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BEAM FORMATION IN THE ALTERNATIVE JLEIC ION COMPLEX

B. Mustapha*† and J. Martinez-Marin, Argonne National Laboratory, Argonne, IL
V. Morozov, F. Lin, Y. Derbenev and Y. Zhang, Jefferson Lab, Newport News, VA

Abstract

The proposed alternative design approach for the JLab-EIC (JLEIC) ion complex uses a more compact linac and pre-booster, and consolidates the electron storage ring (e-ring) as a large booster for the ions. Following a parameter study showing the feasibility of this design approach, we have adapted the e-ring lattice by adding RF sections to accelerate ion beams. In this study, we focus on the transverse beam formation for protons and lead ions from the ion source to collision point including the linac, pre-booster, e-ring and collider ring. Effects such as stripping injection, space charge, intra-beam scattering and beam cooling determine the total charge accumulated in each ring and the final luminosity of the collider

ALTERNATIVE JLEIC ION COMPLEX

The motivations and description of the proposed alternative design approach for the JLEIC ion complex has been presented elsewhere [1,2]. We briefly mention the following proposed changes from the baseline design [3]:

- The 280 MeV SRF linac is replaced with a more compact cost-efficient 130-MeV design [4].
- The 8 GeV figure-8 booster is replaced with a 3-GeV octagonal pre-booster [5]. The spin dynamics in the non-figure-8 pre-booster have been studied [6].
- Use the electron storage ring (e-ring) as large booster for the ions up to 16 GeV/u.
- With 16 GeV/u injection energy, the collider ring could be upgraded to ≈250 GeV with SC magnets.

Figure 1 shows a possible layout of the alternative ion complex.

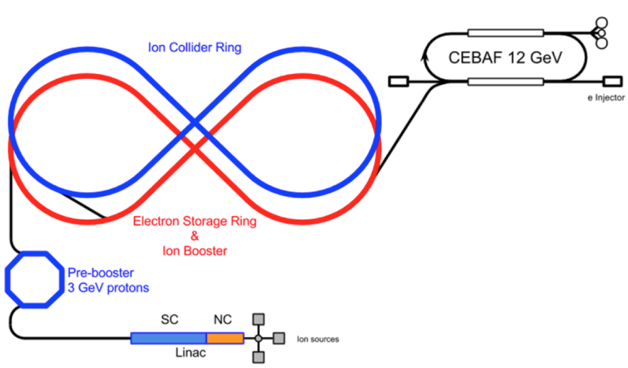

Figure 1: Layout of the alternative JLEIC design.

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† Corresponding author: brahim@anl.gov

Table 1: Transverse RMS Normalized Beam Emittance throughout the Accelerator Chain [π-mm-mrad]

Beam	Proton	Lead
Emittance at the ion source	0.5	0.13
Growth factor in the Linac	2	1.5
Emittance at the end of the Linac	1	0.2
Growth factor at Pre-booster injection	3	15
Emittance in Pre-Booster	3	3
Cooling factor in Pre-Booster: None or cooling only to preserve emittance	1	1
Emittance at injection to Electron ring	3	3
Cooling factor in Electron Ring: DC cooling at an energy of ≈8 GeV/u	0.33	0.33
Emittance at injection to Collider ring	1	1
Cooling factor in Collider Ring: Strong BB cooling at 20-100 GeV/u	0.33	0.33
Emittance at Collision point	0.3	0.3

GENERAL BEAM PARAMETERS

The most important parameters for beam formation are the transverse emittance, the energy spread and the bunch length. Here we focus mainly on the transverse beam parameters while assuming reasonable values for the longitudinal ones. More detailed longitudinal beam dynamics will be the subject of a future study. Table 1 presents the evolution of the transverse beam emittance along the accelerator chain. Reasonable assumptions are made for emittance growth in the linac and at injection to the pre-booster, as well as for emittance reduction by cooling in the rings. Longitudinally, a 0.7 rf bucket filling factor is assumed at injection into each of the rings.

PROTON BEAM FORMATION

Proton Beam Requirements

Starting from the stored beam current in the collider ring required to reach an e-p collision luminosity of 10^{34} cm^{-2}s^{-1}, we can determine the proton beam requirements at the different accelerator stages, listed in Table 2.

Proton/H$^-$ Beam Parameters in the Linac

For polarized protons/deuterons, negatively charged H$^-$/D$^-$ are injected and accelerated in the linac. The proton/H$^-$ beam parameters in the linac are listed in Table 3.

We note that only a quarter of the 0.5ms linac pulse is required to fill the pre-booster. Therefore the linac current

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Table 2: Proton Beam Requirements at Different Stages

Parameter	Value
e-p collision luminosity [cm^{-2}s^{-1}]	>10^{34}
Electron beam current in collider [A]	3
Proton beam current in collider [A]	0.5
Collider & E-ring circumference [m]	2250
Proton revolution period at 100 GeV [µs]	7.5
Required stored charge in collider [µC]	3.76
Pre-Booster ring circumference [m]	120
E-ring harmonic vs. Pre-Booster	18
Pre-Booster to E-ring injection eff. [%]	100
Required stored charge in Pre-Booster [µC]	0.21
Linac to Pre-Booster injection eff. [%]	90
Required beam charge from Linac [µC]	0.23
Design Linac pulse current [mA]	2
Linac pulse length to fill Pre-Booster [ms]	0.12

Table 3: Proton/H$^-$ Beam Parameters in the Linac

Parameter	Value
Injection energy from the source [keV]	25
Linac output energy [MeV]	130
Operating frequency [MHz]	100
Pulse length [ms]	0.5
Pulse current [mA]	2
Pulse charge [µC]	1
Particles per pulse	6.25×10^{12}
Pulse repetition rate [Hz]	5-10
Linac Transmission [%]	>95
Pulse length to fill Pre-Booster [ms]	0.12
Number of pulses to fill Pre-Booster	1
Number of bunches to fill Pre-Booster	12000

for polarized protons and light ions could be reduced from 2 mA to 0.5 mA, hence reducing the required RF power.

Proton Beam Parameters in the Rings

The proton beam parameters from injection to the Pre-Booster, to extraction to the E-ring to end of acceleration in the collider ring are listed in Table 4.

The injection to the pre-booster is a charge-exchange injection for polarized protons and deuterons with an estimated 90% efficiency. The injection from pre-booster to e-ring and from e-ring to collider ring are simple bucket-to-bucket transfer injection with near 100% efficiency. The small pre-booster reduces the required stored charge in the ring and consequently the space charge (SC) tune shift. In all rings, the SC tune shift is below the 0.15 design limit adopted by the JLEIC project.

Table 4: Proton Beam Parameters in the Different Rings: Pre-Booster, E-ring and Collider Ring

Parameter/Ring	Pre-Booster	Booster: E-Ring	Collider Ring
Inj. energy [GeV]	0.13	3	16
End energy [GeV]	3	16	100
Circumference [m]	120	2250	2250
Harmonic	1	18	18
Injection efficiency	90	100	100
Bunch charge [µC]	0.21	0.21	0.21
Ions per bunch [10^{12}	1.32	1.32	1.32
RMS norm. emittance [π-mm-mrad]	3	3	1
Bunch length [m]	84	84	84
SC tune shift at inj.	0.122	0.083	0.013
RF freq. at inj. [MHz]	1.21	2.322	2.394
RF freq. at end [MHz]	2.43	2.394	2.398
RF period at end [µs]	0.41	0.42	0.42
Avg. current at end [A]	0.51	0.5	0.5

Table 5: Proton and Electron Beam Parameters at Collision

Beam	Proton	Electron
Beam Energy [GeV]	100	5
Beam Current [A]	0.5	3
Collision frequency [MHz]	476	
Particles per bunch	6.6×10^{9}	3.9×10^{10}
Bunch RMS length [cm]	1	1
Normalized transverse RMS emittance, assumed symmetric [π-mm-mrad]	0.3	24
Beta function at collision point, $\beta^\star$, assumed symmetric [cm]	3	3
Hourglass effect – reduction factor	0.87	
Collision luminosity [cm^{-2}s^{-1}]	1.1×10^{34}	

Electron-Proton Collision Parameters

Following the final acceleration in the collider ring, the proton beam is split into smaller bunches for a collision frequency of 476 MHz. Table 5 lists the proton and electron beam parameters at collision as well as the expected luminosity for 45 GeV CM energy.

LEAD ION BEAM FORMATION

Lead Ion Beam Requirements

From the stored beam current in the collider ring required to reach an e-Pb collision luminosity exceeding 10^{32} cm^{-2}s^{-1}, we can determine the Pb beam requirements at the different accelerator stages, listed in Table 6.

Lead Beam Parameters in the Linac

The Pb beam parameters in the injector linac are listed in Table 7.

We should mention that the linac peak design current of 0.5 mA is limited by the ion source for a Pb^{30+} beam. The

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Table 6: Lead Ion Beam Requirements at Different Stages

Parameter	Value
e-Pb collision luminosity [$cm^{-2}s^{-1}$]	$>10^{32}$
Electron beam current in collider [A]	3
Lead beam current in collider [A]	0.5
Collider & E-ring circumference [m]	2250
Pb beam revolution period at 40 GeV/u [μs]	7.5
Required stored charge in collider [μC]	3.76
Pre-Booster ring circumference [m]	120
E-ring harmonic vs. Pre-Booster	18
Pre-Booster to E-ring injection eff. [%]	75
Charge state in E-ring [e]	82
Charge state in Pre-Booster [e]	67
Required stored charge in Pre-Booster [μC]	0.23
Linac to Pre-Booster injection eff. [%]	70
Required beam charge from Linac [μC]	0.33
Stripping efficiency to Pb^{67+} in Linac [%]	20
Charge state at the ion source [e]	30
Required beam charge from the source [μC]	0.75
Design Linac pulse current [mA]	0.5
Linac pulse length to fill Pre-Booster [ms]	1.5
Design Linac pulse length for Pb [ms]	0.25
Required no. of pulses to fill Pre-Booster	6

Table 7: Lead Ion Beam Parameters in the Linac

Parameter	Value
Injection energy from the source [keV/u]	20
Linac output energy [MeV/u]	40
Operating frequency [MHz]	100
Pulse length [ms]	0.25
Pulse current before stripping [mA]	0.5
Charge state before stripping [e]	30
Charge state after stripping [e]	67
Stripping efficiency at 13 MeV/u [%]	20
Pulse current after stripping [mA]	0.22
Pulse charge after stripping [μC]	0.056
Pb67+ ions per pulse	5.2×10^9
Pulse repetition rate [Hz]	5-10
Linac Transmission [%]	>95
Required charge to fill Pre-Booster [μC]	0.33
Pulse length to fill Pre-Booster [ms]	1.5
Number of pulses to fill Pre-Booster	6
Number of bunches to fill Pre-Booster	150000

beam is stripped to Pb^{67+} in the middle of the linac for more efficient acceleration in the SRF section. Six linac pulses are required to fill-up the pre-booster with the required charge. The linac repetition rate can be adjusted in the design range as needed by the pre-booster cycle.

Lead Beam Parameters in the Rings

The lead ion beam parameters in the rings, from injection to Pre-Booster to end of acceleration in the Collider ring, are listed in Table 8.

Table 8: Lead Ion Beam Parameters in the Different Rings: Pre-Booster, E-ring and Collider Ring

Parameter/Ring	Pre-Booster	Booster: E-Ring	Collider Ring
Inj. energy [GeV/u]	0.04	0.61	16
End energy [GeV/u]	0.61	16	40
Circumference [m]	120	2250	2250
Harmonic	1	18	18
Charge state [e]	67	82	82
Injection efficiency [%]	70	75	100
Bunch charge [μC]	0.23	0.21	0.21
Ions per bunch [1010]	2.1	1.6	1.6
RMS norm. emittance [π-mm-mrad]	3	3	1
Bunch length at inj. [m]	84	84	84
SC tune shift at inj.	0.086	0.256	0.005
RF freq. at inj. [MHz]	0.74	1.844	2.394
RF freq. at end [MHz]	2.03	2.394	2.398
RF period at end [μs]	0.49	0.42	0.42
Avg. current at end [A]	0.47	0.5	0.5

Table 9: Pb and Electron Beam Parameters at Collision

Beam	Pb^{82+}	Electron
Beam Energy [GeV/u, GeV]	40	5
Beam Current [A]	0.5	3
Collision frequency [MHz]	476	
Particles per bunch	8.0×10^7	3.9×10^{10}
Bunch RMS length [cm]	1	1
Normalized transverse RMS emittance, assumed symmetric [π-mm-mrad]	0.3	24
Beta function at collision point, $\beta^\star$, assumed symmetric [cm]	2	2
Hourglass effect – reduction factor	0.87	
Collision luminosity [$cm^{-2}s^{-1}$]	1.1×10^{32}	

The Pb^{67+} injection from the linac to the pre-booster is a multi-turn injection with painting in all planes with an estimated efficiency of ~70%. The beam is then fully stripped to Pb^{82+} before injection to the e-ring with an estimated efficiency of ~75%. The injection from the e-ring to the collider ring is a bucket-to-bucket transfer with ~100% efficiency. We note that the SC tune shift at injection to the e-ring exceeds the adopted design limit of 0.15. While this is still below the more standard operational limit of 0.3, it's a potential bottleneck for this alternative design, suggesting the need for a higher energy pre-booster. A 5-GeV pre-booster with ~200 m circumference might be a good solution.

Electron-Lead Collision Parameters

Following the final acceleration in the collider ring, the Pb beam is split into smaller bunches for a collision frequency of 476 MHz. Table 9 lists the Pb and electron beam parameters at collision as well as the expected luminosity for the case of ~450 GeV CM energy.

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SUMMARY AND FUTURE WORK

Preliminary beam formation schemes have been devised for both protons and lead ions in the alternative JLEIC ion complex satisfying the projected goal luminosities. The small pre-booster ring lowers the required stored charge reducing both the space charge tune shift and the beam current requirement in the linac. The peak linac current of 2 mA for protons and light ions could be safely reduced to 0.5 mA instead, which also reduces the linac RF power requirements. For the e-ring as large ion booster, there seems to be a space charge limit that will require further study and may need raising the pre-booster energy. A beam optics solution with only RT magnets is being investigated for the e-ring to reach 16 GeV/u for all ions to ensure above transition-energy injection to the collider ring. More detailed studies of the longitudinal and transverse beam dynamics are planned in the future to characterize the actual design limits. The time sequence of beam formation through the whole accelerator chain including accumulation, ramping and beam cooling will be also investigated.

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