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A HIGH-ENERGY DESIGN FOR JLEIC ION COMPLEX*

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Abstract

A recent assessment of the scientific merit for a future Electron Ion Collider (EIC) in the US, by the National Academy of Sciences (NAS), found that such a facility would be unique in the world and that it would answer science questions that are compelling, fundamental, and timely. This assessment confirmed the recommendations of the 2015 Nuclear Science Advisory Committee (NSAC) for an EIC with highly polarized beams of electrons and ions, sufficiently high luminosity and sufficient, and variable, center-of-mass energy. The baseline design of Jefferson Lab Electron-Ion Collider (JLEIC) has been recently updated to 100 GeV center-of-mass (CM) collision energy, corresponding to 200 GeV proton energy. We here present a high-energy design for the JLEIC ion complex, as part of the alternative design approach. It consists of a 150 MeV (~ 40 MeV/u for Pb) injector linac, a 6-GeV (~ 1.5 GeV/u for Pb) non figure-8 pre-booster ring and a 40-GeV proton (~ 16 GeV/u for Pb) large ion booster which could also serve as electron storage ring (e-ring). The energy choice in the accelerator chain is beneficial for future upgrade to 140 GeV center of mass energy. The large ion booster is designed with the same shape and size of the original e-ring and does not preclude the option of having separate electron and ion rings by stacking them in the same tunnel as the ion collider ring. The ion collider ring design is the same as for the baseline design, which was updated to 200 GeV proton energy with 6 Tesla superconducting magnets.

INTRODUCTION

As discussed in previous work [1], the main motivation for the alternative design approach for the JLEIC ion complex is not to replace the baseline design. It is rather to investigate alternative options for the different components of the ion complex that have the potential of lowering the cost, mitigating a risk, and to prepare for possible staging or future upgrades of the project. For example, we list the options we investigated for the low-energy design (65-GeV CM), which we are now updating for the high-energy design (100-GeV CM and higher):

- Reducing the footprint and cost of the ion complex
  - i. A more compact injector linac: ~ 135 MeV instead of 280 MeV
  - ii. A small pre-booster ring: 3 GeV circular ring instead of 8-GeV figure-8 booster
  - iii. Consolidate the electron storage ring as large booster for the ions
- Lowering the overall risk
  - i. Use room-temperature (RT) magnets whenever possible
  - ii. Avoid transition crossing for all ions, which is an operational risk
- Staging or upgrading the project
  - i. Design an ion injector system compatible with 65, 100 and 140 GeV CM energies
  - ii. Upgrade only the ion collider ring with stronger magnets

ALTERNATIVE 65-GEV DESIGN REVIEW

As part of the 65-GeV alternative design, a shorter more compact lower energy injector linac was designed with higher performance superconducting cavities [2]. This was possible due to the recent development at ANL for quarter-wave (QWR) and half-wave (HWR) resonators operating at high voltage (~ 3 MV per cavity) in CW mode [3, 4]. The JLEIC linac requires pulsed mode operation, where 50% higher voltage can be achieved. Similarly, a design for a 3-GeV pre-booster ion ring with RT magnets [5], was developed to serve as pre-booster before injecting the beam into the large booster, which is nothing but the electron storage ring modified to also serve as ion accelerator [6]. Spin preservation and correction schemes were investigated for both protons and deuterons in the 3-GeV pre-booster [7], which is circular and not figure-8. Finally, an ion beam formation scheme through the alternative accelerator chain, from the ion source to the collision point, was proposed and carefully studied in order to ensure the high beam collision luminosity of 10^{34} cm^{-2} s^{-1} or higher [8]. In summary, the lower energy linac seems reasonable for both protons and heavy-ion injection into a small lower-charge pre-booster ring. However, a higher energy pre-booster of ~ 5-GeV maybe needed to lower the space charge tune shift for heavy ions in the large booster (e-ring). The e-ring as large ion booster seems feasible from space and beam optics point of view.

CURRENT 100-GEV BASELINE

A schematic layout of the current high-energy baseline line design [9] is shown in Fig. 1.

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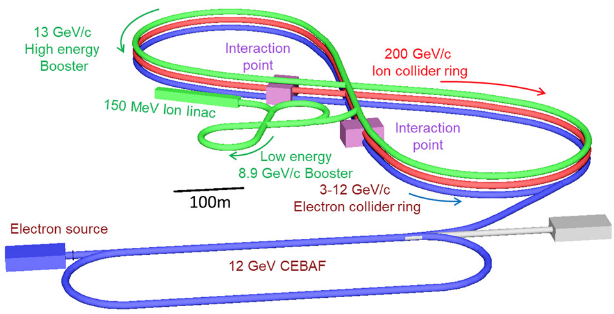

Figure 1: Schematic of current JLEIC baseline design.

We highlight in particular the recent changes adopted from the alternative design approach presented above:

- A lower energy shorter linac for 150 MeV protons (~ 40 MeV/u Pb ions).
- Two boosters approach: Low-energy booster up to 8 GeV and a high-energy one up to 13 GeV protons.
- Room temperature magnets used in the boosters, with superconducting magnets only in the collider ring.

ALTERNATIVE DESIGN APPROACH FOR 100-GEV OR HIGHER

A schematic layout for the proposed alternative design approach is shown in Fig. 2.

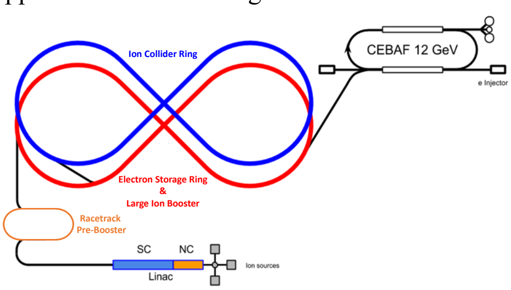

Figure 2: Schematic of the alternative high-energy JLEIC.

In addition to the compact short linac, this design includes:

- A racetrack pre-booster for 5 GeV protons or higher, where spin polarization can be preserved using Siberian snakes.
- A higher energy large booster capable of 16 GeV/u for all ion beams, which is beneficial for 100 GeV CM energy and future upgrades.
- The large ion booster can also serve as electron storage ring.

We note that the electron ring in the baseline design cannot be used as booster for ions. Therefore, a new ion booster design is proposed, which is retrofitted to also serve as electron ring.

Pre-Booster Design

Two racetrack design options were investigated for the pre-booster; one for 6-GeV and the other for 8-GeV proton beam energy. Taking into account the following considerations:

- Ring circumference and spin preservation with Siberian snakes,
- Beam size at extraction and aperture in the large booster,
- Space charge tune shifts for protons and heavy ions,
- Beam formation (cycles) and cooling requirements

we selected the smaller lower energy ring option. Table 1 lists the design parameters for the proposed 6-GeV ring while Fig. 3 shows the proton beam optics.

Table 1: Design Parameters for the 6-GeV Racetrack Pre-booster Ring

Parameter	Value
Circumference, m	256.1
Maximum β_x, m	10.6
Maximum β_y, m	11.1
Max. dispersion, m	1.04
Tune in X	9.45
Tune in Y	9.36
γ	7.39
γ_{tr}	7.91
Quad half aperture, cm	5
Quad. Max. grad., T/m	20
Quad. Length in arc, m	0.56
Dipole max. field, T	1.6
Dipole Length, m	1.5
Cell length, m	6.74

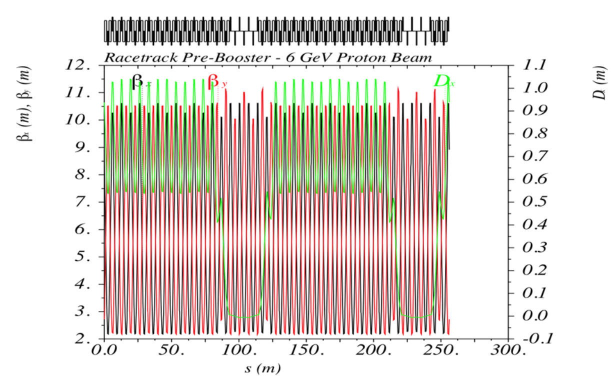

Figure 3: Proton beam optics in the 6-GeV racetrack pre-booster ring.

New Large Booster / Electron Ring Design

The design goals and constraints for the new large booster are:

- Avoid transition energy crossing for all ions
- All magnets are room-temperature with maximum field of 1.6 T for dipoles and 20 T/m for quads.
- To fit in the same tunnel, the shape and size (figure-8 and crossing angle) of the ring are constrained by the ion collider ring.
- Can be used as electron storage ring.

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The proposed design energy is ~ 16 GeV/u for all ions. To avoid transition crossing, all ion beams are extracted from the large booster with $\gamma < \gamma_{\text{large-booster}} \sim 19$ and injected into the collider ring with $\gamma > \gamma_{\text{collider-ring}} \sim 13$. Since the radius and size of the ring is constrained by the collider tunnel, a higher γ_{tr} for the large booster, can only be achieved by stronger beam focusing. To provide the required focusing, three different options were investigated:

- Combined function magnets
- Long quadrupoles in FD lattice arrangement, twice as long as the baseline e-ring quads.
- Quadrupole doublets in FFDD lattice, which may allow the use of existing shorter quads.

More details on the different options can be found in [10]. In the following, we present the long quads option, which is the most straightforward and easier to implement. Table 2 lists the design parameters for this option.

Table 2: Design Parameters for the New Large Ion Booster with Long Quadrupoles

Parameter	Value
Circumference, m	2250.4
Maximum β_x, m	85
Maximum βy, m	73
Max. dispersion, m	1.15
Tune in X	51.2
Tune in Y	45.6
γ	18.2
γ_{tr}	18.6
Quad half aperture, cm	5
Quad. Max. grad., T/m	20
Quad. Length in arc, m	1.35
Dipole max. field, T	1.6
Dipole Length, m	5.4
Cell length, m	17.1

Figure 4 shows the layout of the new large booster / e-ring design with insertions for ions and electrons. Figure 5 shows the beam optics for a16 GeV/u Pb^{82+} ions, while Fig. 6 shows the beam optics in the same ring for 12 GeV electrons.

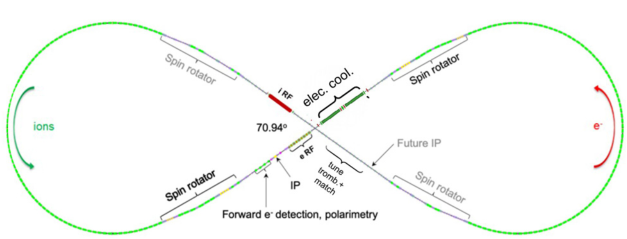

Figure 4: Layout of the new large booster / e-ring with insertions for electrons and ions.

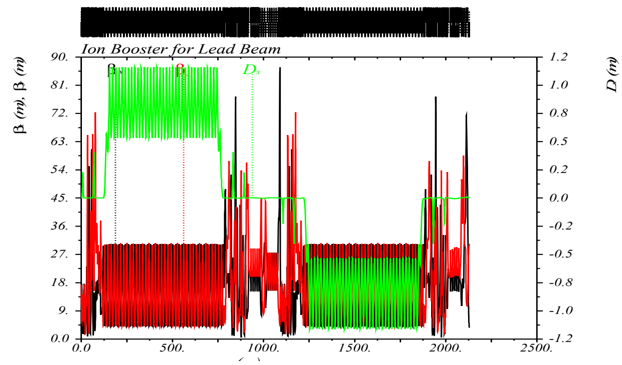

Figure 5: 16 GeV/u lead ion beam optics in the new large booster design with long quads.

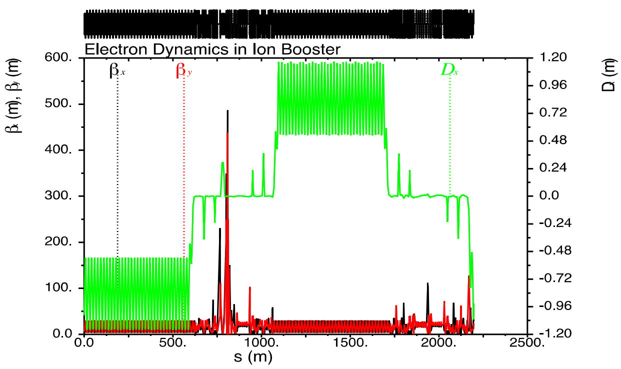

Figure 6: 12 GeV electron beam optics in the new large ion booster, also used as electron ring.

SUMMARY

In summary we can conclude that:

- The first booster (pre-booster) can be a small 6-GeV racetrack with all RT magnets and ~ 250 m circumference. It will require Siberian snakes to avoid spin resonances for proton and helium beams.
- The large booster can be designed for up to 16 GeV/u for all ions in the same footprint as the baseline e-ring will all RT magnets. The higher energy is beneficial for 100-GeV CM and future upgrade to 140-GeV.
- The proposed large booster design can be used as electron ring. It seems feasible from space and beam optics point of view. Other practical and operational considerations need to be properly investigated.
- The new large booster design does not preclude the possibility of separate ion booster and electron ring as in the current baseline design.

Finally, it is important to note that the two design approaches, the baseline and alternative, are converging and that this effort is near completion.

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