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DUAL-FUNCTION ELECTRON RING-ION BOOSTER DESIGN FOR JLEIC HIGH-ENERGY OPTION

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Abstract

As part of the alternative design approach for the Jefferson Laboratory Electron-Ion Collider (JLEIC) ion complex, the electron storage ring (e-ring) is consolidated to also serve as a large booster for the ions. The goal of reaching 16 GeV/u or higher for all ions using only room-temperature magnets forces the re-design of the e-ring because of magnetic field and lattice limitations. The new design is challenging due to several imposed constraints: (1) use of room-temperature magnets, (2) avoiding transition crossing, and (3) maintaining the size and shape of the original e-ring design as much as possible. A design study is presented for a 16 GeV/u large ion booster after analyzing different alternatives that use: (1) combined-function magnets, (2) long quadrupoles or (3) quadrupole doublets in the lattice design. This design boosts the injection energy to the collider ring from 8 GeV (proton-equivalent) in the original baseline design to 16 GeV/u for all ions which is beneficial for the high-energy option of JLEIC of 200 GeV or higher. A scheme for adapting the new large ion booster design to also serve as electron storage ring is presented. The new booster design does not preclude the possibility of separate e-ring and ion booster ring stacked in the same tunnel as the ion collider ring.

INTRODUCTION

The most recent high-energy design for the ion complex of Jefferson Laboratory Electron-Ion Collider (JLEIC) [1] consists of a 150 MeV linac, an 8 GeV figure-8 low-energy booster, a 12 GeV figure-8 high-energy booster and a 200 GeV collider ring. Several changes have been adopted in the baseline design [2] from the alternative design approach [3], such as the lower-energy shorter linac, two boosters before injection to the collider ring and room-temperature magnets in the boosters, with superconducting magnets only in the collider ring. A schematic layout of the JLEIC baseline design is shown in Fig. 1.

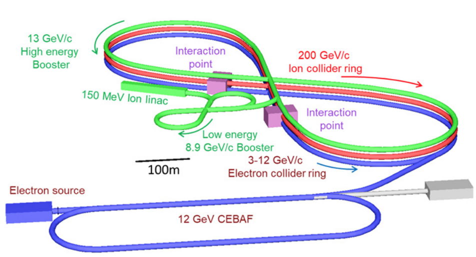

Figure 1: A schematic layout of JLEIC baseline design.

The alternative design approach was proposed in an effort to lower the risk and reduce the footprint of the JLEIC ion complex. As the baseline and alternative designs are converging, the essential part of the current alternative approach is to use a more compact non-figure-8 lower energy first booster (~ 6 GeV pre-booster) followed by a higher energy second booster (~ 16 GeV/u large booster) that could also be used as electron storage ring. However, the requirement to go to higher large booster energy presented further challenges. The main consequence is that the existing electron ring design cannot work as an ion booster up to 16 GeV/u and a new ion booster design is needed, which will be retro-fitted to serve as electron ring.

The first studies for a dual-function electron-ion booster were made for a medium energy option in the alternative design approach. There, the e-ring was adapted to be used also as a large ion booster. The rf sections for ion acceleration were successfully added to the e-ring lattice and the beam optics were re-matched for 11 GeV proton-equivalent with room-temperature magnets [4].

This medium energy option has recently been upgraded to high energy following the National Academy of Sciences (NAS) review [5].

High Energy Option for the Alternative Ion Complex Design

The high-energy option for the alternative design approach (see Fig. 2), consists of:

- A more compact 150 MeV Linac that has also been adopted for the JLEIC baseline design.
- A more compact 6 GeV racetrack pre-booster using room-temperature magnets. At this energy, the figure-8 shape is not required, different mechanisms with reasonable magnetic fields could be used for spin corrections [6].
- A large booster, up to 16 GeV/u for all ions with room-temperature magnets, adapted to also work as e-ring.

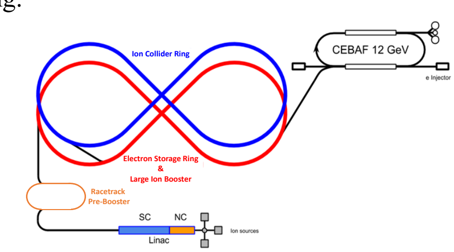

Figure 2: A schematic layout of the high-energy option for the alternative approach JLEIC design.

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E-RING AS LARGE ION BOOSTER FOR THE HIGH-ENERGY OPTION

A first study was carried out to check the feasibility of using the current e-ring lattice as a large ion booster.

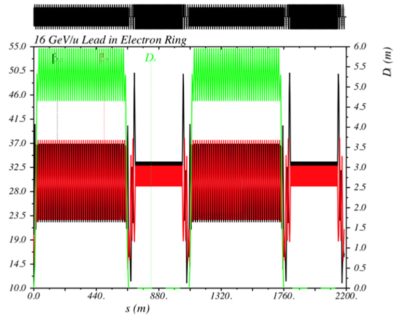

Figure 3: Beam Optics for the E-ring when used as an Ion Booster for 16 GeV/u lead ions without any insertion in the straight section. MAD-X [7]. The beta functions (red, black) and dispersion function (green) are shown.

When using the original e-ring lattice with new room-temperature magnets for 16 GeV/u ions, the focusing power was not sufficient, and the dispersion was too high in the arcs causing the transition gamma to be far below the requirement (see Fig. 3). Therefore, using the original e-ring lattice would require superconducting quadrupoles to reach 16 GeV/u for all ions without crossing transition. In order to use only room-temperature magnets, a new large ion booster design is needed, which will also need to be retro-fitted to use as electron ring.

LARGE ION BOOSTER AS E-RING FOR THE HIGH-ENERGY OPTION

The goal is to design a new 16 GeV/u large booster for all ions with enough room for all electron insertions, so that it may also be used as electron storage ring. The general shape, a figure-8, the crossing angle, and the approximate total length are imposed by the ion collider ring [8]. The beta functions should not exceed 90 m to use typical magnet apertures. In addition, the requirement to use only room-temperature with quadrupole pole-tip field no greater than 1 Tesla and dipole field no greater than 1.6 Tesla, made the process to find a solution more challenging.

Room-Temperature Options for Large Booster

There are several possible ways to reach the necessary transition gamma. However, due to the shape and space constraints only the ones that increase the focusing power in the arcs are taken into consideration. These options use (1) combined-function magnets, (2) long quads in FD lattice or (3) quadrupole doublets in FFDD lattice.

All of these options were fully investigated and a brief summary of associated parameters is shown in Table 1. The option with combined-function magnets (tapered dipoles) is the one that is more complex and difficult to implement than the others. The quadrupole doublets option would be more suitable if existing magnets (from PEP-II for example) are used. The long quadrupoles option is the most practical and easy to implement and is the one chosen for the alternative high-energy design option.

Table 1: Comparison of the Different New Large Ion Booster Design Options

Parameter	Tapered Dipole	Quad. Doublets	Long Quad.
Circumference, m	2256.6	2251.6	2250.4
Maximum β_x, m	~85	~85	~85
Maximum βy, m	~73	~73	~73
Max. dispersion, m	1.05	1.16	1.15
Γ	18.17	18.17	18.17
γ_{tr}	18.6	18.7	18.59
Quad. Max. grad., T/m	20	20	20
Quad. Length in arc, m	1	0.69	1.35
Dipole max. field, T	1.3	1.6	1.6
Dipole gradient, T/m	4	-	-
Dipole Length, m	6	5.4	5.4
Cell length, m	16.4	17.3	17.08

Lattice and Beam Optics

Although all the options were studied, the long quadrupoles option is explained in more detail here since it is the most practical. The lattice for all the options are based on a FODO lattice in both arcs and straights. The three different designs are with:

- Tapered Dipoles: the poles are tapered with ~ 4-deg angle, see the cell beam optics in Fig. 4 left, and ion beam optics for the lattice with electron insertions in Fig. 4 right.
- Quad Doublets: the cell has two quadrupoles for each quadrupole in a normal FODO. See Fig. 5 left.
- Long Quadrupoles: FODO lattice with long quadrupoles. Fig. 5 right.

Each quadrupole is followed by a sextupole for chromaticity compensation.

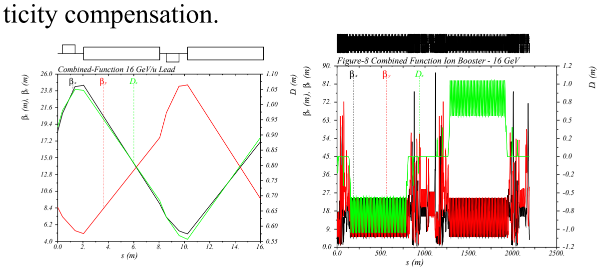

Figure 4: Beam optics for FODO cell with tapered dipoles (left) and for 16 GeV/u lead ion beam in JLEIC alternative large ion booster with tapered dipoles (right).

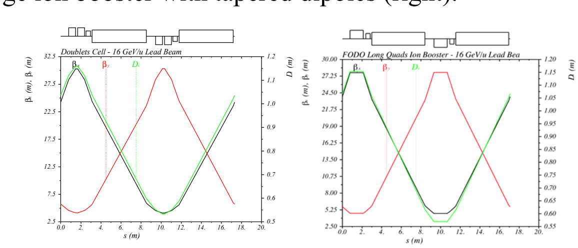

Figure 5: Beam optics for FODO cell with quad doublets (left) and with long quads (right).

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The sextupoles required to correct chromaticity in the long quadrupole case use the 0.4 m space reserved for them. They have strengths of k_{s1}=4.71E-01 m^{-3} and k_{s2}=-8.73E-01 m^{-3}, far away from the room-temperature limit.

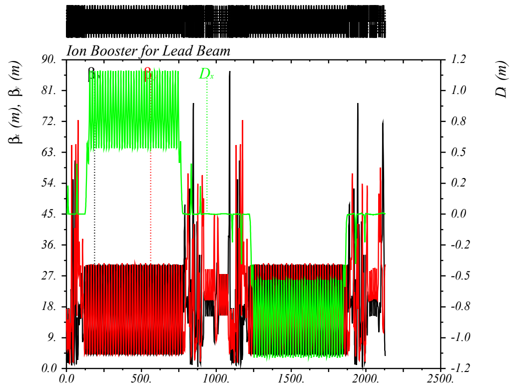

Figure 6: 16 GeV/u lead ion beam optics for the long quad. option for the JLEIC alternative large booster design.

The Large Booster lattice based on FODO cells was adapted to work also as electron storage ring. All the electron insertions needed, except the chicane (including one interaction point) are included in the new Large ion Booster ring. Some details about the most important sections are given below:

- The chicane is part of the interaction region design in the electron collider ring and has three functions: generating a dispersion to enhance the detector momentum resolution, suppressing the dispersion by itself and creating a required environment for Compton polarimeter to measure the electron polarization. The lack of space and focusing power makes it very challenging to control the beam size through the chicane for heavy ions. A solution with room-temperature magnets is being investigated. If this is not possible, stronger magnets will be used before and after the chicane.
- The rf sections included for both electrons and ions are based on previous studies [4, 9]. The goal is to reduce as much as possible the space used by rf sections. Instead of having 2 rf section for each beam, ion and electrons, just 1 rf section with achievable higher voltage is included for each.
- The spin rotators are designed to manipulate the electron polarization in the entire energy range from 3 to 12 GeV. They will be used to correct the spin errors for ions as the figure-8 preserves polarization. Final manipulation of ion polarization before collision will be in the ion collider ring.
- The number of tune trombone sections, used for machine tunes adjustments, have been reduced to give space for cooling and matching insertions needed after adding ion rf section. The remaining cells should be sufficient for adjusting the tune.
- Achieving very small emittance and very short bunch length before the ion collider ring requires at least DC cooling in the large booster. Several simulations were carried out to estimate the intra-beam scattering effect (IBS), the cooling times and the space charge tune shift for several beam formation schemes. The JLab Simulation Package for Electron Cooling (JSPEC) [10, 11] was used for the simulations. The space needed for sufficient cooling used in the simulations was 30 m, two coolers of 15 m each.

Figure 6 shows the ion beam optics for the Large Ion Booster after adding electron insertions. The electron beam optics have been also studied (see Fig. 7 left) and compared with the original e-ring optics (see Fig. 7 right).

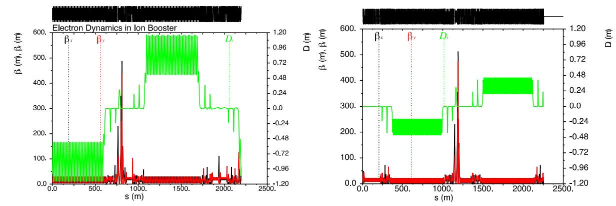

Figure 7: 12 GeV electron beam optics for the long quad. option for the JLEIC alternative large ion booster design (left) and 12 GeV electron beam optics for the JLEIC baseline design [2] (right).

CONCLUSIONS

Different alternatives designs with room-temperature magnets are presented for the new Large Booster for JLEIC. These are lattices with: (1) tapered dipoles, (2) quad doublets or (3) long quadrupoles. The complexity of the combined-function magnets makes the other two options more practical choices. Between these two options, using the quad doublets is more suitable if existing magnets are available, if not, long quadrupoles would be the best option.

A new Large Booster design is presented with all room-temperature magnets that can deliver 16 GeV/u for all ions within the same footprint as the e-ring and the ion collider ring. The higher energy is beneficial for a 200 GeV collider and future upgrade.

The new Large ion Booster design can also be used as the collider electron ring from beam optics point of view. Space for all ion and electron insertions will be tight but feasible. Additional practical and operational issues remain to be studied. In the worst case, this design can be used for a Large Ion Booster separate from the electron collider ring, but stacked in the same tunnel. It would reach higher energy than the actual high-energy booster of the current baseline design.

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