DESIGN OF THE ROOM-TEMPERATURE FRONT-END FOR A MULTI-ION LINAC INJECTOR*

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Abstract

A pulsed multi-ion injector linac is being developed by ANL for Jefferson Laboratory's Electron-Ion Collider (JLEIC). The linac is designed to deliver both polarized and non-polarized ion beams to the booster synchrotron at energies ranging from 135 MeV for hydrogen to 43 MeV/u for lead ions. The linac is composed of a 5 MeV/u room temperature section and a superconducting section with variable velocity profile for different ion species. This paper presents the results of the RF design of the main components and the beam dynamics simulations of the linac front-end with the goal of achieving design specifications cost-effectively.

INTRODUCTION

A pulsed multi-ion linac with a normal conducting front-end up to 5 MeV/u and a superconducting section for higher energies as an injector for the JLab Electron-Ion Collider (JLEIC) was discussed in ref. [1, 2]. Further modifications and improvements of the front-end design are described below.

FRONT-END

A block-diagram of the injector linac is shown in Fig. 1. The JLEIC ion injector linac will consists of both heavy and light ion sources including polarized H^-, $^2D^-$, $^3He^{2+}$, $^6Li^{3+}$ ion sources. The emittance of the polarized beams is usually larger than the emittance of heavy ion beams. For this reason, we propose to use two separate Radio-Frequency Quadrupole (RFQs) sections. The room temperature front-end consists of 2 RFQs, a Medium Energy Beam Transport (MEBT) system to accommodate and match beams from 2 separate RFQs and three tanks of 100 MHz drift tube linac (DTL) as shown in Fig. 1. The FODO lattice of the DTL provides adequate focusing and the required transverse acceptance for both heavy ions and polarized light ion beams. To minimize the overall linac cost, the transition energy between normal and superconducting sections is selected to be 5 MeV/u.

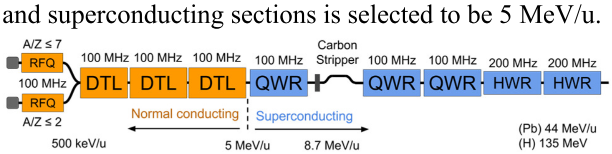

Figure 1: A schematic layout of the JLEIC ion linac.

Ion Sources

Several types of ion sources are being considered: an Atomic Beam Polarized Ion Source (ABPIS), an Optically-Pumped Polarized Ion Source (OPPIS), an Electron Beam Ion Source (EBIS) and an Electron Cyclotron Resonance ion source (ECR). Table 1 provides design parameters of the beams based on the recent data [3] and the JLEIC requirements.

Table 1: Design Parameters of the Beams

Ions	Source	Current, mA	Polari-zation	Emittance, π·mm·mrad
$^1H^-$	ABPIS OPPIS	2	> 90%	1.0
$^2D^-$	ABPIS OPPIS	2	> 90%	2.0
$^3He^{2+}$	EBIS	1	70%	< 1
$^6Li^{3+}$	ABPIS	0.1	70%	< 1
$^{208}Pb^{30+}$	ECR	0.5	0	0.5

LEBT

Low Energy Beam Transport (LEBT) systems for both polarized light ion and non-polarized heavy ion beams have been designed with TRACE3D [4]. The light ion LEBT (see Fig. 2) is based on the BNL OPPIS LEBT design [5]. Two dipole magnets of opposite bend directions are used to keep the spin orientation of polarized ions. Detailed spin dynamics studies in the LEBT will be performed later.

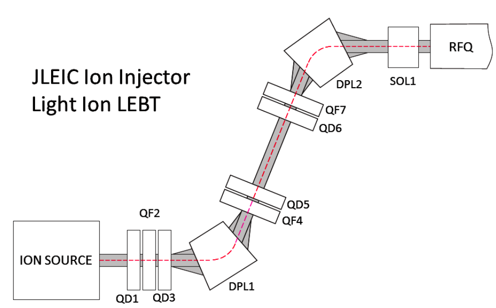

Figure 2: Light ion LEBT.

The heavy ion LEBT, presented in Fig. 3, is based on the CERN Lead Linac3 LEBT design [6]. Here two dipoles act as a mass - spectrometer separating neighbouring charge states.

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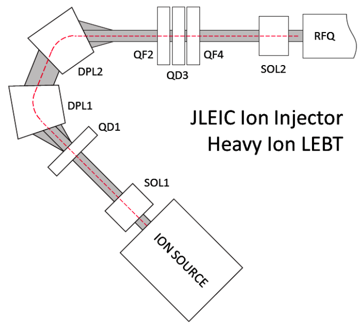

Figure 3: Heavy ion LEBT.

Light Ion RFQ

The heavy ion RFQ design would be too complex to provide both the requisite focusing strength for heavy ions and the large transverse acceptance for polarized light ion beams. It is desirable to avoid transverse losses of the deuterium $^2D^-$ beam, since these losses can cause a set of nuclear fusion reactions on the surface of the electrodes, deuterated by lost $^2D^-$ ions, resulting in their activation. Therefore, a dedicated RFQ for polarized light ion beams ($A/Z \leq 2$) is being developed.

The RFQ is based on a 4-vane resonator with magnetic coupling windows [7]. For a low duty cycle RFQ brazed or welded joints are not required for the resonator fabrication (see Fig. 4 and Fig. 5).

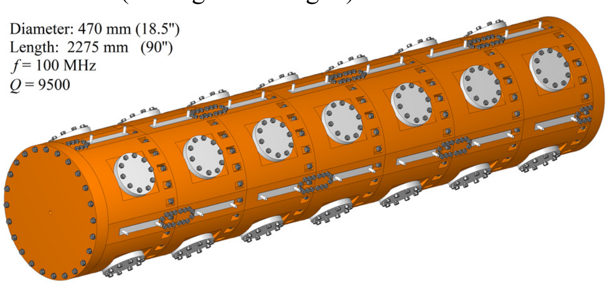

Figure 4: Resonator of the Light Ion RFQ.

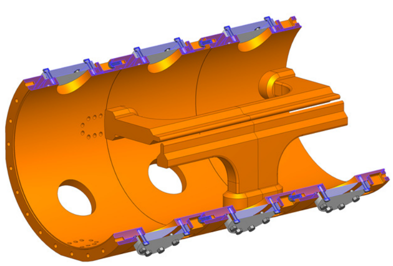

Figure 5: Tank segments and vanes of the 4-vane resonator with magnetic coupling windows for Light Ion RFQ.

At the repetition rate of 10 Hz and 0.5 ms beam pulse width the average power dissipated in the resonator walls is about 700 W. Assuming the water cooling is applied to the tank only, the steady state temperature distribution is shown in Fig. 6. It results in negligible resonator deformations (see Fig. 7). All simulation results obtained with CST STUDIO SUITE [8] are consistent with the analytical estimations.

The main design parameters of the RFQ are listed in Table 2.

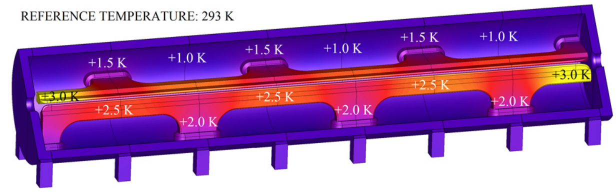

Figure 6: Temperature change steady state distribution over the Light Ion RFQ resonator.

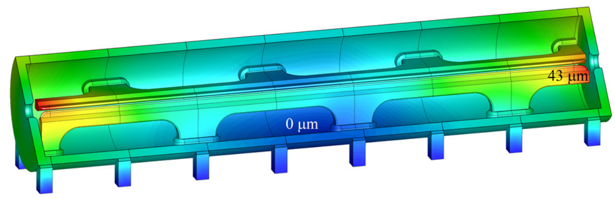

Figure 7: Deformation of the resonator, including effects of gravity, atmospheric pressure and heating.

Heavy Ion RFQ

The Heavy Ion RFQ has the same RF and mechanical design as the Light Ion RFQ, except the number of resonator segments and their changed dimensions.

About 75% of the RFQ length is used for acceleration of the bunched ion beam to the energy of 500 keV/u. Currently, this part has an electrode modulation $m = 2$ of the sinusoidal profile. We are working toward integrating a trapezoidal vane tip modulation in the acceleration section of the RFQ which will shorten the RFQ length to 4.6 m. Also, the pulsed RF power losses will be reduced from 180 kW to 150 kW.

IH-DTL

In the previous design of the linac we proposed to use either a well-known IH-DTL structure with quadrupole triplets or a 4-vane based RF quadrupole focusing DTL [2]. The first option is very efficient, but not acceptable for polarized light ion beams due to a limited transverse acceptance. The second option can provide reliable beam dynamics, but requires 2-3 times greater RF power, than IH-based structures.

Here we propose the IH-DTL structure with FODO focusing lattice [9] for the JLEIC injector as shown in Fig. 8. The focusing quadrupoles are installed inside longer drift tubes which are followed by several short drift tubes without quadrupoles. This design allows us to keep a resonator high shunt impedance, and a large acceptance for both the transverse and longitudinal phase space. The parameters of the IH-DTL sections are shown in Table 2.

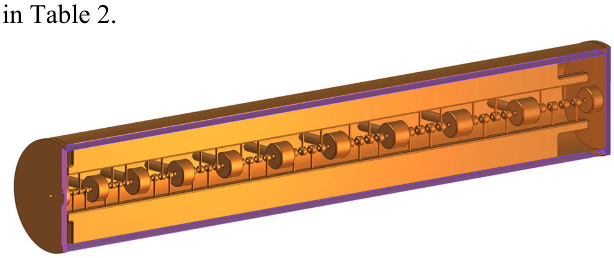

Figure 8: 3D model of the IH-1 section with FODO focusing lattice.

Table 2: Main Parameters of the Front-End Sections for $^{2}D^{-}$ and $^{208}Pb^{30+}$ Ion Beams

Parameter	Units	Light Ion RFQ	Heavy Ion RFQ	IH-1	IH-2	IH-3
Energy range	MeV/u	0.015 – 0.5	0.010 – 0.5	0.5 – 2.0	2.0 – 3.5	3.5 – 4.9
Length	m	2.0	5.6	4.3	3.5	3.4
Diameter	m	0.47	0.44	0.7	0.7	0.7
Voltage	kV	103.4	70.0	200 - 500	500	570
Aperture (R_0)	mm	7.0	3.7	12.5	12.5	12.5
Quality factor		9500	9200	18000	18000	18000
RF power losses	kW	110	180	280	400	620
Peak surface E-field	Kilpat. units	1.84	2.05	2.0	2.0	2.0
Norm. transverse emittance (90%)*	π·mm·mrad	1.47	0.35	1.62 / 0.40	1.66 / 0.41	1.66 / 0.41
Norm. longitudinal emittance (90%)*	π·ns·keV/u	4.9	4.5	4.9 / 4.5	4.9 / 4.5	4.9 / 4.5
Transmission*		99.9%	99.7%	99.8%	100%	100%
Beam current*	mA	2.0	0.5	2.0 / 0.5	2.0 / 0.5	2.0 / 0.5

* Deuterium ion beam / Lead ion beam

BEAM DYNAMICS SIMULATION

Beam dynamics simulations for the linac have been performed with the TRACK code [10] using 3D electromagnetic field distributions. Transverse RMS envelopes of the polarized deuterium and non-polarized lead beam along the injector front-end are shown in Fig. 9. Figure 10 presents the output phase-space plots [11] of the beams. Data on the beam transmission and the emittance growth in each section are listed in Table 2.

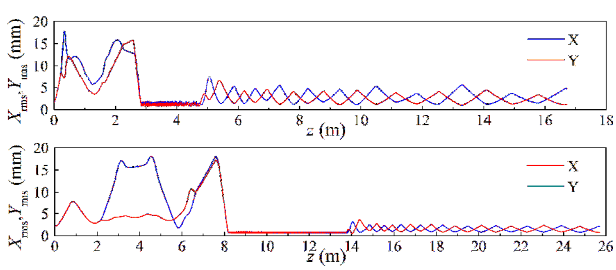

Figure 9: RMS beam envelopes along the front-end: deuterium ion beam (top), lead ion beam (bottom).

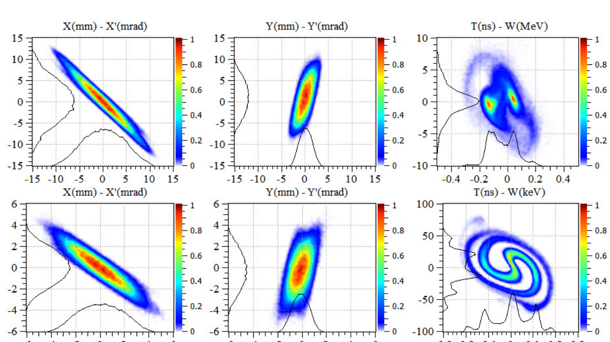

Figure 10: Output phase-space plots of the deuterium (top) and lead ion beam (bottom).

CONCLUSION

We have designed a cost-effective front-end for the SRF-based multi-ion injector linac. Both electromagnetic and beam dynamics simulations show high confidence in technical feasibility of the proposed design.

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