LEIC - A POLARIZED LOW ENERGY ELECTRON-ION COLLIDER AT JEFFERSON LAB*

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Abstract

A polarized Medium energy Electron-Ion Collider (MEIC) is envisioned as the future nuclear science at JLab beyond the 12 GeV CEBAF fixed target program. With some minor changes, this facility should also be able to accommodate electron-ion collisions in a low energy range, covering proton energies from 10 to 25 GeV and ion energies with a similar magnetic rigidity, thus extending its science reach. In this paper, we present a design concept of this low energy electron-ion collider, LEIC, showing its maximum luminosity can reach 10^{33} $cm^{-2}s^{-1}$. The design specifies that the large booster of MEIC is converted to a low energy ion collider ring with an interaction region and an electron cooler integrated to it. LEIC could be positioned as the first and low cost phase of the electron-ion collider program at JLab.

INTRODUCTION

The JLab fixed target program based on 12 GeV CEBAF will keep the lab at the forefront of nuclear science for at least a decade. Beyond that, an electron-ion collider (EIC) has been envisioned as the future science program at JLab. Recently, a conceptual design of a Medium energy Electron-Ion Collider (MEIC) has been completed and a design report [1] was released.

The accelerator design of MEIC provides a straight-forward path for reaching down to a low CM energy range, using only minor changes to the proposed facility. The main idea is to convert the MEIC large ion booster to a collider ring for storing protons with energies ranged from 10 to 25 GeV or ions of a similar magnetic rigidity for electron-ion collisions, while other parts of the MEIC facility could remain basically the same.

In this paper, we first briefly discuss the relationship of MEIC and LEIC from a project point-view. We proceed to present a design concept of LEIC including a first optics design of the ion collider ring. We then discuss several accelerator issues including formation and cooling of low energy ion beams, and beam synchronization.

MEIC AND LEIC

There are two ways to position LEIC strategically in the JLab EIC program. The first approach is to make the low energy collisions an additional capability of the JLab EIC and in parallel with the medium energy collisions. In this case, the MEIC large booster doubles in function as a low energy collider ring. LEIC either shares a detector with MEIC (thus the medium and low energy collisions will be alternating at that collision point) or has a dedicated detector at the third collision point (thus the electron beam will participate in three collisions, two with medium energy ions and one with the low energy ions, in each revolution).

An alternative approach is to make LEIC the first phase of the JLab EIC program, postponing construction of the medium energy collider ring (made of superconducting magnets), thus requiring a significantly lower initial project budget. When LEIC is upgraded to MEIC at a later time, the low energy collider ring can be converted to a large ion booster for MEIC. It is expected that the facilities and major equipment of LEIC will be nearly 100% reused for MEIC. We would particularly anticipate that, assuming a similar requirement of particle detection, the LEIC detector can be used for the MEIC physics program with at most a minor modification.

LEIC DESIGN CONCEPT

In the present baseline, MEIC is a ring-ring collider which accommodates two detectors and covers a CM energy range up to 70 GeV. To realize this EIC at JLab, a new ion acceleration complex consisting of ion sources, a linac, a pre-booster and a large booster must be built, in addition to two new storage-collider rings for electrons and medium energy ions. All booster synchrotrons and collider rings of MEIC have a unique figure-8 shape [1] for achieving superior polarization of stored light ions (proton, deuteron, helium-3 and possibly lithium). Three of them (the large booster and two collider rings) are stacked vertically in a shared tunnel. Figure 1 illustrates a schematic of the MEIC design concept and a cross section of the envisioned MEIC tunnel.

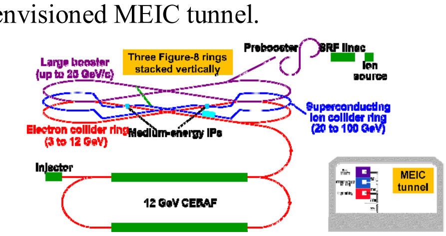

Figure 1: A schematic drawing of the MEIC design concept. The inserted picture on the low right corner shows a cross section of the envisioned MEIC tunnel.

Under this MEIC design, a simple way to realize LEIC is to convert the MEIC large booster to a low energy

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collider ring. This ring should be capable of storing protons with energies ranged from 10 to 25 GeV and ions of a similar magnetic rigidity. The low energy ion beams will be brought down through a vertical chicane to the plane of the electron ring. A low-beta interaction region (IR) must be integrated to the ring for achieving final focusing of the ion beam at the collision points.

To attain high luminosities at LEIC, we adopted the same luminosity concept based on a high bunch repetition rate for colliding beams as the MEIC design [2]. Thus, a 748.5 MHz frequency was chosen for both MEIC and LEIC. As a requirement of this luminosity concept, a crab crossing (utilizing SRF crab cavities) of colliding beams at the collision point is also adopted.

In the meantime, we would preserve the design of the front end of the MEIC ion accelerator complex (ion sources, ion linac and pre-booster) and the scheme of formation of ion beams [2] as discussed below.

Similarly, the MEIC electron ring design should see no fundamental changes. Nevertheless, certain modifications may be required to enable the electron beam to collide with medium or low energy ion beams, such as adding another interaction region for the third detector.

Table 1 presents the nominal parameters of LEIC at three representative design points. They are derived by observing the same limits of the collective beam effects and accelerator technologies as the MEIC design, such as the space charge tune-shift, beam-beam parameters, and the maximum betatron functions at the interaction region.

When the energy is significantly lower, the ion bunch charge is much lower due to limits from the space charge effect. We limit such a tune shift to 0.05. Table 1 shows the proton current is 0.3 A at 25 GeV, compared to 0.5 A for a 100 GeV proton beam in MEIC [1]. One should also note that the proton bunch length is doubled to 2 cm in LEIC for the purpose of gaining a reduction of the proton bunch charge density as well as the space charge tune shift. On the other hand, the beta-star is 2 cm in the LEIC design, thus, there would be a small (~15%) reduction of the luminosity due to the hour-glass effect.

Table 1: LEIC nominal parameters at three design points

		p	E	p	e	p	E
Beam energy	GeV	25	5	25	7.5	25	10
Collision frequency	MHz				748.5		
Particles per bunch	10^{10}	0.25	2.5	0.25	0.76	0.25	0.24
Beam current	A	0.3	3	0.3	0.91	0.3	0.29
Polarization	%	>70	~ 80	>70	~ 80	>70	~ 80
Energy spread	10^{-4}	3	7.1	3	7.1	3	7.1
RMS bunch length	cm	2	0.75	2	0.75	2	0.75
Emittance, normalized	µm rad	0.24	53.5	0.24	110	0.2	250
Horizontal & vertical β*	cm	2	3.3	2	2.3	2	1.4
Beam-beam tune shift		0.013	0.011	0.004	0.005	0.001	0.002
Laslett tune shift		0.053	Small	0.053	small	0.053	small
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	2.1*		0.63*		0.2*	

LOW ENERGY COLLIDER RING

To convert the MEIC large booster to a collider ring for LEIC, the following modifications are needed:

- Introducing a vertical chicane on one of two straights of the figure-8 booster ring;
- Integrating an IR into the collider ring;
- Allocating a 30 m section of beam-line on each of the two straights of the figure-8 for electron cooling;
- Adding a second RF system (high frequency SRF cavities) for bunching of ion beams

Since the large booster is stacked vertically (about 1 m) above the electron ring as shown in Figure 1, like MEIC, we need to bring the low energy ion beam to the plane of the electron ring for a horizontal crossing at the collision point. Presently only one detector was planned for the low energy collisions, we decided to add one vertical chicane to the ring. The other straight will stay on the top plane. A preliminary lattice design of this collider ring has been completed recently [3]. Figure 2 shows the 3D layout of the design, where the vertical axis uses a different scale from the two horizontal axes for better visibility.

When LEIC is run in parallel to MEIC, this ion ring should be operated in a dual mode. At the beginning, it is a booster synchrotron for accelerating a coasting ion beam for MEIC (multiple cycles for multi-injecting into the medium energy ion collider ring). After that, it switches the role to a storage-ring and takes the following steps for the formation and acceleration of the low energy ion beam; (1) turning on the electron cooler for reduction and preservation of the beam emittance; (2) adiabatically switching over to the high frequency SRF system for beam rebunching; (3) finally squeezing down value of the beta-star to enable collisions with the electron beam.

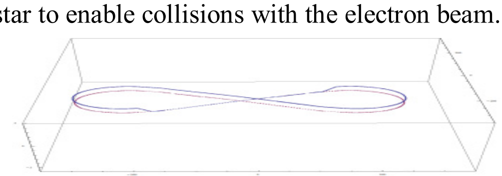

Figure 2: A 3D layout of the LEIC electron (red) and ion (blue) collider rings. The ion beam takes a vertical excursion to collide with electron beam.

The conclusion of our JLab nuclear science colleagues is that the LEIC science program, like MEIC, will be focused on full acceptance detection of all particles over the entire energy range. Thus, the recently developed interaction region [4] for the MEIC full acceptance detector will be adopted without change (besides optics matching) and integrated to the LEIC collider ring.

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The last comment regards ion polarization. To deliver a longitudinal or transverse ion polarization at the collision point, we adopt the same spin manipulation scheme for MEIC as presented in the design report [1]. Further, with the figure-8 ring, the polarized deuterons will be also well supported at MEIC.

BEAM SYNCHRONIZATION

In the low energy range from 10 to 25 GeV/u, ions are far from being ultra-relativistic. Therefore, the revolution time of the collider ring has strong energy dependence for LEIC ions, resulting in an issue of synchronizing the ions and electron beams at the collision point over the entire ion energy range. Assuming a 1350 m nominal ring circumference, the LEIC ion ring must be about 95 cm shorter than the electron ring in order to synchronize the 25 GeV proton beam with the electron beam. It further requires a 5 m path length adjustment of the ion ring to maintain such beam synchronization at 10 GeV/u for ions.

Like the MEIC, this problem can be solved with the scheme presented in [5], namely, (1) varying the bunch number (harmonic number) in the ion ring to synchronize beams for a set of discrete ion harmonic energies; and (2) varying the electron ring circumference and the RF frequency of the both rings simultaneous for covering the ion energies between the harmonic energies. Table 2 below lists all the harmonic numbers and energies in the LEIC ion ring with a 748.5 MHz bunch repetition rate.

In fact, as it can be seen from Table 2, there are 13 harmonic energies between 10 to 25 GeV. We are optimistic that they would provide a very good pool of choices for the LEIC science program.

Table 2: Ion beam harmonic energies in the LEIC collider ring

Harmonic number	β	γ	Ion harmonic energy (GeV/u)
3370	0.99930	26.645	25
3371	0.99900	22.356	20.98
3372	0.99870	19.639	18.43
3373	0.99841	17.722	16.663
3374	0.99811	16.276	15.27
3375	0.99782	15.136	14.20
3376	0.99752	14.206	13.33
3377	0.99722	13.430	12.60
3378	0.99693	12.769	11.98
3379	0.99663	12.198	11.44
3380	0.99634	11.697	10.98
3381	0.99604	11.254	10.56
3382	0.99575	10.858	10.19
3383	0.99546	10.501	9.85

ION BEAM FORMATION AND COOLING

Formation of the ion beams for LEIC is very similar to the case for MEIC [1]. As mentioned above, the front part of the MEIC ion acceleration complex will have no changes. The ions will be generated in the polarized or un-polarized sources, first accelerated in the linac consisting of both normal and superconducting RF cavities, then accelerated in a pre-booster of 3 GeV after being accumulated. The process for ions in the LEIC and MEIC collider rings are almost identical, the ions start by: (1) being accelerated after being injected in five long coasting bunches from the pre-booster; (2) then being re-bunched by the SRF system into short bunches; (3) being electron cooled for reduction of 6D emittance.

Cooling of ion beams is required for LEIC to achieve high luminosities. We have chosen traditional electron cooling as the baseline. Similar to MEIC, an advanced concept of multi-phased cooling [6] has been adopted in the LEIC design. This cooling scheme has been optimized recently for gaining a significant reduction of technical uncertainty and R&D requirements by shifting more cooling tasks to the existing and matured technologies, namely, low energy DC electron cooling. The revised concept [7] can be summarized below:

Phase 1: DC electron cooling (up to 100 keV electron energy) at the ion injection energies of the pre-booster for assisting the accumulation of positive ions;

Phase 2: DC electron cooling (up to 2 MeV electron energy) at the top energies (3 GeV for protons) of the pre-booster for the initial stage of ion emittance reduction;

Phase 3: ERL driven electron cooling (up to 13 MeV electron energy) in the ion collider ring at the ion beam's collision energy (up to 25 GeV for protons) for achieving the designed low 6D emittance and short bunch length;

Phase 4: Continuous electron cooling (up to 13 GeV electron energy) during electron-ion collisions for the purpose of suppressing IBS induced beam degradation.

It can be seen that the first two phases of cooling take place in the pre-booster, utilizing matured DC electron cooling technology and is well within the state-of-art. The other two phases of cooling are in the LEIC collider ring. Since the electron energy is from 5.5 to 13 MeV, thus it must be supported by an ERL driven electron cooler.

It is considered a technical challenge for electron cooling at an energy range much higher than the present state-of-art. However, comparing the MEIC and LEIC cases, the challenge is much less for the latter, since (1) the ion energy is much lower in LEIC, thus electron cooling should be much more efficient; and (2) the ion current in LEIC is also much lower than that in MEIC, thus the required current of the cooling electron beam is far lower than that in MEIC. Our preliminary estimate indicates that a circulator ring, which is a critical component of the MEIC ERL cooler design [1], is likely not needed, since the present state-of-art un-polarized source is very close to what LEIC ERL cooler may need.

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