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IDEAS AND CONCEPTS FOR FUTURE ELECTRON-ION COLLIDERS*

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Abstract

Different versions of future electron-ion colliders have been proposed by Brookhaven National Laboratory (BNL) and Thomas Jefferson National Laboratory (JLAB), one based on colliding protons in a ring with electrons from an Energy Recovery Linac (ERL), the other two based on ring-ring colliders. To attain the luminosity goal strong hadron cooling is required, as could be provided with several proposed new cooling schemes. Polarization of both colliding beams is essential. This invited talk will compare the various designs and highlight some of the novel ideas and concepts.

INTRODUCTION

The U.S. Nuclear Physics community has recommended a high-energy high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) in the Nuclear Science Advisory Committee (NSAC) 2015 Long Range Plan for Nuclear Science [1]. The physics case for an EIC emerged about 20 years ago. Pivotal developments in the process have been the initial endorsement of the EIC in the 2007 NSAC Long Range Plan [2] and the ensuing comprehensive 2013 EIC White paper [3], that set the foundation of the physics case and the high-level requirements for the accelerator facility.

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and compose nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new EIC, providing unprecedented precision and versatility.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

Accelerator design studies for the EIC started in the early 2000's by the Brookhaven National Laboratory (BNL) and the Jefferson Laboratory (JLAB) teams. Three main designs concepts were developed, one ring-ring design at JLAB [4], and two at BNL - an ERL-ring option [5] and a ring-ring option [6]. In 2017 the ring-ring was selected at BNL as the leading option. The ERL-ring option, potentially cost effective but with the drawback of a higher technical risk, will not be discussed here in detail.

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ACCELERATOR REQUIREMENTS AND CHALLENGES

The key machine parameters the EIC should have to address were established in the 2013 EIC White Paper:

- >70% polarized electrons, protons, and light nuclei
- Ion beams from deuterons to the heaviest nuclei
- Variable center of mass energies ~20–100 GeV, with potential to upgrade to ~140 GeV (e-p)
- High collision luminosity ~10^{33-34} cm^{-2} s^{-1}

These are very challenging requirements for colliders and the expertise at many U.S. accelerator laboratories is crucial in meeting the technical challenges to realize the versatile range of kinematics, the broad range in ion beam species, and the high luminosity and beam polarization at the EIC.

Both BNL and JLAB designs leverage the existing infrastructure and facilities available to the U.S. nuclear science community. At JLAB, the JLab Electron-Ion Collider (JLEIC) design employs a new electron and ion collider ring complex together with the upgraded CEBAF operating at 12 GeV. At BNL the electron-Relativistic Heavy Ion Collider (eRHIC) design utilizes new electron injectors and a ring to be built inside the RHIC tunnel to accelerate electron beams and collide them with RHIC's ion and polarized proton beams. Fig. 1 offers a view of eRHIC and JLEIC respectively.

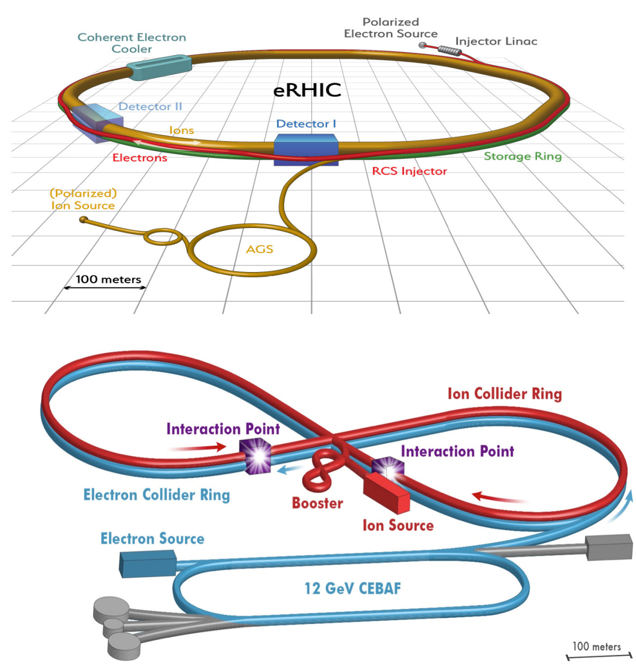

Figure 1: Layout of eRHIC and JLEIC.

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While there are design specific topics that will be addressed in the following sections on eRHIC and JLEIC, many challenges are common to both designs: strong ion cooling is necessary to sustain luminosities at the level of ~10^{34} cm^{-2} s^{-1} and large crab cavity systems are needed to counteract the luminosity loss from the large crossing angles needed to accommodate the detectors. More generally, the physics-driven requirements on the EIC accelerator parameters and extreme demands on the kinematic coverage for measurements make integration of the detector into the accelerator a particularly challenging feature for both designs. Sophisticated modelling is needed for the validation of polarization schemes, cooling rates, and beam dynamics in general. The common and comprehensive EIC research and development (R&D) necessary to respond to these technical challenges will be discussed after a description of the individual designs.

JLEIC DESIGN

The central part of this facility is a set of two figure-8 collider rings (see Fig. 2). CEBAF is a full energy injector to an electron collider ring with energy range 3 to 12 GeV and maximum stored e-current of 3A. The new ion complex includes an ion injector (sources, an SRF linac, a figure-8 booster) and an ion collider ring. The stored ion beam current is up to 0.75 A. The two collider rings are stacked vertically and housed in the same underground tunnel. They have nearly identical circumferences of ~2.2 km and fit on the JLAB site. The center-of-mass (CM) energy of this collider is 15 to 65 GeV. CM of up to 140 GeV can be reached with high-field SC magnets in the collider ring.

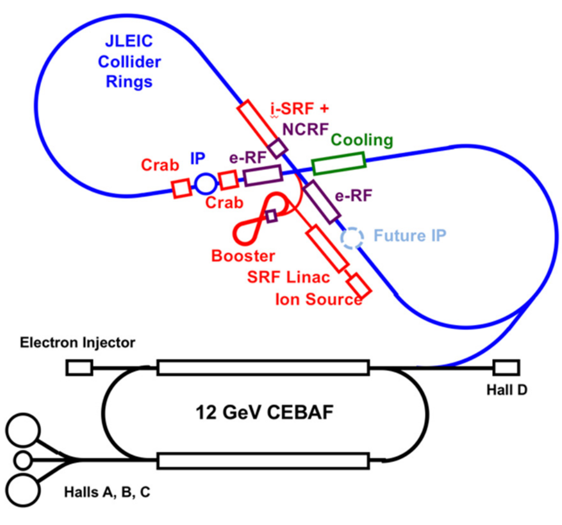

Figure 2: Main components of the JLEIC complex.

The key to the high luminosity in JLEIC is high bunch repetition rate of the colliding beams. Both the electron and ion beams have very short bunch lengths and small transverse emittances such that a strong final focusing can be applied to reduce the beam spot sizes to as small as a few μm at the collision point. This configuration combined with a high bunch repetition rate boosts the collider luminosity. A high bunch repetition rate enables a modest bunch charge to be used, allowing for relatively weak collective and intra-beam effects, particularly in the ion beams, while maintaining high beam current to provide high luminosity. The high-repetition-rate luminosity concept has been validated at today's lepton collider B-factories, which also use very high bunch collision frequency (storing tens to hundreds of times more bunches compared to the hadron colliders) and hundreds of times smaller β (and the corresponding smaller spot sizes) at the collision point through the strong final focusing enabled by short bunch lengths. The JLEIC luminosity concept can be summarized as follows:

- Very short bunches for electron and ion beams
- Very small transverse emittance
- Ultrahigh collision frequency beams
- Multi-stage electron cooling
- Very small final focusing β
- Large beam-beam tune shift
- 50 mrad crossing angle and crab crossing

CEBAF is a full energy polarized electron injector and the polarization in the electron ring can be preserved and enhanced by appropriate spin matching. A set of spin rotators with energy-independent geometry aligns the electron spins in the required longitudinal direction at the collision points and in the vertical direction in the arcs. The spin dynamics is entirely symmetric for oppositely polarized bunches. The electron polarization lifetime in the ring will require top-off injection from CEBAF to replenish the polarization only for energies above 7 GeV.

Achieving high polarization in an ion ring requires state of the art polarized ion sources. In addition, the polarization must be preserved during acceleration. The primary design choice for the JLEIC polarization is to adopt a figure-8 layout for the booster and collider rings. This breakthrough concept enables energy-independent spin tune and thus effectively eliminates crossing of any spin resonances. Moreover, only weak magnetic fields are necessary for spin control and manipulation, and that offers the capability of colliding polarized deuterons. The resulting polarization in the electron and ion ring exceeds 80%.

Because of the option to reuse PEP-II warm RF cavities and RF stations for the JLEIC electron collider, the bunch repetition rate of the JLEIC stored beams is 476 MHz. A conceptual scheme has been developed for injecting the electron bunches from the CEBAF SRF linac (which has a 1.497 GHz frequency) into the collider ring. All new SRF cavities and RF stations required for the ion collider ring will have a frequency of 952 MHz, thereby enabling cost effective future improvements in luminosity and energy. The designs of the booster and collider rings are based on the superconducting (SC) magnet technology

Conventional electron cooling is the technology choice for reducing the ion beam emittance and a multi-phased cooling scheme is used to achieve the required high cooling efficiency. The scheme utilizes a DC cooler in the booster synchrotron, and a DC cooler and a magnetized bunched beam cooler based on an energy recovery linac (ERL) in

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the collider ring. Cooling in the booster is used to assist accumulation of the injected positive ions and for emittance reduction. The DC and ERL coolers in the collider are needed to suppress IBS to maintain emittance during stacking at injection and in collision, respectively. The schematic design of the ERL Cooler is shown in Fig. 3.

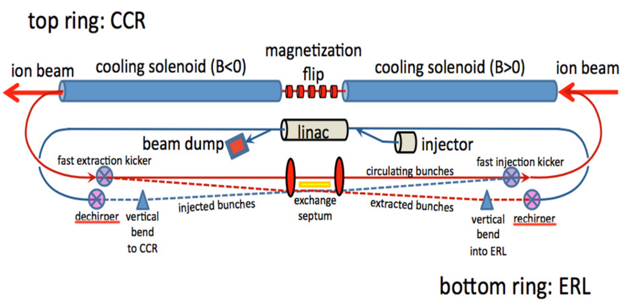

Figure 3: Schematic view of the JLEIC electron cooler, consisting of an ERL (bottom ring) and a circulator cooler (top ring).

A single-turn ERL Cooler enables luminosity of ~$4\mathrm{x}10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. A fast kicker allows for multi-turn e-beams, and hence higher current. The efficiency of electron cooling can be significantly enhanced by circulating the cooling beam 11 times, and that enables luminosity in excess of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Circulating the cooling beam also relaxes the electron source requirements. The main challenge of such a multi-pass cooling is development of a fast kicker to kick the cooling bunches in and out of circulation: a prototype produced very encouraging results.

The design of the JLEIC interaction region is well advanced, aims at ~100% acceptance and is based on a large 50 mrad crossing angle with large final focus magnets and forward dipoles.

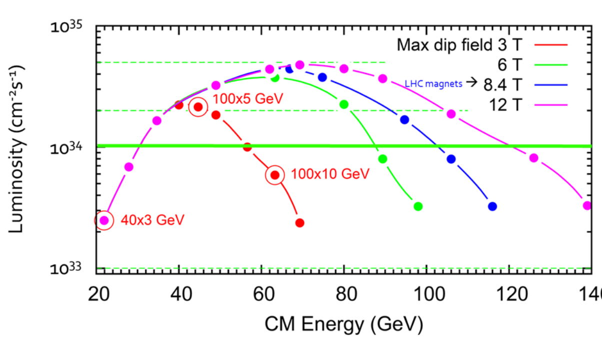

Figure 4: JLEIC luminosity and energy range.

The maximum luminosity and energy range depend on the technical choice of the ion ring SC magnets, as exemplified in Fig. 4. A 3T to 6T magnet can be based on established super-ferric or cos-theta designs; a LHC-like magnet at 8.4T, or an FCC-type magnet can further extend the energy reach of the JLEIC design. The luminosity is generally limited by ion beam space charge in the low energy end, by beam-beam in mid- range, and by the reduced electron current necessary to keep, by design, the electron beam power under 10 MW at the high-energy end. The JLEIC beam parameters for the 3T magnets are listed in Table 1:

Table 1: JLEIC Parameters for High Luminosity with Strong Cooling (3T Magnets)

Parameter		ions	electrons
Energy	GeV	100	5
Frequency	MHz	476	476
Particles/bunch	10^{10}	0.98	3.7
Beam current	A	0.75	2.8
Polarization	%	80%	80%
Bunch length	cm	1	1
Norm.emittance	µm	0.5/0.1	54/10.8
H and V β*.	cm	6/1.2	5.1/1
V beam-beam par.		0.015	0.068
Laslett tune shift		0.055	0.0006
Detector L	m	3.7/7	3.2/3
Hourglass		0.87	0.87
Lumi	$10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$	21.4	21.4

A graded approach without strong cooling yields a maximum luminosity of ~$0.3\ \mathrm{x}10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

eRHIC DESIGN

The eRHIC design is based on RHIC and the design goal is for luminosity $>10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$. eRHIC currently consists of an electron storage ring with an energy range from 5 to 18 GeV to be co-located in the RHIC tunnel. The electron beam is brought into collision with the hadron beam in the RHIC Yellow ring in two interaction regions. The energy range for RHIC polarized protons is 41-275 GeV and that results in a center mass (CM) energy for eRHIC of 29-141 GeV. The eRHIC ion beam parameters are close to the present operational RHIC parameters, other than the number of bunches, ~ a factor 10 higher and the beam current, ~40% higher. The total power for the electron storage ring is limited by design to 10 MW, based on the B-factories operational experience. The basic design assumption, that also guided the design of HERA, is that each beam will have parameters, and in particular the beam-beam tune shift as operationally demonstrated in collision between equal species: $\xi_e \leq 0.1$ (B-factories); $\xi_p \leq 0.012$ (RHIC).

The electron storage ring is composed of 6 FODO arcs with 60°/cell and super-bends for emittance control in the 5-10 GeV range and 90°/cell in the 11-18 GeV range. Six simple straight sections complete the layout. Eleven 2-cell 500 MHz SRF cavities compensate for the 10 MW synchrotron radiation power.

The requirement to store electron beams with a variable spin pattern requires a full-energy, spin transparent injector. A comprehensive study resulted in the choice of a spin-transparent rapid-cycling synchrotron in the RHIC tunnel.

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High lattice quasi-symmetry (achieved by straight sections designed as unity transformations) suppresses systematic depolarizing resonance during the ramp. A 200 msec ramp is sufficiently fast to cross resonances without loss of polarization. Systematic tracking calculation results in stringent orbit control needs, orbits should not deviate by more than 0.5 mm from ideal. While this is a demanding requirement, it is believed to be feasible by using state of the art controls and correction tools. Magnetic stray-field from the injector experienced by the storage ring have been calculated as negligible. The bypasses around the detectors are accomplished without distorting the quasi symmetry.

Layout and polarization preservation for the spin transparent injector cyclotron are shown in Figs. 5 and 6 respectively.

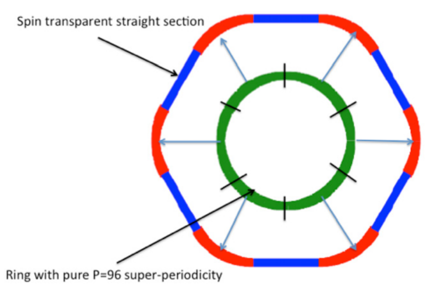

Figure 5: Rapid cycling synchrotron layout.

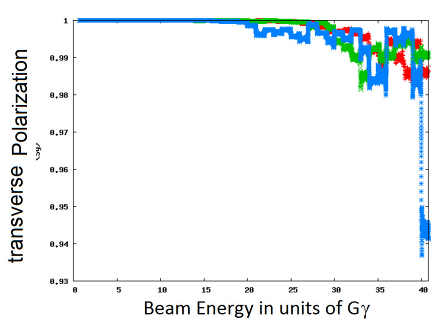

Figure 6: Polarization preservation in a 200 msec ramp.

The most promising approach to cool up to 275 GeV protons is micro-bunching with 2 plasma amplification stages. Achievable cooling rates with 100 mA electron current and flat beams are ~1 h which would be sufficient for RHIC. Main challenges to overcome are the 100mA electron source that is beyond state of the art and the design of the hadron chicanes needed to compensate for electron delays in the micro-bunching chicanes. Short bunches might boost the cooling rates and therefore the electron current and the number of amplifications. A vigorous R&D program is required.

The proton and light ion polarization strategy for eRHIC is based on the operational experience at RHIC and the use of additional Siberian snakes to boost the polarization to the ~70% level. The electron ring needs to store bunches with 85% initial polarization with spin parallel ↑ ↑ and spin antiparallel ↑↓ to guide field in the arc. The need to replace bunches with parallel spin with a rate of up one every 5 minutes because of Sokolov-Ternov depolarization defines the injection chain. Studies are in progress to validate the polarization scheme for the electron complex.

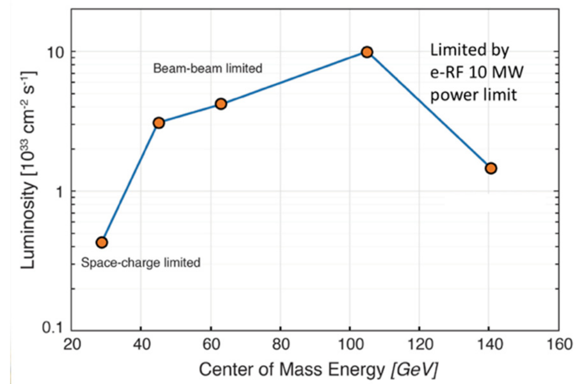

Figure 7: eRHIC luminosity as a function of center-of-mass energy with strong cooling.

The fundamental limits to the eRHIC luminosity in Fig. 7 and the JLEIC design in Fig. 4 are qualitatively the same.

Table 2: eRHIC Parameters for High Luminosity

	hadron	**electron**
Parameter	100.2	137.0
Energy GeV	275	10
N of bunches	1320	1320
Part/bunch 10^{10}	6.0	15.1
Beam current. A	1.0	2.5
H emittance nm	9.2	20.0
V emittance nm	1.3	1.0
β_H* cm	90	42
β_V* cm	4.0	5.0
H betatron tune	0.08	0.3
V betatron tune	0.06	0.31
H divergence mrad	0.101	0.219
V divergence mrad	0.179	0.143
H beam-beam par	0.013	0.064
V beam-beam par	0.007	0.01
L IBS growth hrs	2.19	
H IBS growth hrs	2.06	
Bunch length cm	5	19
Hourglass	0.87	0.87
Lumi 10^{33}cm^{-2}sec^{-1}	10.5	10.5

The eRHIC parameters for high luminosity are listed in Table 2. A fall-back position without strong cooling and more conservative parameters results in a maximum luminosity of 0.44 x10^{33}cm^{-2}sec^{-1}.

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EIC ACCELERATOR R&D

JLAB, BNL and collaborators have been engaged in EIC accelerator R&D for more than 10 years to validate the EIC design concepts. The R&D program up to 2017 has been executed on Nuclear Physics (NP) EIC R&D funds, operating funds, state funds, SBIR and state seed funds. The entire scope of EIC accelerator R&D was thoroughly reviewed and prioritized at the NP EIC Community Review Panel ("Jones Panel") in November 2016 and the final Panel Report [7] was released in March 2017. A Funding Opportunity Announcement (FOA) [8] with higher funding levels on R&D for next generation nuclear physics accelerator facilities was issued in December 2018; proposals were reviewed, and the award selections have been finalized based on merit of proposals and R&D priorities established by the "Jones Panel".

Accelerator R&D on the following challenging topics is common to all EIC concepts and requires community focus and collaborative effort:

- Strong cooling, in particular the design and validation of high energy ion coolers: the ERL/CCR electron cooler, the micro-bunched electron beam cooler and the FEL based coherent electron cooler; high current un-polarized electron sources beyond state-of-art are also necessary.
- The challenging configuration of the EIC IRs with large crossing angles to allow ~100% detector acceptance drives the R&D on novel types of IR magnets (large acceptance, high fields, radiation resistant) and large crab cavity systems.
- Extensive code development and benchmarking is needed to validate single particle beam dynamics, collective effects and high bandwidth feedback systems, cooling processes, polarization concepts (i.e., figure-8 rings and spin-transparent rapid cycling synchrotron).

FUTURE DIRECTIONS

In addition to working on accelerator and detector design R&D, the EIC community is engaged in many activities necessary to prepare for CD0 and the ensuing formal CD process. The National Academy of Sciences has formally studied the merits of a U.S.-based EIC in 2017 and 2018 and the final report is expected to be released in the next few months, hopefully endorsing the EIC as the premier future facility for nuclear physics.

The U.S. EIC community is engaging very successfully in national and international collaborations, driven by the challenging accelerator and detector R&D.
An EIC Users Group (see Fig. 8) was formed in 2016 and currently lists more than 700 members, and more than 150 institutions in 29 countries with the following membership: 46% in North America, 32% in Europe, 17% in Asia, and 5% from the other regions.

Both the JLEIC and eRHIC design teams are preparing technical pre-conceptual design reports (pre-CDR) to better articulate the physics reach and the respective accelerator and detector design in preparation for the site selection process.

Figure 8: Membership of the EIC Users Group.

CONCLUSIONS

The recognition in the U.S. of the EIC as the highest priority for new construction in nuclear physics has set firm foundations to build this challenging accelerator. Two alternative designs exist at BNL and JLAB that capitalize on the existing RHIC and CEBAF facilities respectively.

In order to achieve the challenging beam requirements, the designs use strong cooling for high luminosity, novel concepts for polarization and a high level of integration between accelerator and detectors in the interaction regions. A strong collaborative R&D program is in place to validate the most challenging design elements.

The EIC program and the nuclear physics community are engaging the national and international scientific communities towards the realization of this challenging and exciting project.

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