ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPS038

LOW ENERGY BEAM TRANSPORT LINE DESIGN FOR THE SARAJEVO ION ACCELERATOR (SARAI)*

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Abstract

The University of Sarajevo Physics Department, in collaboration with CERN's Accelerator Beam Physics group, proposes a compact linear accelerator design for applied physics research spanning from beam dynamics studies to material surface analysis. The Sarajevo Ion Accelerator (SARAI) consists of an electron cyclotron resonance ion source, a low energy beam transport line (LEBT) and a radiofrequency quadrupole (RFQ). The ion source can produce an array of ions extracted with 30 kV. This study presents an iterative parameter optimization method that suggests two LEBT optics: one for beam diagnostics and another for compact beam matching to the RFQ acceptance. The RFQ discussed here is a 750 MHz, 2.5 MeV/u RFQ, used for medical applications. SARAI RFQ aims at 0.5 – 2 MeV/u. A novel RFQ technology allows a significant reduction in footprint. This paper further discusses plans for source commissioning and potential research applications.

INTRODUCTION

The expertise gained during the design and construction of the LINAC4 radiofrequency quadrupole (RFQ) [1, 2], followed by the design of the high-frequency RFQ [3, 4], along with the successful development of the high-frequency RFQ for proton therapy [5], contributed to the creation of compact, low-energy proton RFQs for societal applications [6-10]. Both the MACHINA and the ELISA layouts utilize two identical RFQs designed for applications in art diagnostics and surface analysis, respectively [8, 9]. Furthermore, another 750 MHz RFQ with trapezoidal vanes was developed as an injector for a carbon ion therapy linac [11]. The Sarajevo ion accelerator (SARAI), follows a similar path and is intended for a multitude of ion beam research topics with an RFQ under development for alpha particles and heavier ions with charge over mass ratio 1/2. This paper introduces SARAI and focuses on its two low energy beam transport lines (LEBTs): a spectrometer-based test bench (LEBT1), and a 2-gridded lens (GL)-based line for compact matching (LEBT2) into the trapezoidal-vane RFQ designed for 2.5 MeV/u C ions [11].

* Work supported by The Three Physicists Foundation grant.
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SIMULATION SETUP AND DESIGN

Beamline simulations were performed using both TRAVEL [12] and TRACE3D codes [13]. While TRAVEL was employed for its robust field map support and particle tracking accuracy, particularly useful for simulating beam dynamics through gridded electrostatic lenses designed at CERN [14], TRACE3D was used to efficiently perform beam matching via its built-in iterative matching algorithms. This dual-tool approach enabled a complementary design workflow, where the beamline elements could be optimized in TRACE3D for beam injection into the RFQ and then more detailed beam dynamics, including field non-linearities, non-uniform beam distributions and losses, could be modelled in TRAVEL.

ECR Supernanogan Source

The SARAI source is a commercial electron cyclotron resonance (ECR) supernanogan source, able to produce a range of ions (H, He, C, N, Ar, Xe, Au, Pb) extracted with a maximum of 30 kV voltage [15]. The two LEBTs were optimized for He^{2+}, with an intended immediate experimental follow-up with protons and C^{6+} ions. Thus, the focus of all simulations presented in this paper is on the He ions. The beam extracted from the source was defined in TRAVEL and TRACE3D as He^{2+} with 60 keV mean energy and 1% root mean square (RMS) energy spread and no space charge. The beam's RMS normalized emittance (RMSNE) was conservatively defined as 0.32 mm mrad in the transverse phase space (Fig. 1 - left), and simulated through LEBT1. A beam based on the source factory acceptance test, consisting of 0.3 mA He^{2+} and He^{+} ions with RMSNE of 0.028 mm mrad (Fig. 1 - right), was also generated and tracked through LEBT2 and the RFQ.

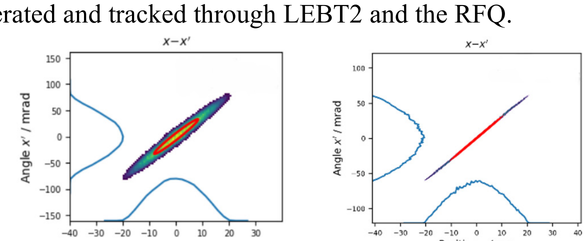

Figure 1: He^{2+} beam (left) and a He^{2+}/He^{+} mixed beam (right) extracted from the source generated in TRAVEL.

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Solenoid-Gridded Lens Equivalence

One of the key goals of the simulation campaign was to identify an equivalent solenoid (SL) configuration that replicates the beam focusing characteristics achieved by the gridded lens (GL), thus enabling flexible experimental setups using either GLs or SLs. For instance, TRACE3D can optimize the beamline for an array of predefined elements, but GL is not one of them. Hence, a SL producing an equivalent effect on the beam as a GL was used at the first stage of beamline optimization in TRACE3D, after which the GL electrostatic field map was used in TRAVEL to track the beam along the beamline. An equivalent SL configuration was derived by tuning the SL magnetic flux density strengths in TRAVEL until similar effect on the beam parameters at the exit was achieved (Fig.2).

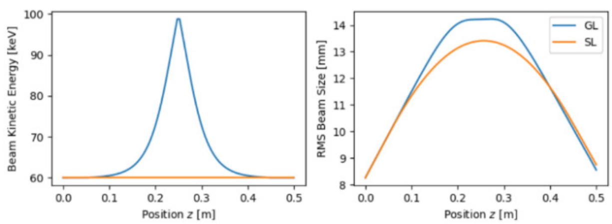

Figure 2: Beam energy (left) and size (right) in GL or SL.

The 2 SARAI LEBTs

Two LEBT layouts were proposed for the SARAI design. The first LEBT (LEBT1) was defined for separating He^{2+} and He^{+} ions at the dipole magnet acting as a spectrometer, while preserving compatibility with the trapezoidal vane RFQ (750 MHz, 2.5 MeV/u) matching requirements. Furthermore, a more compact second LEBT (LEBT2) was designed to test the flexibility of using only GLs to match the beam into the RFQ, since they were demonstrated to exhibit the highest focusing power for low-intensity, low-energy beams of most commonly used electromagnetic focusing elements [14].

LEBT1: Spectrometer-Based Test Bench

The dipole has a horizontal plane bending angle of 90°, pole face rotation angles of 22.5°, bending radius of 0.2 m, 31.4 cm effective length and a vertical gap of 4 cm; it requires a field of 0.176 T for He^{2+} ion beam with 60 keV kinetic energy. After identifying the SL-GL equivalence principle, the SL-based beamline was established in TRACE3D, where a quadrupole triplet and a final solenoid stage were optimized to match the beam to the RFQ acceptance for a complete LEBT1 design, as shown in Fig. 3. Quadrupole gradients and the drift distance to the final focusing SL were used as the matching parameters in TRACE3D. The resulting quadrupole gradients from the dipole to the final solenoid (SL2) were respectively: -1.23 T/m, 1.73 T/m and -1.95 T/m, while the selected SL1 and SL2 field strengths were 0.255 T and 0.485 T, respectively.

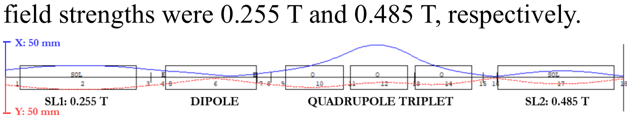

Figure 3: TRACE3D-optimized LEBT1 layout using SLs with the 1-σ beam envelopes (x-blue, y-red).

Final simulations were conducted for He^{2+}, He^{+}, and mixed He^{2+}/He^{+} beams with GL and SL optics. Full LEBT1 schematics with the equivalent GLs is shown in Fig. 4.

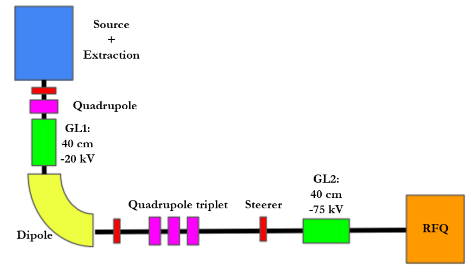

Figure 4: LEBT1 block diagram with equivalent GLs.

LEBT2: 2 GLs for Compact Matching to RFQ

The LEBT2 (Fig.5) consists of 2 GLs. The values shown in Fig.5 were determined using the SL-GL equivalence principle established earlier, after the SLs' magnetic flux density strength and the drift lengths between them were used in TRACE3D as matching parameters to iteratively optimize the LEBT2 design for matching to the RFQ. Note that the GLs' field maps (with expected fringe field) are 40 cm-long, rather than the actual mechanical length of the GLs, which consists of a 0.1 mm-thick tungsten wire mesh.

Figure 5: LEBT2 block diagram with equivalent GLs.

LEBT BEAM DYNAMICS

LEBT1 Beam Dynamics

Figure 6 shows transverse beam size and emittance propagation of the He^{2+} beam (from Fig.1-left) through the LEBT1 with either SLs or GLs used in LEBT1. After accounting for mixing of planes in the solenoid, the beam exhibits comparable behaviour passing through both versions of LEBT1, implying GL can serve as a substitute for SL in LEBT designs for beams of low energy and low intensity. Furthermore, no significant transverse emittance increase was observed in the gridded lenses for the beam dynamics simulation without space charge in LEBT1.

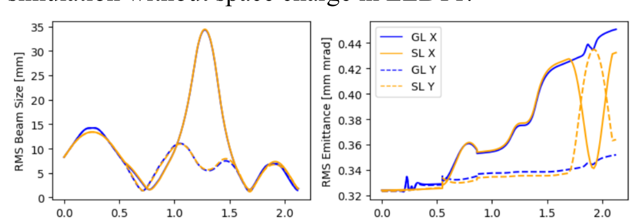

Figure 6: Transverse RMS beam size (left) and RMS emittance (right) through GL- (blue) and SL-LEBT1 (orange).

A mixed He ion beam was further defined and tracked through LEBT1 to investigate the dipole magnet's capability of separating ions. The mixed beam consisted of He^{2+} ions contaminated with He^{+} ions at a particle number ratio 2:1 (He^{2+}: He^{+}). The right plot in Fig. 7 confirms the He^{2+}:He^{+} separation of 36.75 mm at the exit of the dipole magnet, validating its spectrometer purpose.

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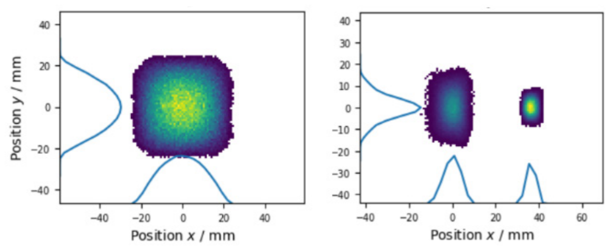

Figure 7: LEBT1 dipole magnet input beam (left) and the output (right) phase-space for the mixed He ion beam.

LEBT2 Beam Dynamics

For assessing the LEBT2 performance with the RFQ, several more realistic beams were generated and tracked through LEBT2 and the RFQ. Presented here is a He ion mixed beam (He^{2+}:He^{+}=2:1) extracted with 30 kV voltage, 1% RMS energy spread, 0.3 mA beam current and 0.028 mm mrad RMSNE. By the time the beam passed through the LEBT2, its RMSNE increased to 0.056 mm mrad. The transverse xx' and xy phase spaces of the beam at the RFQ matching plane are shown in Fig. 8 together with the RFQ acceptance. Most of the beam phase-space distribution matches the RFQ acceptance, signifying successful usage of 2 GLs in LEBT2 for compact matching.

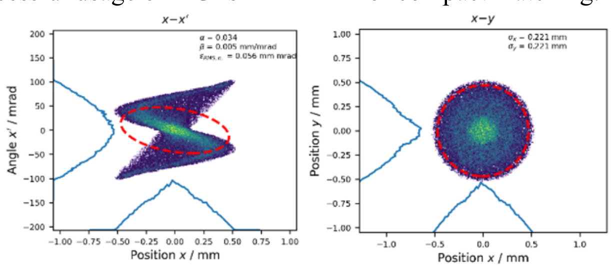

Figure 8: Transverse beam phase-space (xx' left, xy right) particle distribution (blue/green) at the RFQ matching plane compared to the RFQ acceptance (red).

Further parameters through the LEBT2 and the RFQ are shown in Fig. 9, demonstrating overall transmission of 26% for the mix beam from the source to the RFQ output, with 35% transmission for the He^{2+} ion beam alone.

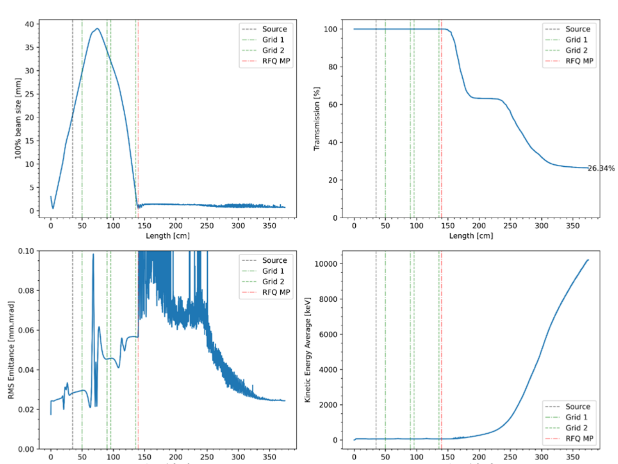

Figure 9: Beam size (top left), transmission (top right), RMS emittance (bottom left) and kinetic energy (bottom right) of the He mix beam through the LEBT2 and RFQ.

FURTHER PLANS

The SARAI project is a long-term collaboration, and the full design is still in development. While the LEBTs have been designed and the source installed at CERN, the RFQ design is ongoing. The aim is to have flexible transfer lines and a low-energy accelerator for a variety of societal applications.

Source Commissioning

The source commissioning is in its initial phases. Primary goals consist of tuning the system and setting up the gas and plasma conditions along with the extraction system voltages, so that the normalized RMS emittance of the He^{2+} ion beam is of the order 0.025 mm mrad. The source will then be studied using GL-LEBT1, starting in proton mode, and continuing in He ion mode to validate the simulations, with the source then iteratively reconditioned so that there is at least twice more He^{2+} than He^{+} ions in the beam.

RFQ Design

Taking into account the success the LINAC4-inspired RFQ designs have had [1-11], the accelerating part of the SARAI is following a similar path. SARAI intends to use a 750 MHz, 0.5 - 2 MeV/u RFQ. It is planned to start with a 0.5 MeV/u RFQ for Rutherford Backscattering (RBS) as a proof of concept, with a potential upgrade to 2 MeV/u using a cascaded RFQ system for further ion beam analysis applications.

Applications

Aiming initially for protons in the energy range 0.5 – 2 MeV, and 2 - 8 MeV for alpha particles (He^{2+}), there is a plethora of research applications intended for SARAI: ion beam analysis (IBA) for material science, art and cultural heritage, time-resolved analysis in biochemical samples, sub-micro beams for nitrogen vacancy implantation and qubits exploration, simulation and experimental analysis of the cosmic rays interaction with electronic equipment travelling to outer space, and possible injection studies for larger synchrotrons, such as those used in hadron therapy or the Future Circular Collider (FCC).

CONCLUSION & OUTLOOK

This paper announces the Sarajevo Ion Accelerator (SARAI) to the Accelerator Physics community, presenting its 2 LEBT lines and analysing beam dynamics associated with them. The 2 LEBT designs are shown to be compatible with the 750 MHz, 2.5 MeV/u RFQ for carbon ions, so they can be tested at CERN for experimental confirmation. LEBT1 is intended to study the source and evaluate the spectrometer's ability to separate ions, while the LEBT2 is for compact matching with gridded lenses. The 2 LEBTs are in line with the SARAI plan for designing an RFQ for ion beam analysis with alpha particles and ions with charge to mass ratio of 1/2. The SARAI RFQ design is under development, with a wide range of potential research topics to follow at the SARAI lab at the University of Sarajevo in collaboration with CERN and other partners.

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