DESIGN AND BEAM DYNAMICS STUDIES OF A MULTI-ION LINAC INJECTOR FOR THE JLEIC ION COMPLEX*

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Abstract

The electron-ion collider (JLEIC) being proposed at JLab requires a new ion accelerator complex which includes a linac capable of delivering any ion beam from hydrogen to lead to the booster. We are currently developing a linac which consists of several ion sources, a normal conducting (NC) front end, up to 5 MeV/u, and a SC section for energies > 5 MeV/u. This design work is focused on the beam dynamics and electrodynamics studies performed to design efficient and cost-effective accelerating structures for both the NC and SC sections of the linac. Currently, we are considering two separate RFQs for the heavy-ion and light-ion beams including polarized beams, and different types of NC accelerating structures downstream of the RFQ. Quarter-wave and half-wave resonators can be effectively used in the SC section.

INTRODUCTION

Recently, we have proposed a pulsed multi-ion linac with a normal conducting (NC) front-end up to 5 MeV/u and a superconducting (SC) section for higher energies as an injector for the JLab electron-ion collider (JLEIC) [1]. Separate radio-frequency quadrupole (RFQ) sections for heavy (A/Z ≤ 7) and light (A/Z ≤ 2) ions (polarized or non-polarized) and high-performance superconducting quarter-wave and half-wave coaxial resonators make the injector linac capable of effectively accelerating any ion species from hydrogen (up to 135 MeV) to lead (up to 44 MeV/u). This linac can be used for other purposes during the idle time of the booster ring; for example, isotope production.

LINAC LAYOUT

A block-diagram of the injector linac is shown in Figure 1 and the basic design parameters are listed in Table 1. The JLEIC ion linac will use both heavy and light ion sources including polarized H^+, $^2H^+$, $^3He^{2+}$, $^7Li^{3+}$ ion sources. The emittance of polarized beams is usually larger than the emittance of heavy-ion beams. For this reason, we propose to build two separate RFQs.

RFQ

Both RFQs operate at 100 MHz and accelerate ions up to 500 keV/u. Both of them produce low longitudinal emittance while the light-ion RFQ has larger transverse acceptance which is required for polarized light-ion beams.

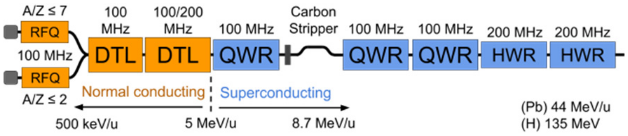

Figure 1: A schematic drawing of the JLEIC ion linac.

Table 1: Main Parameters of the Linac

Parameter	Value	Units
Ion species	H^+ to Pb	
Fundamental frequency	100	MHz
Kinetic energy of protons & lead ions	135&44	MeV/u
Maximum pulse current		
Light ions (A/q ≤ 2)	2	mA
Heavy ions (A/q > 2)	0.5	mA
Pulse repetition rate	up to 10	Hz
Pulse length		
Light ions (A/q ≤ 2)	0.5	ms
Heavy ions (A/q > 2)	0.25	ms
Maximum pulsed beam power	260	kW
# of QWR cryomodules	3	
# of HWR cryomodules	2	
Total length	~55	m

A higher injection energy into the light-ion RFQ allows us to mitigate beam space charge effects. Parameters of the RFQs are presented in Table 2. There are several possible electromagnetic and mechanical designs for the RFQ resonator such as a four-rod structure, a compact 4-vane RFQ resonator with magnetic coupling windows [2, 3] and the so-called "4-ladder" structure [4].

DTL

The drift tube accelerating section (DTL) is conceived to accelerate any ion species up to 5 MeV/u for injection into the superconducting part of the linac. We are considering either IH-DTL with triplet focusing [5, 6] or a spatially-periodic radio-frequency quadrupole focusing structure (see Figure 2) [7]. Both accelerating structures are highly efficient in this energy range, especially in pulsed

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*This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract DE-AC02-06CH11357. This research used resources of ANL's ATLAS facility, which is a DOE Office of Science User Facility.

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ISBN 978-3-95450-178-6

Table 2: Main Parameters of the RFQs

Parameter	**Units**	**Heavy-ion RFQ**	**Light-ion RFQ**
Frequency	MHz	100	
Energy range	keV/u	10 - 500	15 - 500
Highest A/q		7	2
Length	m	5.6	2.0
Average radius	mm	3.7	7.0
Voltage	kV	70	103
Transmission	%	99	99
Quality factor		6600	7200
Pulsed RF power	kW	210	120
Output long. emittance (Norm., 90%)	π keV/u ns	4.5	4.9

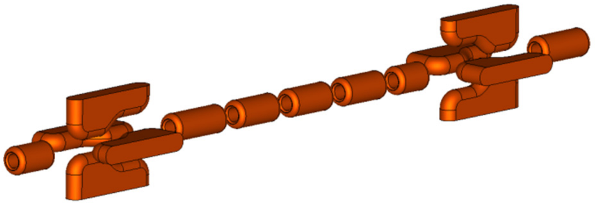


Figure 2: Spatially-periodic RF quadrupole focusingr channel.

linacs. The IH-DTL structure is a proven option as it is used in recently built heavy-ion injectors. The RF focusing DTL (Figure 2) provides similar real-estate accelerating gradient while avoiding significant longitudinal emittance growth.

The peak surface electric field assumed for the DTL design is ~2.5 Kilpatrick units, which is compatible with the pulsed operational mode of the injector [8]. Estimated pulsed RF power for the first DTL tank is 900 kW and 3 MW for the second one.

SC Section

The ion beams will be subsequently accelerated by the SRF section of the linac which comprises two different types of accelerating cavities to cover the velocity range from 0.1c to 0.5c where c is the speed of light. The QWRs and HWRs operating at 100 MHz and 200 MHz respectively are similar to those that have been developed recently at ANL for the ATLAS upgrade and the FNAL PIXE project. Photos of the QWR and HWR resonators developed and successfully operated at ANL are shown in Figure 3 and 4. Based on our experience, we propose to operate the JLEIC linac at peak surface fields up to ~86 mT and ~58 MV/m. In the low duty-cycle pulsed operating regime, these fields can be readily achieved and maintained in operation. Operating in pulsed mode reduces the dynamic heat load to a level where the static load dominates our cryogenic losses. Because of this we are planning on operating at 4.5 K to reduce the overall power requirements for the cryogenic system

The linac comprises 35 SC cavities housed in 5 cryomodules, with the RF parameters listed in Table 2. The cavity parameters were approximated from previously built QWRs and HWRs and refined with MWS simulations [9].

Figure 3: 72.75 MHz quarter wave resonator.

A dog-leg magnet system is foreseen after the stripping foil to dump unwanted charge states in a designated area. The economic acceleration of lead ions to 44 MeV/u requires a stripper in the linac with a stripping energy of ~8.7 MeV/u. The stripping efficiency of lead ions to the most abundant charge state 62+ is 17.5%. The linac can be rephased to accelerate any ion from proton to lead. Though this linac was originally designed to provide optimal voltage gain for lead ions, due to the wide velocity acceptance of the proposed cavities, lighter ions can be accelerated to higher velocities. Figure 5 shows the cavity effective voltage for lead ions and protons as a function of beam energy.

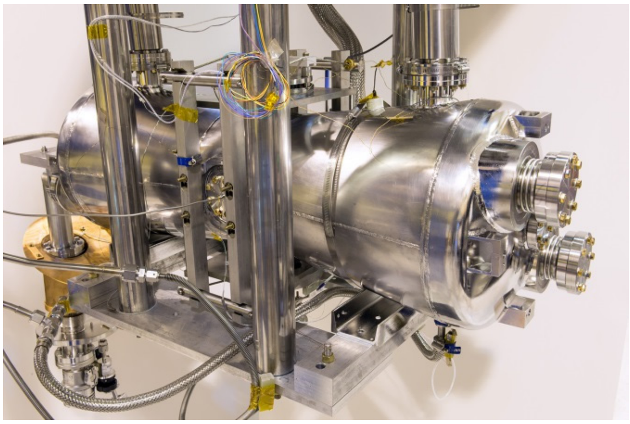


Figure 4: 162.5 MHz half wave resonator.

BEAM DYNAMICS

Beam dynamics simulations for the linac have been performed with the TRACK code [10] using 3D electromagnetic field distribution. The MEBT dipoles and mass separator after the first cryomodules as well as the stripper effects are not yet included in the simulations.

Transverse RMS envelopes of the beam along the injector linac with RF focusing structure are shown in Figure 6. Total transmission of both light and heavy ion beams are kept above 98% with some controlled losses in the RFQ to

ISBN 978-3-95450-178-6

Table 2: Design Parameters of SRF Resonators for JLEIC Ion Linac

Parameter	Units	QWR	HWR
β_{OPT}		0.15	0.30
f	MHz	100	200
Length ($\beta_{OPT}\lambda$)	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	Ω	42	84
E_{PEAK}	MV/m	57.8	51.5
B_{PEAK}	mT	86.1	72.5
E_{ACC}	MV/m	10.5	10.5
Phase	deg	-20	-15
Number of cavities		21	14

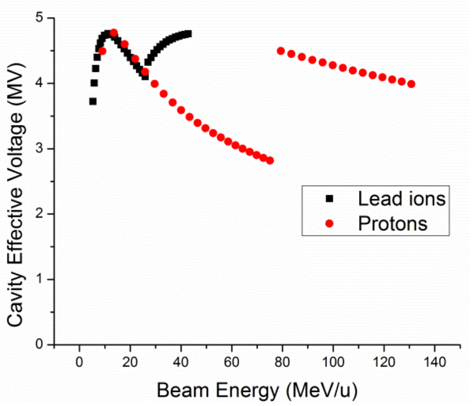
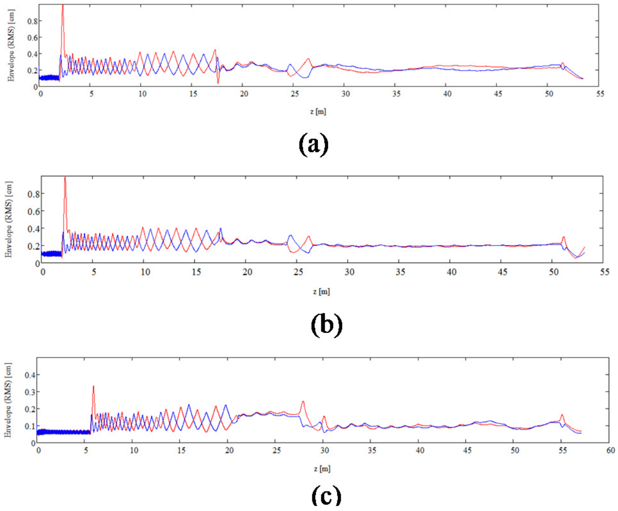


Figure 5: Cavity effective voltage as a function of beam energy.



(a)

(b)

(c)

Figure 6: Beam RMS transverse envelopes along the linac: (a) – H^+, (b) – $^2H^+$, (c) – $^{208}Pb^{62+}$.

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ISBN 978-3-95450-178-6