum surface field as a function of the initial aperture of the RFQ for different inter-vane voltages. Although an increase in aperture results in a growth of the RFQ acceptance, it leads to a much higher power

Table 1: RFQ Characteristic Parameters

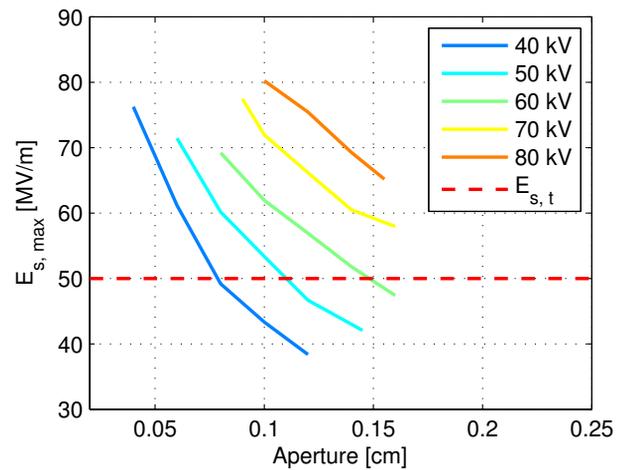| Parameter	Value
RF frequency [MHz]	750
Ion species	$^{12}C^{6+}$
Input energy [keV/u]	15
Design input current [mA]	0
Output energy [MeV/u]	2.5 / 5
Input transv. emittance 90% norm [π mm mrad]	0.08
Repetition frequency [Hz]	200
Vane voltage [kV]	50
Average aperture r_0 [mm]	1.4
ρ/r_0	0.9

Figure 2: Parametric scan of the inter-vane voltage as a function of the input minimum aperture between the vane and the resulting maximum surface field in the RFQ.

consumption ($P \propto V^2$) due to the higher vane voltage needed to keep the beam focused. Therefore a good compromise between these two aspects has to be found depending on the specific design requirements. The selected values of aperture and voltage, together with the other parameters, (summarized in Table 1) were used as input for the RFQ codes Curli, RFQuick, Pari and Parmteq [7].

The initial designs have been modified to make it more suitable for this specific application. The first modification was to increase the final modulation of the RFQ. Together with a proper redesign of the modulation profile along the RFQ, it leads to a considerable reduction in the structure length (25%), keeping the transmission (99%) unchanged.

A strong constraint on the RFQ design is given by the longitudinal and transverse acceptance of the structure coming downstream in the accelerator. Two possible accelerating structures are considered. For the 2.5 MeV/u RFQ, the most suitable solution would be a 750 MHz IH-structure [8]. In the case of the 5 MeV/u the output energy would be high enough to inject directly into a 3 GHz structure.

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In both cases the longitudinal acceptance is small compared to the initial design output beam. The RFQ was hence re-designed following the procedure illustrated in [9]. The initial phase, that is usually set to −90 deg to capture the continuous beam coming from the source, was set to −50 deg in order to capture only the particles that could fit in the longitudinal bucket of the structure following the RFQ. In this particular design solution, all the losses occur at low energy, avoiding activation of the cavities.

Final Layout

The parameters of the final layout for both the 2.5 MeV/u and the 5 MeV/u RFQ are summarized in Table 2

Table 2: RFQ final layout parameters

Parameter	2.5 MeV/u	5 MeV/u
Output energy [MeV/u]	2.5	5
Length [m]	2.7	5.8
Nominal transmission [%]	54.6	54.6
Max. Surface field [MV/m]	51.6	52.3
Input phase [deg]	-50	
Output phase [deg]	-20	
Power consumption [kW]	280	600
Vane voltage [kV]	50	
Modulation (max.)	2.8	
Average aperture r_0 (const.) [mm]	1.4	
Acceptance 100% norm. [π mm mrad]	1.7	

The nominal transmission refers to a perfectly matched beam with a normalized RMS emittance of 0.02 π mm mrad.

Figure 3 shows the evolution of the main parameters of the 2.5 MeV/u RFQ along the beam axis. The curves for the 5 MeV/u are identical, with the difference that the accelerating section is longer to achieve the required higher energy.
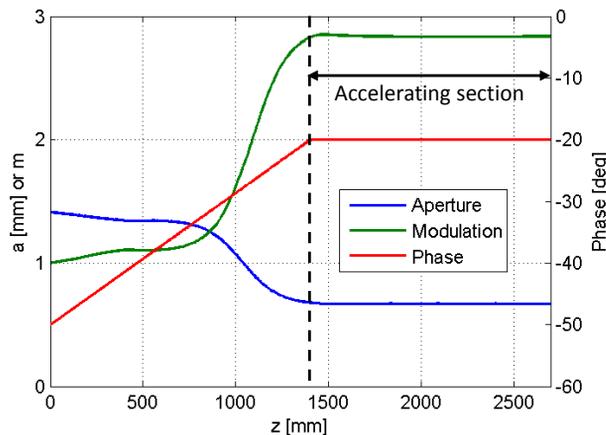

Figure 3: Phase, aperture and modulation along the RFQ.

TRACKING

The beams resulting from the LEBT matching were tracked through the RFQ to evaluate the transmission. The tracking was performed for the zero space charge, the 0.38 mA and the 3 mA input beam through both the 2.5 MeV/u and the 5 MeV/u RFQs. Table 3 summarizes the main parameters of the output beam for the different currents and final energies.

Table 3: Results of Tracking 10000 Particles into the RFQ

I=0 mA	2.5 MeV/u	5 MeV/u
Transmission [%]	57.6	50.3
Transv. input emittance 90% norm. [π mm mrad]	0.09	
Transv. output emittance 90% norm. [π mm mrad]	0.09	0.09
Long. output emittance 90% norm. [π deg MeV]	0.42	0.45
I=0.4 mA		
Transmission [%]	56.6	49 .8
Transv. input emittance 90% norm. [π mm mrad]	0.11	
Transv. output emittance 90% norm. [π mm mrad]	0.11	0.11
Long. output emittance 90% norm. [π deg MeV]	0.46	0.46
I=3 mA		
Transmission [%]	52.3	45.3
Transv. input emittance 90% norm. [π mm mrad]	0.14	
Transv. output emittance 90% norm. [π mm mrad]	0.11	0.11
Long. output emittance 90% norm. [π deg MeV]	0.52	0.51

CONCLUSIONS AND NEXT STEPS

The matching of the LEBT was performed at different currents with the aim of validating its flexibility. The LEBT will be installed and tested during the next year, providing the opportunity to verify the validity of the simulations and to adapt the design of the RFQ to the measured distribution. Tracking through the RFQ shows the capability of the system to provide an ion current that exceeds significantly the clinical requirements. Moreover, this study showed that the LEBT and the RFQ can transport and accelerate relatively high currents (compared with clinical ones), making the present design suitable for different ions with the same charge over mass ratio and for different applications.

ACKNOWLEDGEMENTS

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