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MULTIPARTICLE BEAM DYNAMICS OF ELEBT INTEGRATED WITH UPGRADED RFQ IN LINAC4

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Abstract

Electrostatic low-energy beam transport (ELEBT) section as a part of future upgradation proposal in LINAC4 at CERN, is proposed to handle 45 keV H^- ion beam with 70 mA max beam current. The design allows maximum input rms normalized emittance of 0.5 π mm mrad without significant growth. A dual einzel system is incorporated in the decelerating-accelerating (DA) mode to control beam blow up within 70% of the beam pipe aperture. The ground electrode of these einzel systems also houses radio frequency electrodes for beam chopping. It chops the beam as per the requirement of the upgraded radio frequency quadrupole (RFQ). The transverse and longitudinal beam optics are studied for the full system of ELEBT + RFQ. It is also validated theoretically using multi particle beam analysis. We achieved beam transmission more than 90% with all emittances well in control. The design details with respect to field computation and beam dynamics will be presented.

INTRODUCTION

Linear accelerators (LINACs) are widely used as injectors to big synchrtrons and have wide range of applications in nuclear physics, medical applications, neutron generation, and material science research. The beam quality produced at the low-energy injector stage strongly affects the performance of the complete accelerator system; therefore, efficient beam transport and matching at low energies are essential. LINAC4 [1–4] is a normal conducting H^- linear accelerator developed at CERN as an injector to the Proton Synchrotron Booster (PSB), to support future high luminosity Large Hadron Collider (LHC) upgrades. The accelerator is approximately 86 m long and consists of an H^- ion source, a Low Energy Beam Transport (LEBT) section, a 352 MHz Radio Frequency Quadrupole (RFQ), a chopping line, Drift Tube Linac (DTL), Cell-Coupled Drift Tube Linac (CCDTL), and Pi-Mode Structures (PIMS). The H^- beam extracted at 45 keV is accelerated to 3 MeV by the RFQ and finally up to 160 MeV before injection into the PSB. The use of H^- ions enables efficient charge-exchange injection, reducing beam losses and improving beam brightness for the CERN accelerator chain.

The LEBT section transports the beam from the ion source to the RFQ while preserving beam quality. Conventional magnetostatic LEBT (MLEBT) systems based on solenoids are widely used in facilities such as J-PARC, ESS, IFMIF, and LINAC4. However, MLEBT systems require space charge compensation, which can lead to emittance growth and beam losses. Electrostatic low energy beam transport (ELEBT) systems provide an alternative solution with compact geometry, absence of transverse coupling, and reduced emittance growth for intense low-energy beams. Among the two operating configurations of the einzel lens, the deceleration-acceleration (DA) mode provides higher refractive power than the acceleration-deceleration (AD) mode for the same applied voltage, enabling shorter focal lengths at lower voltages and making it suitable for compact ELEBT designs.

Recently, compact ELEBT systems for LINAC4 [5] have been simulated with 93% beam transport of 70 mA H^- beams at 45 keV and proper matching to the RFQ acceptance. Previously, RFQ design and upgrade studies [6] explored beam dynamics, vane geometries, and other design parameters for compact high-current RFQ systems. Compact RFQ [7] have been studied in terms of maximum energy gains by exploiting the maximum surface fields allowed by vane materials. Furthermore, start-to-end simulation approaches [8] provide a consistent framework for understanding the complete beam transport and acceleration process. Following these studies, the present work simulates the integrated ELEBT and RFQ system for the LINAC4.

DESIGN CRITERIA FOR THE ELEBT AND RFQ

The ELEBT is designed to transport 45 keV H^- beams with minimum emittance growth and beam losses. The simulated beam transmission was optimized for beam currents up to 70 mA while matching the RFQ. A compact dual einzel lens system operating in deceleration–acceleration (DA) mode was adopted for stronger focusing and reduced emittance growth. The RFQ was designed to accelerate the H^- beam from 45 keV to 3 MeV RFQ [6] in LINAC4 RFQ, designed and upgraded with a design normalized rms transverse emittance of 0.5 π mm mrad for high-current operation (70 mA beam). The beam dynamics inside the RFQ are governed by the transverse focusing and longitudinal bunching RF fields. The longitudinal equation of motion of

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particles with respect to the synchronous particle is given by [9]

$$\frac{d(\phi - \phi_s)}{dz} = -\frac{2\pi(W - W_s)}{mc^2 \beta_s^3 \lambda} \qquad (1)$$

where ϕ is the particle phase, ϕ_s is the synchronous phase, W is the particle energy, W_s is the synchronous particle energy, m is the mass of the particle, $\beta_s = v_s/c$ is the normalized synchronous particle velocity, and λ is the RF wavelength. The transverse equation of motion of particles inside the RFQ is expressed as

$$\ddot{x} + \left[\frac{qXV_0}{ma^2} + \frac{q^2 kAV_0}{4m}\cos(kz)\right] x \sin(\omega t + \phi) = 0 \qquad (2)$$

where x is the transverse displacement of the particle from the beam axis, $\ddot{x} = d^2x/dt^2$, q is the particle charge, X is the quadrupole focusing factor, V_0 is the inter-vane voltage, a is the minimum bore radius, A a dimensionless acceleration parameter, $k = 2\pi/\beta\lambda$ is the wave number, ω is the RF angular frequency. The RFQ was optimized to achieve beam transmission greater than 90%. The input beam parameters to study the beam dynamics of the ELEBT + RFQ system are listed in Table 1.

Table 1: Input Beam Parameters

Parameters	**Value**
Ion Beam	H^-
Beam Current	70 mA
Input Energy	5 eV
Beam Size (x and y)	4 mm
Beam Divergence (x’ and y’)	500 mrad
Transverse Normalized Emittance	0.042 π mm mrad
Longitudinal Normalized Emittance	0.036 π deg.keV
Energy Spread	16%

MULTIPARTICLE BEAM DYNAMICS

Both ELEBT and RFQ were simulated for field computational analysis. The extracted electric field maps were coupled in the TRAVEL code [10] to perform multiparticle beam dynamics simulations of the complete ELEBT + RFQ system. Figure 1 shows the transverse beam size (σ_x, σ_y) envelope evolution along the complete system. The beam size initially increases in the low-energy region due to space-charge effects, then decreases due to the focusing action of the einzel lenses. The beam spot size reduces from about 4 mm to 2 mm at the RFQ exit, indicating the beam is finely focused inside the RFQ in both transverse planes due to strong adiabatic focusing. The overlapping behavior of σ_x and σ_y confirms symmetric beam transport. The evolution of the transverse twiss parameter β is shown in Fig. 2.

Figure 3 shows the evolution of transverse rms emittance. It initially increases in the low-energy region and is matched to the RFQ acceptance and finally minimized inside the RFQ. The input and output phase space distributions are shown in Fig. 4. Beam energy spread at the exit of the ELEBT + RFQ system is 2.3%. Lastly, beam energy evolution is shown in Fig. 5, which shows that the beam energy gets boosted to 3 MeV upon exiting the RFQ.

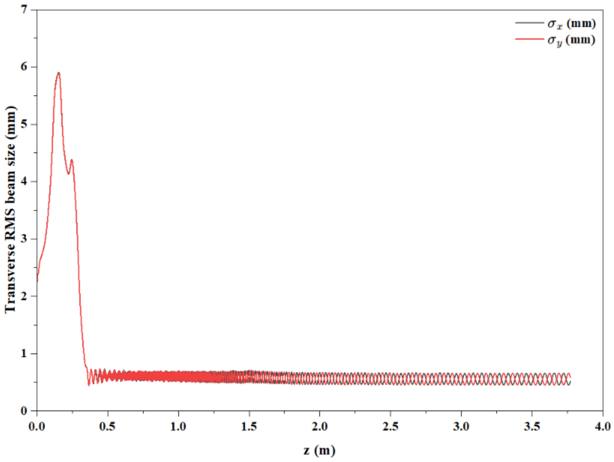

Figure 1: Evolution of transverse rms beam sizes (σ_x and σ_y) along the ELEBT and RFQ system.

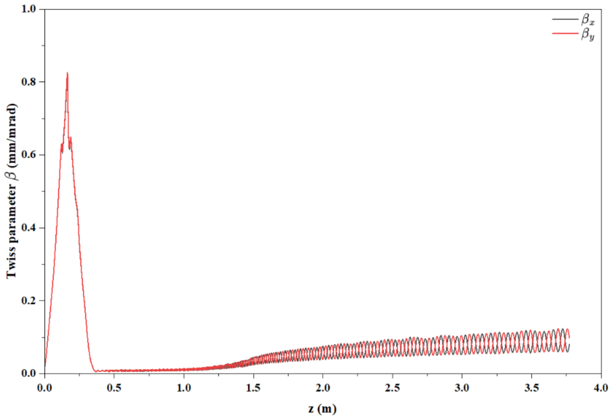

Figure 2: Evolution of transverse Twiss beta parameters (β_x and β_y) along the complete ELEBT and RFQ system.

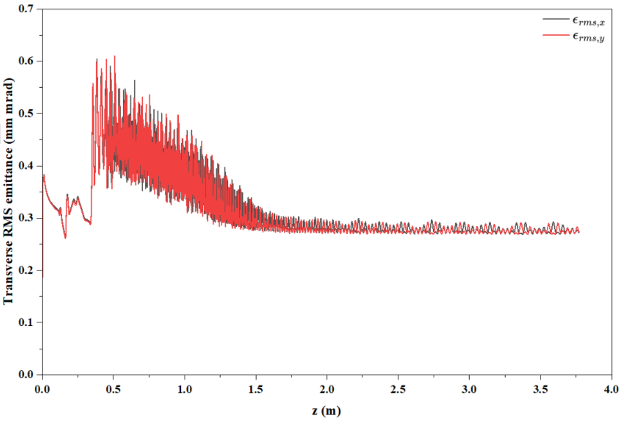

Figure 3: Evolution of transverse rms emittances ($\epsilon_{\text{rms,x}}$ and $\epsilon_{\text{rms,y}}$) along the ELEBT and RFQ.

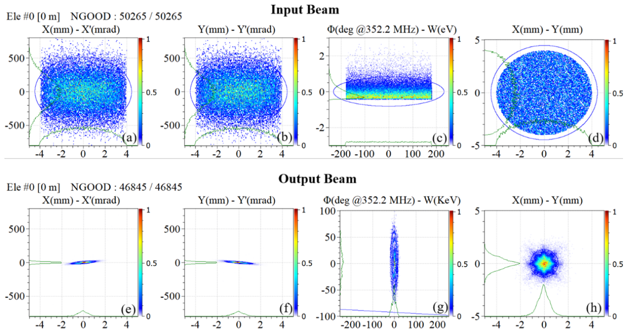

Figure 4: Transverse and longitudinal phase space plots at the input and output of the ELEBT + RFQ system. Phase space plots (a), (b), and (c) represent the beam distributions at the input of the system, whereas plots (e), (f), and (g) correspond to the beam distributions at the output. The beam spot sizes are shown in plots (d) and (h) at the input and output, respectively.

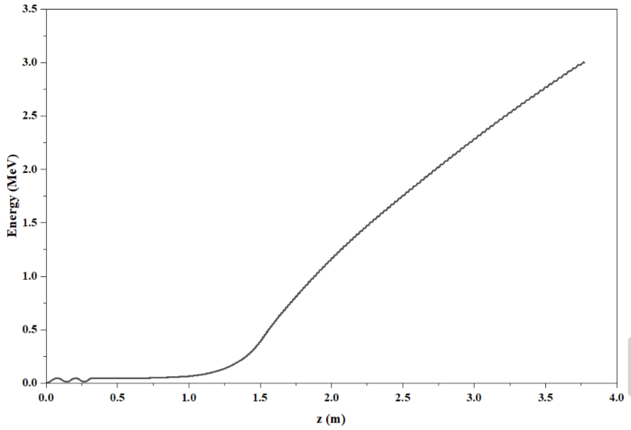

Figure 5: Beam kinetic energy evolution along the ELEBT and RFQ system.

CONCLUSION

A compact ELEBT along with an upgraded RFQ has been designed for the LINAC4 injector upgrade at CERN to handle a 70 mA H^- beam. The proposed system efficiently transports and accelerates the beam to 3 MeV with optimum emittance growth and high beam transmission. The dual einzel lens ELEBT operating in DA mode provides strong focusing, compact geometry, and proper matching to the RFQ acceptance. The simulated results demonstrate beam transmission around 93% with acceptable transverse and longitudinal emittance growth, making the proposed design a suitable candidate for future LINAC4 upgrades. In the future, we shall integrate further to consolidate on the optics part.

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