

DESIGN OF THE MULTI-ION INJECTOR LINAC FOR THE JLAB EIC (JLEIC)*

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Abstract

An Electron Ion Collider (EIC) is the highest priority for future U.S. accelerator-based nuclear physics facility following the completion of the Facility for Rare Isotope Beams (FRIB). Two laboratories are competing to host the future EIC: Brookhaven National Lab. (BNL) and Jefferson Lab. (JLab). The baseline design of JLab's Electron Ion Collider (JLEIC) ion complex comprises a pulsed superconducting (SC) linac injector capable of accelerating all ions from protons to lead, where proton and light ion beams can be polarized. After reviewing the design requirements for the injector linac, important design choices such as the room-temperature (RT) section design, the transition energy between the RT and SC sections and the stripping energy for heavy ions will be discussed. The design of the different linac sections will be presented as well as the results of end-to-end beam dynamics simulations for polarized deuterons and un-polarized lead ions.

INTRODUCTION

The electron-ion collider concept proposed by JLAB (JLEIC) requires a new ion accelerator complex which includes a multi-ion linac capable of delivering any ion beam from hydrogen to lead to the Booster. We have developed a design for a pulsed linac which consists of different ion sources, a room-temperature (RT) front-end, up to 5 MeV/u followed by a superconducting (SRF) section to the full linac energy. This work includes the beam dynamics and electrodynamic studies performed to design efficient and cost-effective accelerating structures for both the RT and SRF sections of the linac. The current design includes two separate RFQs one for heavy ions and one for polarized light-ion beams, and a common RT section with a special IH DTL design downstream of the RFQs. Quarter-wave and half-wave resonators are effectively used in the SRF section of the linac.

DESIGN REQUIREMENTS AND CHOICES FOR JLEIC INJECTOR LINAC

Design Requirements for JLEIC Injector Linac

The baseline design of the JLEIC ion complex [1] calls for the following requirements from the injector linac:

- Capable of accelerating all beams from protons to lead ions, including polarized light ion beams
- Deliver 280 MeV protons and 100 MeV/u lead ions Pb^{67+} for injection to the Booster, and equivalent energies for other ion beams

- Pulsed beam structure with 5-10 Hz repetition rate and 0.2 - 0.5 ms beam pulse length
- Pulsed beam current of ~ 2 mA for light ions and ~ 0.5 mA for heavy ions
- Compact and cost efficient

Important Design Choices for the Linac

In order to satisfy the design requirements listed above, the following design choices were made for the JLEIC injector linac:

- To accommodate the significantly different beam parameters from polarized light-ion and heavy-ion sources, the linac includes two separate RFQs, one for mass-to-charge ratio $A/q \leq 2$ and one for heavy ions with $A/q > 2$.
- As a consequence, two separate low-energy beam transport (LEBT) lines are required. However, this separate front-end choice allows a special LEBT design for polarized light ions to preserve polarization.
- Based on similar pulsed ion linacs [2, 3], a room-temperature (RT) section up to an energy of ~ 5 MeV/u is the most efficient and cost-effective option for the JLEIC linac, followed by a SRF section up to the full linac energy.
- A pulsed SRF linac can be more compact and cost-effective than the full RT option [4, 5]. It also offers wider acceptance and more tuning flexibility for light and heavy ion beams. In addition, taking advantage of state-of-the-art performance of quarter-wave (QWR) and half-wave (HWR) resonators [6, 7], which can deliver higher voltages in pulsed mode, the linac can be even more compact.
- In order to deliver Pb^{67+} at 100 MeV/u, the optimum stripping energy was found to be ~ 13 MeV/u, which is the energy following two QWRs modules made of 7 cavities each.

DESIGN OF THE DIFFERENT SECTIONS OF THE LINAC

Figure 1 shows the layout of the designed JLEIC injector linac with separate front-ends for light ion and heavy-ion beams, a DTL section made of three IH tanks followed by an SRF section made of three QWR cryomodules operating at 100 MHz and nine HWR cryomodules operating at 200 MHz. A stripper section for the heaviest ions is located between the second and third QWR modules.

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structure can be either brazed or bolted. For the JLEIC RFQs, we propose the brazed 4-vane window-coupled structure for both its mechanical and field stabilities [15].

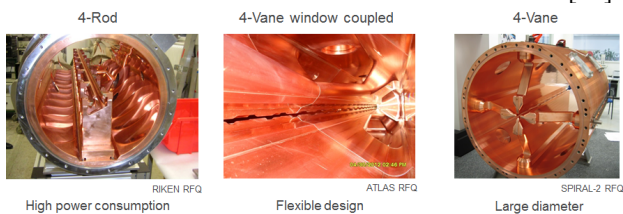


Figure 4: RFQ Design options.

DTL Section Design

During the design of the RT section [16] of the JLEIC linac, we investigated different DTL design options, see figure 5. The first was an IH structure with triplet focusing similar to the BNL EBIS injector [2]. The second option was a special DTL design with RF quadrupole focusing [17]. The third option, which was selected for the JLEIC linac, uses a FODO focusing lattice which offers a large acceptance with minimal emittance growth while preserving a good power efficiency.

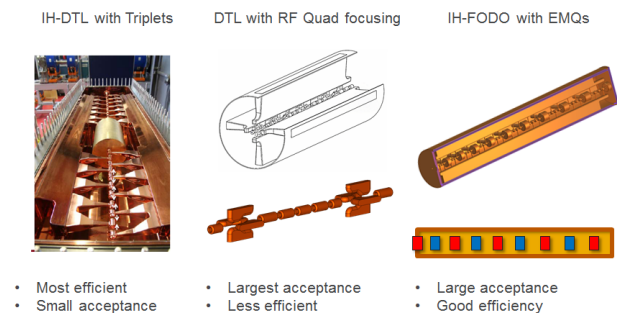


Figure 5: Design options for the DTL section of the linac.

The design parameters for the three DTL tanks required to reach 5 MeV/u energy for all ion beams are listed in Table 3. The DTL section delivers ~ 30 MV over ~ 11 m and requiring ~ 1 MW total power. A schematic of the DTL section showing the three tanks made of 19 accelerating gaps and 20 quadrupoles in a FODO arrangement is shown in Fig. 6.

Table 3: Design Parameters for the Three IH-DTL Tanks with FODO Focusing

Parameter	Units	DTL-1	DTL-2	DTL-3
Input Energy	MeV/u	0.5	2.0	3.6
Output En.	MeV/u	2.0	3.6	5.0
Accel. sections	No.	10	5	4
Length	m	4.3	3.5	3.4
RF power	kW	280	400	620



Figure 6: Layout of the DTL section made of 3 tanks including 19 accelerating gaps and 20 quadrupoles in a FODO lattice arrangement.

SRF Section Design

A schematic layout for the SRF section of the linac is shown in Fig. 7. It is made of three QWR and nine HWR cryomodules. Each cryomodule is made of seven cavities and four solenoids in the arrangement shown in Figure 8 for both the QWR and HWR modules. A stripping section for the heaviest ions is located after the second QWR module at an energy of ~ 13 MeV/u for lead ions.



Figure 7: Schematic layout of the SRF section of the JLEIC including a stripper section after the second QWR module.



Figure 8: Layouts of the QWR and HWR cryomodules each with seven cavities and four solenoids.

The design of both the QWR and HWR cavities are shown in Fig. 9 along with their electromagnetic field distributions. The corresponding RF design parameters are summarized in Table 4.

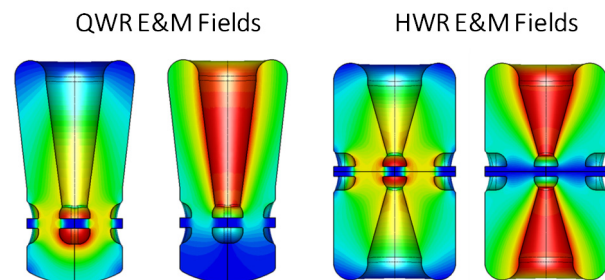


Figure 9: Geometry and electromagnetic field distributions for the QWR and HWR cavities (E-Field on the left and B-Field on the right for each cavity).

Table 4: RF Design Parameters of the QWR and HWR Cavities

Parameter	Units	QWR	HWR
Design β_{opt}	-	0.15	0.3
Frequency	MHz	100	200
Length ($\beta\lambda$)	cm	45	45
E_{peak}/E_{acc}	-	5.5	4.9
B_{peak}/E_{acc}	mT/(MV/m)	8.2	6.9
R/Q	Ω	475	256
G-factor	Ω	42	84
E_{peak} in operation	MV/m	58	52
B_{peak} in operation	mT	86	73
E_{acc}	MV/m	10.5	10.5
Voltage per cavity	MV	4.7	4.7
Cavity phases	Deg	15-30	15-30
No. of Cavities	-	21	63

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Stripper Section Design

The Pb beam is used as a reference for the design of the stripper section. The optimum stripping energy on a carbon foil to produce lead ions Pb^{67+} for injection to the JLEIC booster is about 13 MeV/u [18]. This energy maximizes the beam fraction in the desired Pb^{67+} charge state which is about 20% and minimizes the total voltage requirements for the linac up to the full-energy of 100 MeV/u for lead ions as shown in Fig. 10.

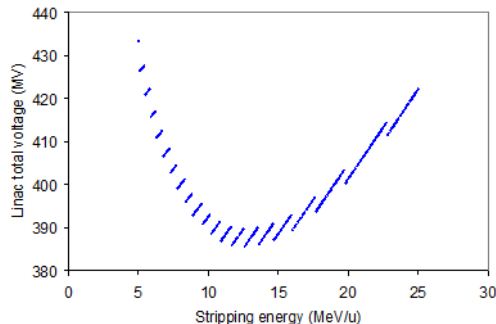


Figure 10: Total linac voltage as function of stripping energy for lead ions.

In order to separate the desired charge state from unwanted charge states and other reaction products, a chicane can be used for a straight linac option or a 180-deg bend for a folded option. Figure 11 shows a preliminary concept of a stripping chicane, where the beam is focused onto the stripper foil using a triplet and the desired charge state is separated and selected using the slits in the middle plane. A rebuncher and another triplet are used at the end of the chicane to longitudinally and transversely match the beam to the following section.

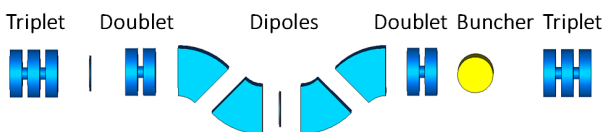


Figure 11: A possible layout for a stripping chicane to be installed between the second and third QWR cryomodules.

BEAM DYNAMICS IN THE LINAC

Beam Dynamics Design

The beam dynamics design is straightforward for the SRF section of the linac, a focusing period made of two accelerating cavities and one solenoid is the main building block. Exception is made at the end of every cryomodule where a missing cavity accounts for the extra drift space between modules where beam diagnostic devices can be installed. The general design rule is to start with a phase advance below 90-deg for the zero current beam and maintain periodic focusing by smoothly decreasing the phase advance along the linac. The accelerating voltage profile in the cavities is shown in Fig. 12. It clearly shows that the HWR covers very well the velocity range from 0.2 to 0.35 and no need for a different cavity type at the higher energies. This simplifies the overall design and fabrication of

the linac with only two cavity types, one QWR and one HWR. The proposed operating voltage per cavity of 4.7 MV which will require 9 Tesla superconducting solenoids for lead beam focusing.

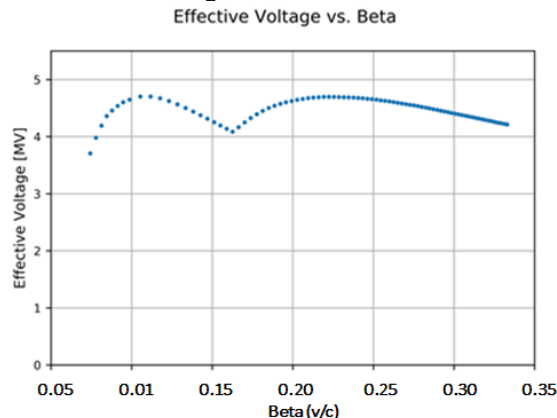


Figure 12: Effective cavity voltage as function of β along the linac showing that the HWR is fairly efficient up to the full energy of the linac.

Beam Dynamics Simulations

The results of end-to-end beam dynamics simulation in TRACK for a 2-mA polarized deuteron beam are shown in Fig. 13. The simulation starts from the ion source through the RT section, and ends with the SRF section at the full linac energy required for injection to the booster. In this case, we note $\sim 100\%$ transmission of the deuteron beam with about 30% emittance growth. Similar results were obtained for a 2-mA polarized proton beam.

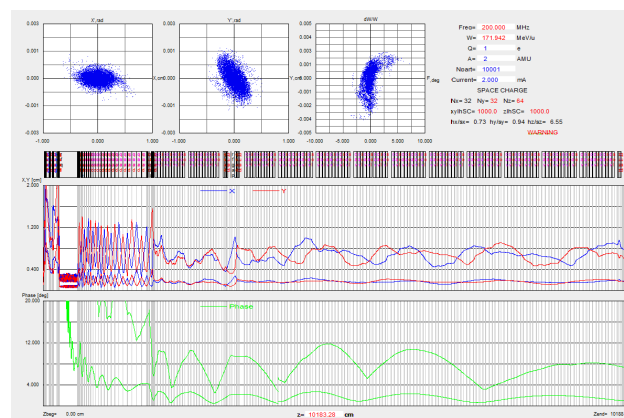


Figure 13: End-to-end beam dynamics simulation results for deuteron beam with $\sim 100\%$ transmission through the whole linac.

For lead ions, the beam dynamics simulation results are shown in Fig. 14.

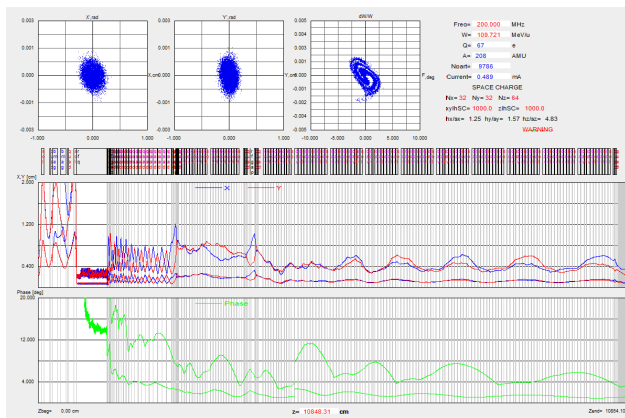


Figure 14: End-to-end beam dynamics simulation results for lead ions with beam stripping at ~ 13 MeV/u.

SUMMARY

We have designed a pulsed multi-ion injector linac that satisfies all the requirements for the baseline design of the Jefferson Lab EIC concept (JLEIC). The design is based on a 5 MeV/u room-temperature section followed by an SRF linac using QWRs and HWRs taking advantage of the most recent developments of similar structures at Argonne.

ACKNOWLEDGEMENT

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Table 5 summarizes the beam parameters from the linac for protons, deuterons and lead ions.

Table 5: Important Beam Parameters in the Linac for Protons, Deuterons and Lead Ions

Parameter	H-	D-	Pb ³⁰⁺ → 67+
Input Transverse emittance (π .mm.mrad)	2.0	2.0	0.5
Output energy (MeV/u)	299	172	110
Transmission (%)	99.7	99.9	97.9
Output Transverse emittance (π .mm.mrad)	3.0	3.0	1.0
Output Longitudinal emittance (π .keV/u.ns)	7.5	7.5	7.0
Beam energy spread (%)	0.1	0.1	0.1

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