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Preliminary Design of an RFQ for the CERN Laser Ion Source

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Abstract

A laser ion source is presently under study at CERN in the frame of the LHC heavy ion program. This source requires a dedicated injection scheme into the CERN ion linac (Linac III). In particular, the beam parameters must be matched to the tight longitudinal acceptance of the IH structures. We present a preliminary design of an RFQ based on estimated source parameters and the acceptance of the Linac III IH structure.

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1 Introduction

The LHC heavy ion program calls for a new, high-intensity ion source. Possible candidates are an upgraded ECR source, a new ECR source as well as a laser ion source. In order to match the beam parameters from the source to the acceptance limits of the CERN ion linac (Linac III), a dedicated injection scheme consisting of low-energy beam transport line (LEBT), radio-frequency quadrupole (RFQ) and beam transfer lines is needed. For the example of the Laser Ion Source (LIS), the extraction scheme and the design of the LEBT are discussed in [1], [2].

In this note we present, again for the example of the LIS, a preliminary design of an RFQ and the associated beam transfer lines from the RFQ to the CERN ion linac (Linac III). We have based our simulations on estimated source parameters (beam emittance, current) and we have, for the time being, only done simulations for one charge state ($208Pb^{25+}$). These simulations will be refined. In particular, we will do a sensitivity study (beam dynamics in the case of misalignments and changing beam parameters) and track several charge states through the system. It should also be stated that a final design of RFQ and beam lines can only be done once the source parameters have experimentally been determined. In the case, that a source other than the LIS is chosen as injector for the LHC, the design will be modified accordingly.

2 Assumed Beam Parameters from Source

For the moment, experimental data from the final LIS set-up operated with a 100 J laser are not available. We have to base therefore the design of RFQ and beam lines on estimated beam parameters as well as on extrapolations from experimental data obtained with a 30 J laser test set-up.

The total beam current is estimated in [1] as 92 mA for an aperture of the extraction electrodes of 24.4 mm. This total current consists of a variety of charge states, out of which 9 mA are estimated to be $208Pb^{25+}$. An alternative extraction system (30 mm aperture) would provide up to 13.6 mA of $208Pb^{25+}$. We have based the present RFQ design on a current of 10.0 mA $208Pb^{25+}$.

The beam emittance from the source can be extrapolated from measurements with a LIS test stand in 2000. These measurements were done with a 30 J laser, Ta^{20+} with a source current of 77.0 mA and an extraction voltage of 110 kV. The measurements were taken 5 cm downstream of the exit grid of the Gridded Electrostatic Lens (GEL) LEBT [3] with the electrodes set to 20, 40 and 35 kV. The measurement system was a moving slit and a fluorescent screen, from which an image was obtained with a gated CCD camera. The measured 4 r.m.s. emittance was 360 π mm mrad (non normalised), which is equivalent to 1.85 π mm mrad normalised ($\beta = 5.1485 \times 10^{-3}$) [4]. The statistical error of three subsequent measurements was less than 1%. However, we assume a systematic error of about 20% for these measurements.

The source extraction voltage has typically values between 60 kV and 110 kV. In experiments, we have used V_{extr} = 60, 80 and 110 kV, where increased voltage has resulted in increased extracted beam current. In [1] the value of 110 kV is quoted for the final set-up.

3 Required Beam Parameters at Injection

The beam parameters at the exit of the RFQ are dictated by the acceptance of the CERN ion linac (Linac III). They can be found in [5]. In particular, the frequency of the RFQ is fixed to 101.28 MHz which is the frequency of the Linac III IH structure. Some important parameters

energy [keV/u]	250.0
horizontal acceptance [π mm mrad], not norm.	44.0
horizontal acceptance [π mm mrad], norm.	1.0
horizontal α	1.69
horizontal β [mm/mrad]	0.94
vertical acceptance [π mm mrad], not norm.	44.0
vertical acceptance [π mm mrad], norm.	1.0
vertical α	0.47
vertical β [mm/mrad]	0.55
longitudinal acceptance [deg MeV/u]	0.105
energy spread [MeV/u]	0.0054

Table 1: Nominal beam parameters at injection into the CERN Linac III IH structures.

of Linac III are listed in Tab. 1.

In particular, we find that the longitudinal acceptance is very difficult to achieve with a high current beam. From [5] we find the value of 0.105 MeV deg/u (at 101.28 MHz). In a previous RFQ design [6], the value of 0.018 deg MeV/u (r.m.s.) has been assumed as required output emittance, which, multiplied by 5, yields a total longitudinal emittance of 0.09 deg MeV/u and is hence a slightly tighter constraint. In addition, Ratzinger [7] gives the value of 1.5 keV ns/u which corresponds to 0.055 MeV deg/u. This value was used as input emittance in simulations; the acceptance is estimated to be about twice that value, i.e. 0.11 MeV deg/u. We have used in our design the most stringent value of ε_l = 0.018 MeV deg/u r.m.s. The goal was to form in the RFQ a longitudinal emittance which is about 10-15% below this value to allow for some emittance dilution in the injection line.

4 RFQ Beam Dynamics

The design of the RFQ was done using the codes CURLI, RFQUICK, PARI and PARMTEQM [8]. 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 high beam current and rigidity.

As the source parameters of the final LIS set-up have not been determined at this time, we have started our study with a preliminary investigation of the parameter space. We have used a 208Pb^{25+} beam at 60, 80 and 110 kV extraction voltage. Preliminary simulations at V_{extr}= 110 kV indicate problems to achieve the required longitudinal emittance at the RFQ output. We have therefore decided to consider as a baseline scenario the case with V_{extr}= 80 kV.

As far as the transverse optics is concerned, the measured emittance from the source indicates a value which is about twice as high as the acceptance of the IH. Preliminary simulations of an RFQ with a transverse acceptance of 2πmm mrad (tot.,normalised) have shown that this requires a large aperture and hence a very high vane voltage. We have therefore based our present RFQ design on an input beam emittance of 1πmm mrad (tot., norm.) which corresponds to the acceptance of the subsequent IH.

In order to obtain a small longitudinal emittance at the exit of the RFQ, two design choices have been made already 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 (98.0%), but an unacceptable longitudinal emittance which is 36% 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) ramp quickly the phase after the shaper to accelerate quickly, thus reducing space charge effects while keeping the longitudinal emittance constant.

c) have a large beam size along the RFQ.

We find an RFQ with good transmission (97.6%) and a longitudinal emittance of ε_l = 0.016 MeV deg/u (r.m.s.). This is 12% below the value required by the IH and leaves hence some margin for blow-up in the injection lines. The vane voltage is 90 kV and the total length of the RFQ is 375 cm. The main RFQ parameters are listed in Tab. 2. Table 3 summarises the input and output beam parameters for this RFQ. 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.

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
vane length [cm]	374.8
number of cells	307
power loss per meter [kW] for 60 kΩm	135.0
minimum aperture [cm]	0.334
max. modulation factor	1.7
transmission[1] [%]	96.9
r_o [cm]	0.46
ρ/r_o	0.65

1) For 1 π mm mrad input emittance (tot., norm.) and 10 mA, 1000 particles.

Table 2: Parameters obtained for baseline RFQ.

	RFQ input	RFQ exit
α_x	0.8	-1.75
β_x [m/rad]	0.0406	0.16
ε_x (r.m.s., norm.) [mm mrad]	0.17^2	0.17^2
α_y	0.8	1.52
β_y [m/rad]	0.0406	0.14
ε_y (r.m.s., norm.) [mm mrad]	0.17^2	0.17^2
α_l	-	-0.23
β_l [deg MeV]	-	28.24
ε_l (r.m.s.) [MeV deg/u]	-	0.016

[2)] 1/6 of total emittance for waterbag distribution.

Table 3: Input and output beam parameters for baseline RFQ, computed with 1000 particles.

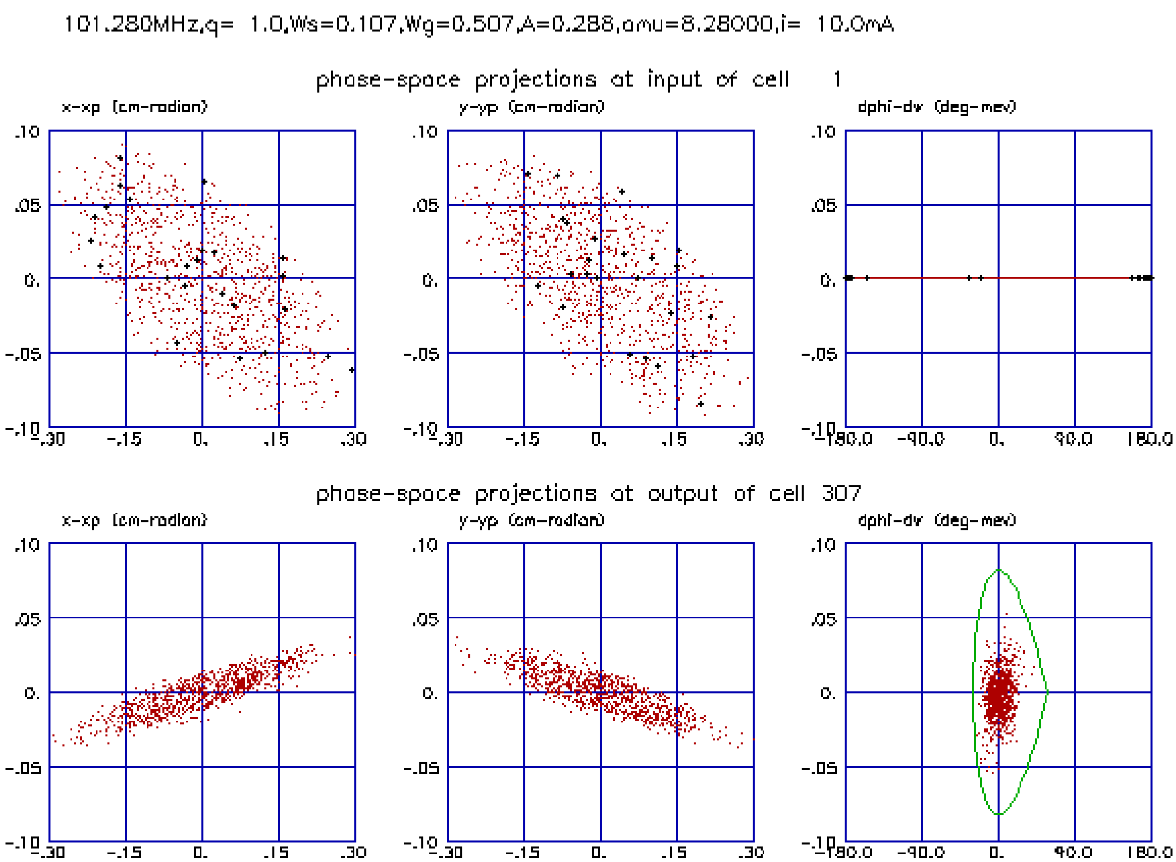

Figure 1: Input (upper plots) and output (lower plots) beam of the RFQ as simulated with PARMTEQM.

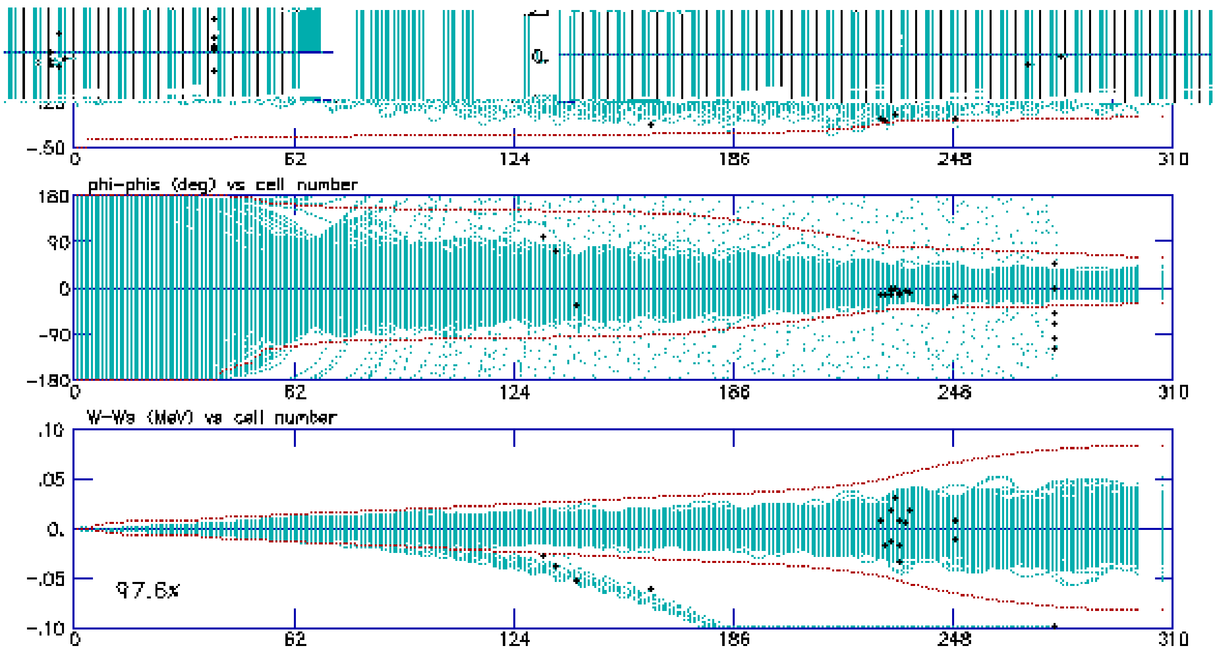

Figure 2: Evolution of beam parameters versus cell number as simulated with PARMTEQM. The dashed line indicates the physical aperture.

4.1 Future Work

We will refine the RFQ design, taking into account the multi-charge state beam provided by the LIS. We will do a sensitivity study to understand the stability of the RFQ in case of misalignments and changing input beam conditions.

In a future note, we will report on possible injection lines into Linac III. We are furthermore planning a full simulation through the Linac III.

Once the beam parameters from the LIS have experimentally been determined, we will be able to do the final RFQ design. Alternatively, if a source other than the LIS is chosen as LHC ion injector, we will adapt the RFQ and its associated beam lines to this scheme.

References

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