ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-TUP11

EFFICIENT INJECTION OF HIGH-INTENSITY LIGHT IONS FROM AN ECR ION SOURCE INTO AN RFQ ACCELERATOR

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Abstract

This study investigates an efficient injection of high-intensity light ions from an Electron Cyclotron Resonance (ECR) ion source into a Radio Frequency Quadrupole (RFQ) accelerator. An often-adopted solution for the beam matching between an ion source and an RFQ is to apply two solenoids as a Low Energy Beam Transport (LEBT) section. There are also other solutions which skip the LEBT section and inject the ion-source output beam directly into an RFQ e.g. the so-called Direct Plasma Injection Scheme (DPIS). For this study, a compact electrostatic LEBT using an einzel lens as well as an efficient RFQ based on a special design method have been developed to achieve high transmission of a 60 mA proton beam. Additionally, the RFQ design has been also checked with the LEBT removed. The design and simulation results will be presented.

INTRODUCTION

Usually a particle beam extracted from an Ion Source (IS) is defocused in both transverse (x and y) planes. At the entrance to an RFQ accelerator, however, an input beam focused in both x and y planes are desired. To transport a particle beam from an IS to an RFQ accelerator, there are different approaches:

- Using a magnetic LEBT (M-LEBT) typically consisting of two solenoids, e.g. [1].
- Using an electrostatic LEBT (E-LEBT) with one or two einzel lenses, e.g. [2].
- Using a zero-length LEBT (Z-LEBT) i.e. direct injection, e.g. [3].

An M-LEBT often needs more space than an E-LEBT and a Z-LEBT solution usually causes high beam losses at the injection due to lake of beam matching, this study focuses on the R&D of a compact einzel lens for an efficient injection of a 50 keV, 60 mA proton beam into an RFQ.

EINZEL-LENS DESIGN

For the design of the aimed einzel lens, a particle distribution with 10000 macro particles (see the left graphs of Fig. 1) generated at the extractor exit of an ECR-IS was taken as the input beam. This generated 50 keV, DC input beam has a transverse size of ~5 mm in diameter and it is defocused in both transverse planes. The task of the aimed einzel lens is to convert the particle beam to be focused in both transverse planes, whereby the beam energy should be kept almost unchanged and the transverse beam size should not increase too much.

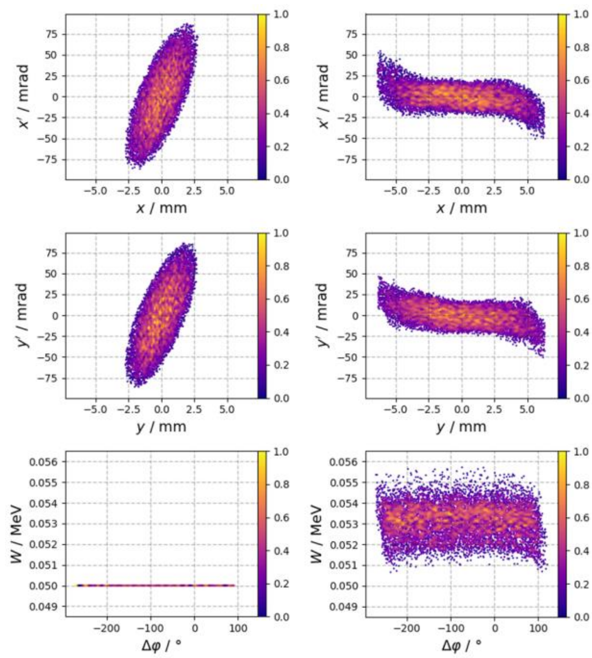

Figure 1: Particle distributions at the extractor exit of the ECR-IS (left) and at the RFQ entrance (right, obtained from the beam dynamic simulation using TraceWin [4]).

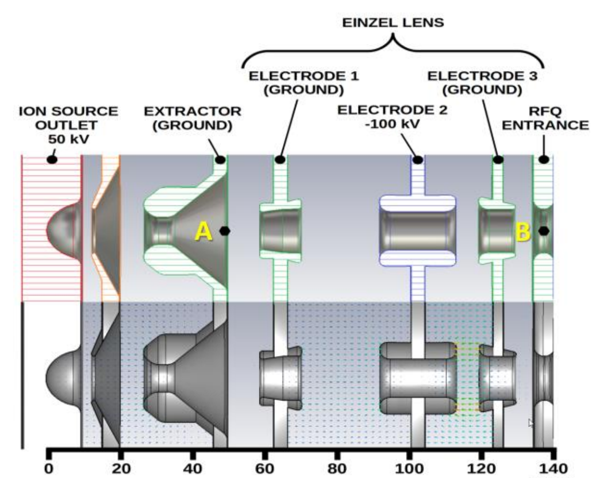

Figure 2: Schematic layout of the designed einzel lens, where Points A and B represent the start and end positions of the beam transport simulation through the einzel lens, respectively (the electrostatic field calculated using the CST Studio Suite [5] is shown in the bottom graph).

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As shown in Fig. 2, a defocusing-focussing scheme has been chosen for designing a ~8 cm long einzel lens. The defocussing part of the lens system (between the first and second electrodes) tries to smoothly increase the transverse beam size, the transverse diverging angles, and the beam energy. The focussing part (between the second and third electrodes) will then try to reduce the above-mentioned parameter values, whereby the position and shape of the electrodes as well as the applied potential were optimized to obtain a particle beam focused in both x and y planes with minimum emittance growth and energy spread. The resulted particle distribution at the exit of the einzel lens can be found in the right graphs of Fig. 1, which shows that the einzel-lens output beam has a transverse size of ~12 mm in diameter and ±4% of energy spread. The beam dynamics simulation through the einzel lens was performed using the TraceWin code with electrostatic field calculated by the CST Studio Suite.

EZ-LEBT RFQ DESIGN

Due to the relatively large transverse size and energy spread of the input beam for the downstream RFQ, the following RFQ design parameters have been decided:

- A relatively low working frequency i.e. 176.1 MHz was taken to allow a relatively large electrode aperture for the beam transport.
- The RFQ output energy was chosen to be 1.5 MeV in order to keep the structure length below 4 m.

In addition, for such an RFQ input beam, the ratio of longitudinal to transverse emittance $\frac{\varepsilon_l}{\varepsilon_t}$ will be very likely beyond the optimal emittance-ratio range ($0.9 \le \frac{\varepsilon_l}{\varepsilon_t} \le 1.4$) required by the MEGLET (Minimizing Emittance Growth via Low Emittance Transfer) method [6–8] after the prebunching, so another method so-called SEGLER (Small Emittance Growth at Large Emittance Ratios i.e. $2.0 \le \frac{\varepsilon_l}{\varepsilon_t} \le 4.0$) [7, 8], which provides a “safe ¼ ellipse” (the orange-marked area with $\frac{\sigma_l}{\sigma_t} = 0.0 \sim 1.0$ and $\frac{\sigma}{\sigma_0} = 0.25 \sim 1.0$ in Fig. 3) for the tune footprints of the beam motion on the corresponding Hofmann Chart, has been adopted.

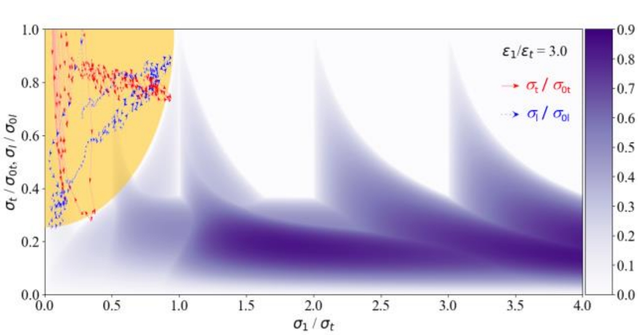

Figure 3: Hofmann chart for $\frac{\varepsilon_l}{\varepsilon_t} = 3.0$ with the “safe ¼ ellipse” (and the tune footprints of the EZ-LEBT RFQ from the beam beam dynamics simulation mentioned later).

For this study, a SEGLER-style RFQ (hereafter also referred to as the EZ-LEBT RFQ, because this RFQ has been designed for an E-LEBT and later will be checked for the Z-LEBT case) has been designed. The main parameters of the EZ-LEBT RFQ are given in Fig. 4.

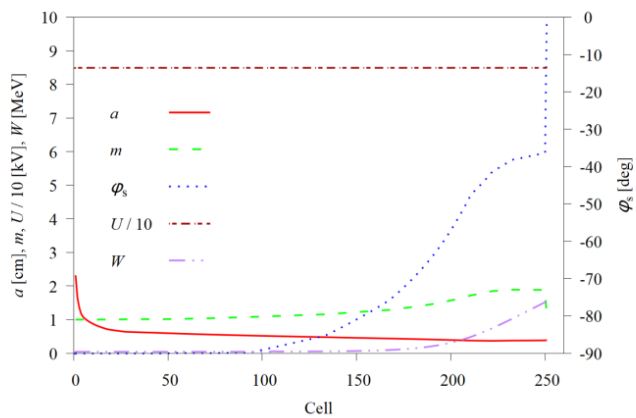

Figure 4: Main design parameters of the EZ-LEBT RFQ, where a is the minimum electrode aperture, m is the electrode modulation, φ_s is the synchronous phase, U is the inter-vane voltage, and W is the beam energy.

The beam dynamics simulation performed with the RFQGen code [9] tells that that the pre-bunching ends at around Cell 90 (see Fig. 5) where $\frac{\varepsilon_l}{\varepsilon_t} \approx 2.0$ and afterwards $\frac{\varepsilon_l}{\varepsilon_t}$ is still increasing up to $\frac{\varepsilon_l}{\varepsilon_t} \approx 4.0$ (see Fig. 6, the average $\frac{\varepsilon_l}{\varepsilon_t}$ for the main RFQ is ~3.0). As the transverse emittance keeps relatively constant after the pre-bunching, it indicates that the increase of the longitudinal emittance was not caused by emittance transfer, but because of the particles that were not well captured by the pre-bunching and were moving further and further away from the bunch center (see Fig. 5). The tune footprints of the EZ-LEBT RFQ are plotted on the $\frac{\varepsilon_l}{\varepsilon_t} = 3.0$ Hofmann Chart in Fig. 3. It is clear that most of the footprints are well located in the “safe ¼ ellipse” and only touch the resonance peaks very briefly, which explains the low emittance transfer.

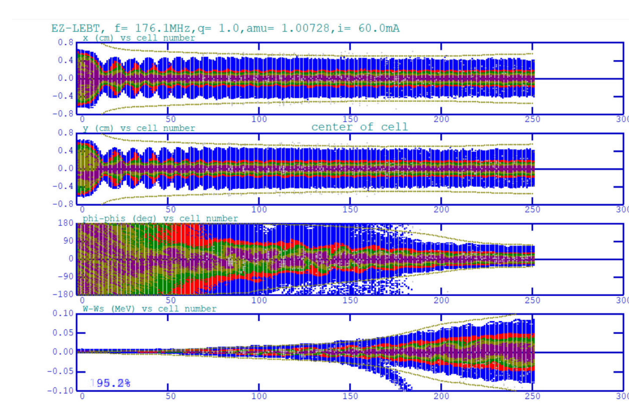

Figure 5: Beam transport simulation along the EZ-LEBT RFQ.

26th Int. Workshop Electron Cyclotron Resonance Ion Sources ECRIS2024, Darmstadt, Germany JACoW Publishing
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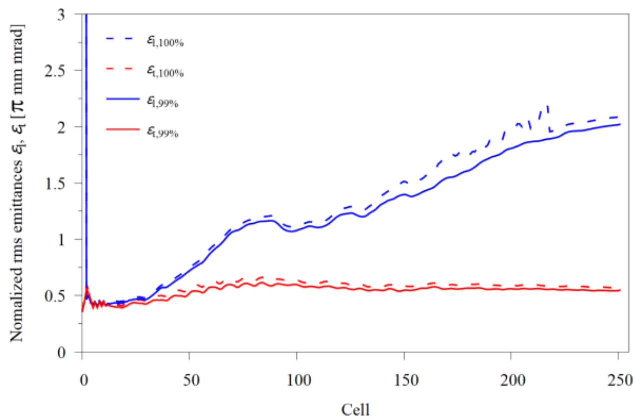

Figure 6: Evolution of emittances along the EZ-LEBT RFQ.

Z-LEBT (NO LEBT) CASE

The EZ-LEBT RFQ was also checked in case the Einzel-Lens LEBT is removed namely the IS output beam (see the left graphs of Fig. 1) will be injected into the RFQ directly. Obviously, the orientations of the transverse emittance ellipses for both the Einzel-Lens LEBT case and the Z-LEBT (i.e. no LEBT) case are quite different. To improve the matching at the entrance, the RFQ design shown in Fig. 4 has been slightly adjusted in the beginning part for the Z-LEBT case.

In Fig. 7, one can see that with a defocused input beam, the oscillation of the transverse beam envelopes becomes much stronger (compared with that shown in Fig. 5), while the beam transmission is about 10% lower

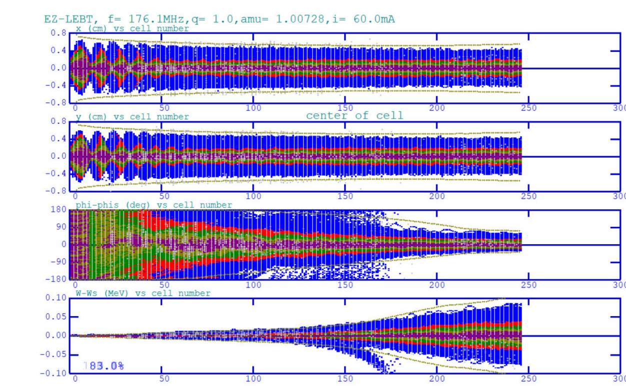

Figure 7: Beam transport simulation along the EZ-LEBT RFQ for the Z-LEBT case.

Figure 8 shows that for the Z-LEBT case, $\frac{\varepsilon_l}{\varepsilon_t}$ reaches ~1 which is actually ideal for applying the MEGLET method, but the tune footprints (see Fig. 9) are not located in the "safe rectangle" ($\frac{\sigma_l}{\sigma_t}$ = 0.5 – 2.0 and $\frac{\sigma}{\sigma_0}$ = ~ 0.25 – 1.0) [6–8] required by MEGLET.

For the Einzel-Lens LEBT case and the Z-LEBT case, the main design and simulation results are summarized in Table 1 and the corresponding RFQ output distributions are compared in Fig. 10, respectively.

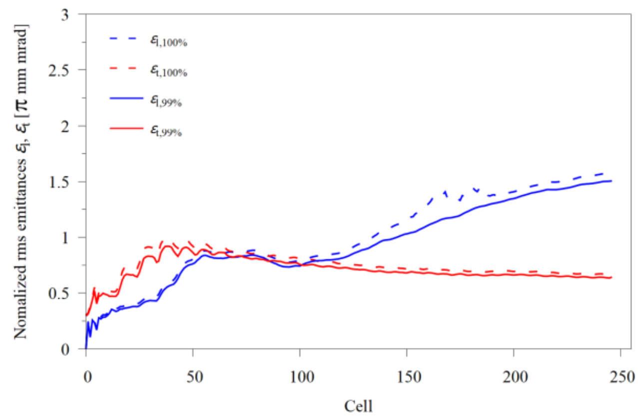

Figure 8: Evolution of emittances along the EZ-LEBT RFQ for the Z-LEBT case.

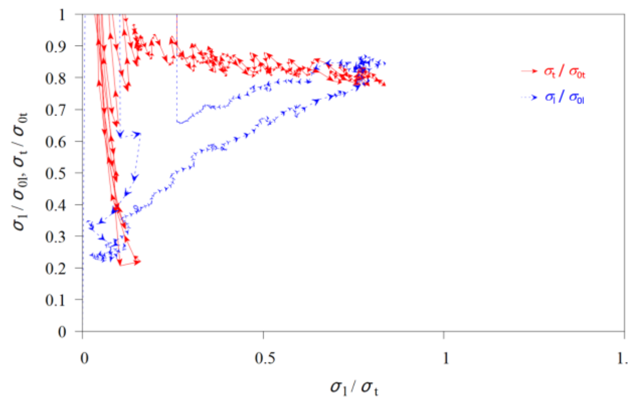

Figure 9: Tune footprints of the EZ-LEBT RFQ for the Z-LEBT case.

Table 1: RFQ Design and Simulation Results

Parameter	Einzel-Lens LEBT	No LEBT
f [MHz]	176.1	176.1
W_{in} / W_{out} [MeV]	0.053 / 1.512	0.050 / 1.511
I [mA]	60	60
U [kV]	85	85
$\varepsilon_{x, in, n., rms}$ / $\varepsilon_{x, out, n., rms}$ [π mm mrad]	0.3767 / 0.5592	0.3001 / 0.6783
$\varepsilon_{y, in, n., rms}$ / $\varepsilon_{y, out, n., rms}$ [π mm mrad]	0.3599 / 0.6068	0.3001 / 0.6726
$\varepsilon_{z, in, n., rms}$ / $\varepsilon_{z, out, n., rms}$ [π MeV deg]	4.8870 / 0.4148	0.0000 / 0.3123
N_{cell}	251	246
RFQ length [cm]	383.9	385.0
Transmission [%]	95.2	83.0

CONCLUSION & OUTLOOK

It has been demonstrated that one can use a very compact (<10 cm) einzel lens and a SEGLER-style RFQ to achieve an efficient injection of a 50 keV, 60 mA proton beam from an ECR-IS into an RFQ. With small modifications at the

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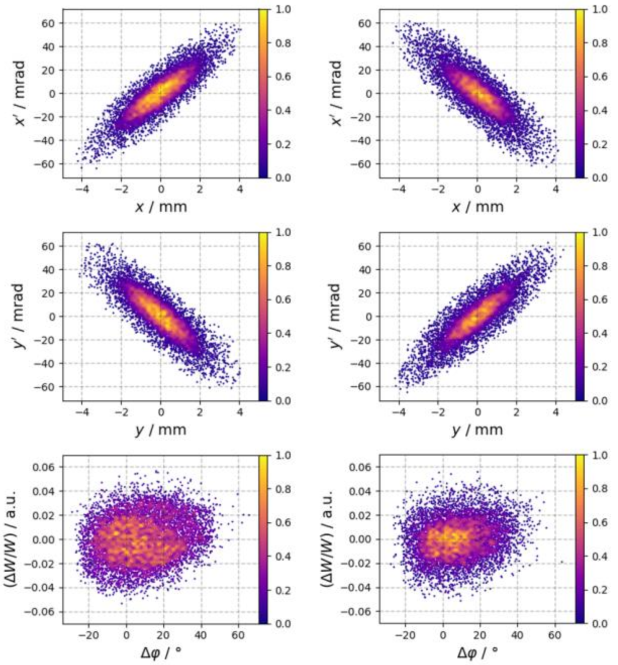

Figure 10: Output particle distributions of the EZ-LEBT RFQ for the E-LEBT case (left) and for the Z-LEBT case (right), respectively.

entrance, the SEGLER-style RFQ can still reach 83% of beam transmission even for a direct injection from the IS into the RFQ. Further improvements, e.g. to remove the "wings" in the einzel-lens output distribution (see Fig. 1) by optimizing the einzel-lens design and to change the SEGLER-style RFQ to a MEGLET-style RFQ for the Z-LEBT case, have been foreseen.

ACKNOWLEDGEMENTS

Thanks to Dr. Rustam Berezov for the discussion on output distributions of ECR proton sources as well as to Dr. Didier Uriot for his help in einzel-lens beam dynamics simulation with TraceWin.

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