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CONCEPTUAL DESIGN OF A POLARIZED MEDIUM ENERGY ELECTRON-ION COLLIDER AT JLAB*

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Abstract

A medium energy electron-ion collider is envisioned as the primary future of the JLab nuclear science program beyond the 12 GeV upgraded CEBAF. The present conceptual design selects a ring-ring collider option, covers a CM energy range up to 65 GeV for collisions of polarized electrons with polarized light ions or unpolarized light to heavy ions, and reaches a luminosity at above 10^{34} cm^{-2}s^{-1} per detector over multiple interaction points. This paper presents a brief description of the current conceptual design of the accelerator.

INTRODUCTION

An electron-ion collider (EIC) has long been considered a great gluon microscope for exploring and understanding QCD [1]. Over the last decade, JLab has been engaged in feasibility studies and preliminary conceptual design of an EIC based on the CEBAF recirculated electron linac. The initial design concept considered a linac-ring collider scenario in which a polarized electron beam from CEBAF collides with an ion beam in a storage ring [2]. The CEBAF facility would be converted to an energy-recovery linac (ERL) in order to provide a high current beam. Later, a circulator electron ring was added to the ERL-ring design to achieve a factor of several hundreds reduction of average current from a polarized source [3]. The design has now finally evolved into a ring-ring collider in which the colliding electron beam will also be stored in a ring while CEBAF will only be used as a full-energy injector [4], thus requiring no further upgrade beyond 12 GeV. The ring-ring scenario does not suffer any disadvantage in reaching high luminosity compared to an ERL-ring scenario under a luminosity concept based on high repetition CW beam [5,6]; and it eliminates the burden of challenging R&D for the high current polarized electron source required for the ERL-ring scenario.

During the last two years, driven by nuclear physics

needs and also a staging approach mandated by the DOE, accelerator design of the JLab EIC has been focusing on a medium CM energy range up to 65 GeV as an immediate goal, but has retained an option of a future upgrade for reaching much higher CM energies and luminosities for an expanded science program. Such a staging approach is considered an optimized balance of science program, accelerator R&D and project cost. Presently a comprehensive document which summarizes design studies of the *M*edium energy *E*lectron-*I*on *C*ollider (MEIC) is in preparation [7]; this paper will provide an abridged version to highlight the current machine design. Other details and R&D progress can be found in [7].

BASELINE DESIGN

The MEIC proposal takes full advantage of three unique design features: a high repetition CW electron beam from CEBAF; a new ion complex specially designed to deliver ion beams that match time and phase space structures of the colliding electron beam; and a new ion collider ring in figure-8 shape which is an optimization for preserving ion polarization during acceleration as well as the only practical way for accelerating and storing polarized deuteron beam [8].

The center part of the MEIC facility is two collider rings stacked vertically as shown in Figures 1 and 2. The electron ring stores 3 to 11 GeV electrons or positrons injected at full energy from CEBAF while the superconducting ion ring stores 20 to 100 GeV protons or up to 40 GeV/u fully stripped ions up to lead. The large figure-8 rings of grey color in Figure 1 represent a future upgrade for reaching up to 20 GeV electrons, and 250 GeV protons or 100 GeV/u ions. In the present design, the ion beams execute a vertical excursion to the plane of the electron ring for collision at two interaction points (IP) as illustrated in Figure 2. An optional third detector may be placed at another IP for collisions of electrons with low energy ions stored in a ring yet to be designed.

The MEIC nominal parameters at a design point of 60⊗5 GeV^2 *e-p* collision are presented in Table 1. The luminosity reaches 5.6⊗10^{33} cm^{-2}s^{-1} for a full acceptance detector. To reach this exceptionally large acceptance, the

detector space, i.e., the distance from an IP to the front face of the 1st final focusing quad, must be at least 7 m for ions; however, it can be shortened to 3.5 m for electrons. For a secondary detector optimized for higher luminosity while still retaining a fairly large detector acceptance (down to 1 degree), the detector space can be reduced to 4.5 m so the luminosity is doubled to above 10^{34} cm^{-2}s^{-1}.
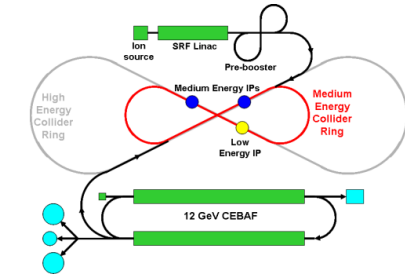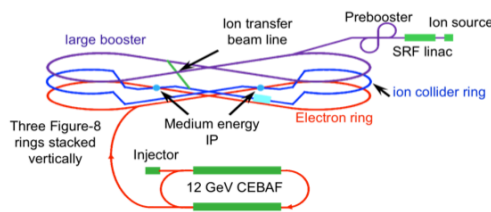

Figure 1: A schematic layout of MEIC.

Figure 2: A schematic layout of MEIC.

Table 1: MEIC Parameters for a Full-Acceptance Detector.

		Proton	Electron
Beam energy	GeV	60	5
Collision frequency	GHz	0.75	
Particles per bunch	10^{10}	0.416	2.5
Beam current	A	0.5	3
Polarization	%	>70	~80
RMS bunch length	Mm	10	7.5
Normalized emit. (ε_x / ε_y)	μm	0.35/0.07	53.5/10.7
Horizontal beta-star	Cm	10 (4)	
Vertical beta-star	Cm	2 (0.8)	
Vert. beam-beam tune-shift		0.015	0.03
Laslett tune-shift		0.06	Small
Detector space	M	±7 (4.5)	±3.5
Luminosity per IP (10^{33})	cm^{-2}s^{-1}	5.6 (14.2)	

(Values for a high-luminosity detector are given in parentheses.)

In deriving this parameters set, certain limits were imposed on several machine or beam parameters in order to reduce accelerator R&D challenges and to improve robustness of the design. These limits, based largely on previous lepton and hadron collider experiences and present state-of-the-art of accelerator technologies, are:

- The stored beam currents are up to 1 A for protons or ions and 3 A for electrons.
- Electron synchrotron radiation power density should not exceed 20 kW/m.
- Maximum bending field of ion SC dipoles is 6 T.
- Maximum betatron function at a beam extension area near an IP is 2.5 km.

In addition, MEIC bunch repetition rate is reduced to 750 MHz, half of the nominal CEBAF frequency, in order to ease R&D and hardware cost of a high-current high-repetition electron ring RF system.

ION COMPLEX

A schematic layout of the MEIC ion complex as shown in Figure 3 characterizes a scheme of formation and acceleration of ion beams. The ions, coming out from the polarized or un-polarized sources, will be accelerated step-by-step to the colliding energy in the following machine components: a 285 MeV pulsed SRF linac, a 3 GeV pre-booster, a 20 GeV large booster and finally a medium-energy collider ring of 20 to 100 GeV. All rings are in figure-8 shape for benefit of ion polarization.
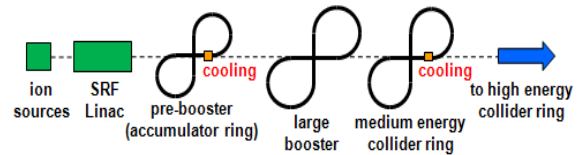

Figure 3. A schematic layout of MEIC ion complex.

Ion Sources

The MEIC ion sources will rely on existing and mature technologies: an Atomic Beam Polarized Ion Source (ABPIS) with Resonant Charge Exchange Ionization for producing polarized light ions H$^-$/D$^-$ and ^{3}He^{++}, and an Electron-Beam Ion Source (EBIS) currently in operation at BNL for producing un-polarized light to heavy ions. Alternatively, an Electron Cyclotron Resonance Source (ECR) can generate ions with 10 or more times charge per pulse than an EBIS source.

Ion Linac

The technical design of a pulsed SRF ion linac, originally developed at ANL as a heavy-ion driver accelerator for FRIB [9], has been adopted for the MEIC proposal. This 150 m long linac is very effective in accelerating a wide variety of ions from H$^-$ to ^{208}Pb^{30+}.

Pre-Booster/Accumulator Ring

The pre-booster accepts pulses of any ion species from the linac and, after accumulation and acceleration, transfers them to the large booster for further acceleration. The circumference of the pre-booster is about one-fourth that of the large booster. The mechanisms of pre-booster operation depend on the ion species, relying on either combined longitudinal and transverse paint technique for H$^-$/D$^-$ or conventional DC electron cooling for lead or other heavy ions during multi-turn injection from the linac. One design consideration is sufficiently high transition gamma such that the ions never cross the transition energy during acceleration in order to prevent particle loss associated with such crossing [10].

Large Booster

The large booster is currently designed to share the same tunnel with the collider rings, and will be responsible for accelerating protons from 3 to 20 GeV or ions from 1.8 to 12 GeV/u before transporting them to the medium-energy collider ring. A key design requirement is

that a crossing of the transition energy must be avoided for all ion species.

COLLIDER RINGS

The MEIC electron and ion collider rings have nearly identical footprints, and circumferences are approximately 1340 m. The figure-8 crossing angle is 60°, partitioning the ring roughly equally on two arcs and two long straights. The two rings intersect at two symmetric points in two long straights for medium energy collisions. There can be a possible 3rd interaction point in the electron ring for collisions of electrons with low energy ions stored either in the large booster or in a dedicated small ring. The long straights also accommodate necessary utility accelerator components such as injection and ejection, RF systems and electron cooling. There are two short (20 m) straights in the middle of the two arcs of the ion ring for two Siberian snakes, and a 60 m Universal Spin Rotator consisting of two SC solenoids and two sets of arc bending dipoles on each end of two electron arcs. It should be pointed out that a transition from a low bunch frequency associated to the ion linac to 750 MHz repetition rate of the ion colliding beam takes place after injection into the collider ring through a procedure of RF de-bunching and re-bunching.

INTERACTION REGIONS

The MEIC primary detector is unique in its ability to provide almost full acceptance for the produced particles of collisions. An integration of the detector with the final focusing magnets has been achieved in the IR, as shown in Figure 4, to support the detector acceptance [11].
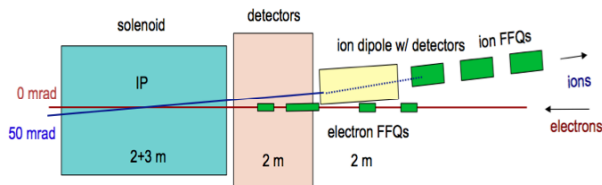

Figure 4: MEIC full acceptance IR layout.

The bunch spacing of the MEIC colliding beams is about 40 cm. A crab crossing of 50 mrad provides a simple way to separate the two colliding beams quickly near an IP to avoid undesired parasitic collisions. Currently, two ways are under evaluation to tilt orientation of the colliding electron and ion bunches by a half crab crossing angle in order to restore head-on collisions [12]. The first approach is placing crab cavities on each side of an IP. Such an approach has been proved at KEK-B factory and led to a record-high luminosity [13]. An alternative approach is dispersive crabbing [14], in which tilting of the bunch is achieved through purposely leaking dispersion into accelerating RF cavities.

For the MEIC IR design with a 2 cm or less β^*, chromatic aberration of the final focusing quads is an important issue requiring special attention. A dedicated chromaticity compensation block including a set of sextupoles is inserted in the beam extension area on both sides of an IR to mitigate this aberration. The initial

studies indicated the natural chromaticity can be reduced dramatically to single digits. Particle tracking simulations for dynamic aperture are current underway.

ELECTRON COOLING

Cooling of ion beams is essential to achieve high luminosity in any EIC design. In MEIC, we rely on a concept of staged cooling of bunched ion beams of medium energies. Electron cooling is called for at the injection energy of the collider ring and also after acceleration to the collision energy. Most importantly, electron cooling will be continued during collisions to suppress IBS induced beam emittance growth. Shortening the bunch length (1 cm or less) that results from electron cooling of the ion beam captured in a high voltage SRF field is critical for high luminosity in the MEIC since it facilitates an extreme focusing of the colliding beams and also an implementation of crab crossing at the IPs for achieving an ultra-high bunch collision rate.

A schematic drawing of the MEIC electron cooler is shown in Figure 5. Two technologies, ERL and a circulator ring, play critical roles in the success of this facility by providing perfect solutions to two bottlenecks of the facility: the high current and high power of the cooling electron beam [15]. For example, a 3 A, 50 MV (150 MW of power) cooling beam can effectively be provided by a 30 mA, 2 MV (60 kW of active beam power) beam from the injector/ERL.
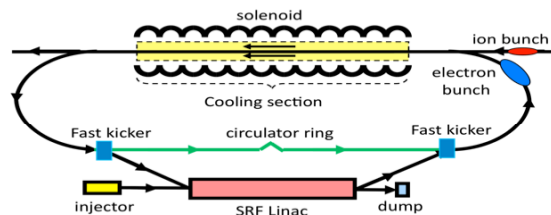

Figure 5: Schematic of electron cooling for the MEIC.

ACKNOWLEDGEMENT

REFERENCES

[1] DOE/NSF NSAC Long Range Plan (2007) (http://science.energy.gov/np/nsac/).
[2] L. Merminga, et al., Proc. of 2nd EPIC (2000).
[3] L. Merminga, et al., Proc. of EPAC 2002 .
[4] A. Bogacz, et al., Proc. of PAC 2007.
[5] G. Krafft, et al., JLab Technote JLAB-TN-06-32.
[6] Ya. Derbenev, et al., Proc. of HB2010 .
[7] MEIC Intermediate Design Report, ed. Y. Zhang (2011).
[8] Ya. Derbenev, Proc. of EPAC 2002.
[9] B. Mustapha, et al., Proc. of PAC 2007.
[10] B. Erdelyi et al., Proc. of PAC 2011.
[11] T. Horn and P. P. Nadel-Turonski, private communications.
[12] S. Ahmed, et al., Proc. of PAC 2011.
[13] Y. Yamamoto, et al., Proc. IPAC 2010.
[14] G. Jackson, Fermilab Tech. Note. FN-542 (1990).
[15] Ya. Derbenev and Y. Zhang, Proc. of COOL 2009.

Colliders