DESIGN OF A HIGH-INTENSITY RFQ FOR A POSSIBLE LHC LASER ION SOURCE

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Abstract

We have designed a 100 MHz RFQ to accelerate Pb^{25+} ions from 9.6 keV/u to 250 keV/u for the LHC ion program. We assume an input beam from a laser ion source with a total beam current of 90 mA, out of which 9 mA is Pb^{25+}. The main challenge of the design is to match the tight longitudinal acceptance of the downstream Interdigital H structure while dealing with a high intensity beam composed of a variety of charge states. In this paper, we present a baseline set-up optimised for nominal conditions, and show the sensitivity of the RFQ performance to varying input beam characteristics and RF parameters. Further studies will cover the compatibility of this design with an upgraded ECR source under investigation at CERN.

1 INTRODUCTION

The LHC heavy ion program calls for a new, high-intensity ion source. A laser ion source (LIS), presently under development at CERN, is a possible candidate. In order to match the beam parameters from the source to the acceptance limits of the CERN ion linac, a dedicated injection scheme consisting of extraction system, low-energy beam transport line (LEBT), radio-frequency quadrupole (RFQ) and beam transfer lines is needed. While the extraction scheme and the design of the LEBT are discussed in [1] and [2], we present here a possible design for the RFQ. We have based our simulations on estimated source parameters (beam emittance, current) and present a baseline solution for these nominal conditions. Furthermore, we have performed a parameter scan where we investigate the performance of the RFQ for beam parameters other than the nominal ones and for a multi charge-state beam.

2 BEAM CHARACTERISTICS AND REQUIREMENTS

At this time experimental data from the LIS are not available. We have therefore based the design of the RFQ on estimated beam parameters as well as on extrapolations from experiments done with a prototype of the final source. The constraints at injection into the CERN ion linac have been assumed to be as in [3].

The total beam current is estimated in [1] as 92 mA for the proposed extraction system. This total current consists of a variety of charge states, out of which 9 mA are estimated to be 208Pb^{25+}. We have based the baseline RFQ design on a current of 10.0 mA 208Pb^{25+}.

The beam emittance from the source can be extrapolated from measurements, which indicate a total normalised emittance of about 2 π mm mrad. Preliminary simulations have shown, that an RFQ at 101.28 MHz having such a large transverse acceptance requires large aperture and high vane voltage, and is disadvantageous from an rf power point of view. As the normalised transverse acceptance of the CERN ion linac is only 1 π mm mrad, we assume this value as nominal input parameter.

The longitudinal acceptance of the IH linac is 0.018 deg MeV/u r.m.s. (0.09 deg MeV/u total) at 101.28 MHz. We have aimed at a longitudinal emittance at the exit of the RFQ which is 10-15% below this value to allow for some emittance dilution in the transfer lines.

The longitudinal emittance which can be achieved at the exit of an RFQ is essentially determined by the input beam energy which, in turn, is given by the source extraction voltage V_{extr}. In experiments with the LIS test set-up, V_{extr} had typically values between 60 kV and 110 kV. We discuss in this paper a baseline scenario with V_{extr}= 80 kV (9.6 keV/u) as well as a solution for V_{extr}= 100 kV (12.0 keV/u).

3 BASELINE RFQ

The design of the RFQ was done using the codes CURLI, RFQUICK, PARI and PARMTEQM [4]. The input beam parameters are those discussed in Section 2, with an input beam energy of 9.6 keV/u. The main design goals were to match the acceptance of the IH (in particular in the longitudinal plane) while at the same time dealing with the high beam current and rigidity. In order to obtain a small longitudinal emittance at the exit of the RFQ, two design choices have already been made in this first design stage:

a) The synchronous phase is ramped to only -40 deg at the end of the gentle buncher.

b) The starting point of the ramping is set to 1/3 of the shaper length rather than to the beginning of the shaper.

We have found a solution with good transmission but an unacceptable longitudinal emittance, which is more than 30% larger than the IH acceptance. An analysis of the beam evolution in the longitudinal phase space reveals that the problem is due to space charge effects: particles in the centre of the bunch rotate at a different speed than those further outside. In order to fight space charge effects, we have chosen the following design principles:

a) Delay the ramping of the synchronous phase in the shaper where the longitudinal emittance is formed.

b) Quickly ramp the phase after the shaper in order to accelerate quickly, thus reducing space charge effects while keeping the longitudinal emittance constant.

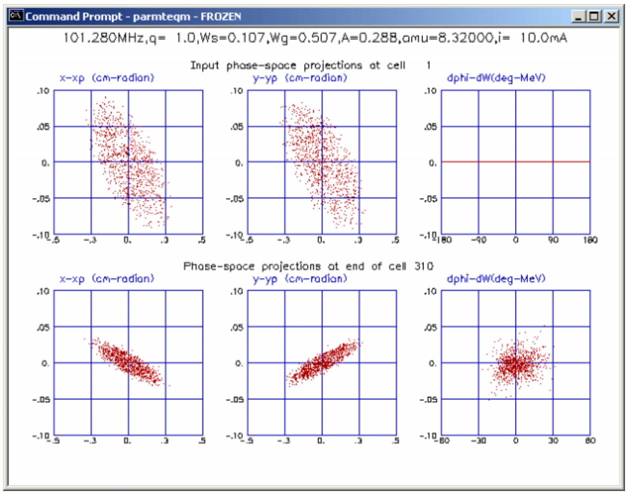
c) Increase the transverse beam size along the RFQ by reducing the focusing parameter.

In practice this can be accomplished by adjusting the vane modulation in the first part of the RFQ, where the longitudinal emittance is formed. We find an RFQ with good transmission (97.5%) and a longitudinal emittance of ε_l = 0.015 MeV deg/u r.m.s. (0.075 MeV deg/u total). This is 20% below the IH acceptance and hence leaves some margin for blow-up in the injection lines. The transverse emittance is essentially unchanged. The vane voltage is 90 kV and the length of the RFQ is 396 cm. The radius of curvature of the vane tips was chosen to ρ/r_0=0.65 in order to reduce the maximum electric field. The main RFQ parameters are listed in Table 1. Figure 1 shows the input and output beam as computed with PARMTEQM and Fig. 2 shows the evolution of beam parameters versus cell number in the RFQ.

Table 1: Important parameters of baseline RFQ.

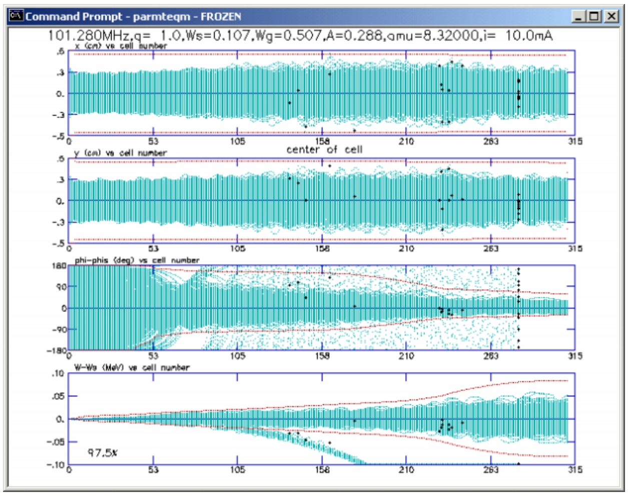
design ion	$208Pb^{25+}$
current [mA]	10.0
input energy [keV/u]	9.6
output energy [keV/u]	250.0
design emittance (tot., norm) [mm mrad]	1.0
frequency [MHz]	101.28
vane voltage [kV]	90.0
max. electric field [MV/m]	26.0
RFQ length [cm]	396
number of cells	310
power loss (for 60 kΩm) [kW]	540
minimum aperture [cm]	0.333
max. modulation factor	1.7
transmission^1 [%]	97.5
mid-cell radial aperture r_o [cm]	0.458
vane tip radius of curvature ρ/r_o	0.65

$^{1)}$ For 1 π mm mrad input emittance (tot., norm.) and 10 mA, simulation with 1000 particles.



101.280MHz,q= 1.0,Ws=0.107,Wg=0.507,A=0.288,amu=8.32000,i= 10.0mA

Figure 1: Input (upper plots) and output (lower plots) beam of the RFQ as simulated with PARMTEQM.



101.280MHz,q= 1.0,Ws=0.107,Wg=0.507,A=0.288,amu=8.32000,i= 10.0mA

Figure 2: Evolution of beam parameters versus cell number as simulated with PARMTEQM. The lines indicates the physical aperture in the upper two plots and the separatrix in the lower two plots.

4 PARAMETER SCAN

4.1 Beam Energy

The input beam energy is a trade-off between extracted beam current and achievable longitudinal emittance. The higher the input beam energy, the longer the RFQ and the more difficult it is to form a small longitudinal emittance. We have found a solution for V_{extr}=80 kV. However, we have investigated the possibility of designing an RFQ for V_{extr}=100 kV (12.0 keV/u). We find a solution with a length of 435 cm (390 cells) and an output longitudinal emittance of ε_l=0.016 MeV deg/u, which is 12% below the IH acceptance. However, this solution is unstable and already minor variations of the modulation lead to unacceptable blow-up of the longitudinal emittance. We will therefore in the following sections only consider in more detail the reference case with V_{extr}=80 kV.

4.2 Energy Spread

The simulations shown in Section 3 have been done with zero energy spread. As from the real source we expect a significant energy spread, we have changed in the simulation the input beam accordingly. Figure 3 shows transmission and longitudinal emittance versus energy spread for the baseline RFQ. It can be seen that the transmission drops down to about 85% for 10% energy spread. More important, the longitudinal emittance increases significantly already for small values of ΔE.

4.3 Beam Emittance

Figure 4 shows transmission versus input transverse emittance. For values smaller than the nominal value of 1 π mm mrad, the transmission is constant around 98%.

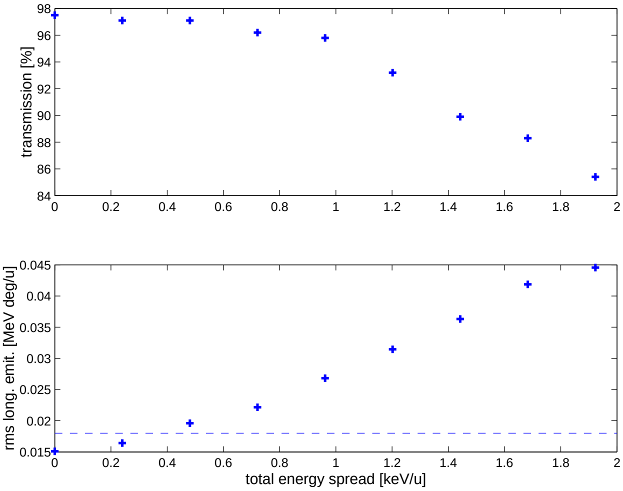


Figure 3: Transmission (upper plot) and longitudinal emittance (lower plot) versus input energy spread. The dashed line represents the longitudinal acceptance of the IH.

No higher transmission can be achieved, as the losses have their origin in the longitudinal plane. For higher input emittance than the nominal one, the transmission drops down until about 87% for twice the value of the nominal input emittance. However, the acceptance of the RFQ is such that even for 1.5 π mm mrad the transmission is still about 94%.

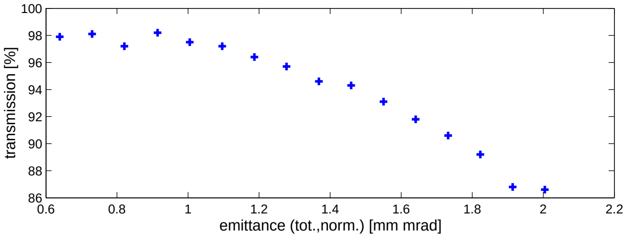


Figure 4: Transmission versus input beam emittance.

4.4 *Beam Current and Composition*

The charge state distribution expected from the CERN LIS is shown in Fig. 5. It peaks at Pb^{25+} but there is a significant contribution of neighboring charge states to the total beam current. The total beam current is here 92.0 mA, which is distributed among the various species accordingly. We have tracked several charge states simultaneously through the RFQ using the code TOUTATIS [5]. For technical reasons we can only track a total of 10 ion species in parallel, so we have selected charge states between +21 and +30 with their corresponding current and a total beam current of 73 mA. The transmission is 47.9% of the full current and 70.0% for $208Pb^{25+}$. The reduced transmission of $208Pb^{25+}$ can be explained by the increased space charge. The longitudinal parameters for the design ion as well as for all 10 charge states are summarised in Table 2.

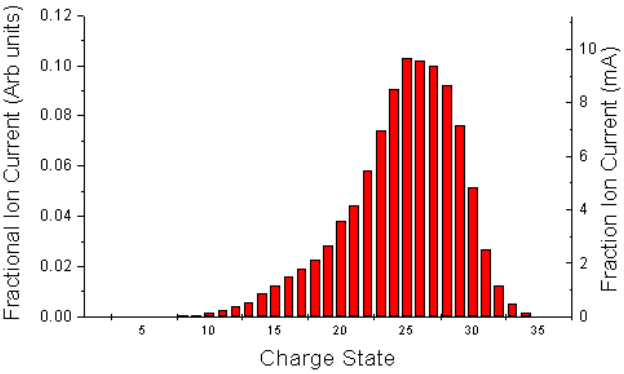


Figure 5: Charge state distribution as expected from CERN laser ion source.

Table 2: Longitudinal beam parameters for baseline RFQ for a beam composed of 10 different ion species.

	$208Pb^{25+}$	total beam
α_l	0.057	1.014
β_l [deg/MeV]	588.66	752.03
ε_l (r.m.s.) [MeV deg]	0.24942	335.48
ε_l (r.m.s.) [MeV deg/u]	0.030	-

5 CONCLUSIONS

We have found a beam dynamics solution for an RFQ which matches the assumed beam parameters of the CERN laser ion source and the constraints given by the CERN ion linac. The transverse acceptance is the one given by the linac, leaving sufficient margin. The longitudinal emittance formed in the RFQ is well below the one required by the IH. Simulations of a multi-charge state beam have been performed. The design can be finalised as soon as the definite source parameters are known.

6 ACKNOWLEDGMENTS

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7 REFERENCES

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