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JLEIC: A HIGH LUMINOSITY POLARIZED ELECTRON-ION COLLIDER AT JEFFERSON LAB*

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Abstract

JLEIC, a polarized electron-ion collider for the QCD frontier, was proposed and studied at JLab utilizing the existing CEBAF SRF linacs. The JLEIC accelerator design promises to deliver unrivaled performance in collider luminosity and beam polarization, and outstanding capabilities in detection. In this paper we present a brief summary of the JLEIC accelerator design.

INTRODUCTION

A recent assessment by the US National Academies of Science concluded the science questions that could be answered by an electron-ion collider (EIC) are significant to advancing our understanding of the atomic nuclei that make up all visible matter in the universe [1]. JLEIC, an EIC at JLab, was envisioned as an advanced facility for this science need. Over the past 18 years, JLab, in collaborating with other institutions, has been actively engaged in design study and R&D for JLEIC [2-4]. The study and R&D focus on achieving or exceeding the following machine requirements set by the EIC White Paper [5]:

- **CM energy**: ~20–~100 GeV, upgradable to ~140 GeV for electron-proton (*ep*) collisions, and an equivalent energy range for electron-ion (*eA*) collisions;
- **Particle species**: polarized electrons and a large array of ion species including polarized protons, deuterons and helium-3, as well as un-polarized light to heavy ions up to lead, all ions are fully stripped at collisions;
- **Detectors**: up to two, both supporting full acceptance of particle detection;
- **Luminosity**: in the range of 10^{33} to $>10^{34}$ $cm^{-2}s^{-1}$ per interaction point (IP) over the entire CM energy range for both *ep* and *eA* collisions;
- **Beam Polarization**: higher than 70% in the longitudinal direction at IPs for both beams, and also in the transverse directions for light ion beams only, and with capability of spin flipping (alternate polarization).

The JLEIC design is already mature with stable design concepts for high performance [2-4]. Recent design optimization includes expanding the CM energy to 100 GeV for better science reach. The accelerator R&D focuses on critical accelerator physics studies and selected hardware prototyping. A comprehensive pre-Conceptual Design Report (pre-CDR) [6] was recently completed to summarize this design.

THE JLEIC DESIGN

JLEIC is designed as a ring-ring collider, i.e., both colliding beams are stored in two figure-8 shaped rings shown in Fig. 1. The electron complex includes a new storage ring for 3–12 GeV beam energy, the 12 GeV CEBAF recirculated SRF linac as a full-energy injector, and a transport beam line between them. The electron ring is made of warm magnets, and reuses magnets and vacuum chambers of the decommissioned PEP-II *e+e-* collider for cost efficiency. The design plans to reuse PEP-II ring RF systems (up to 14 MW) as well [7].

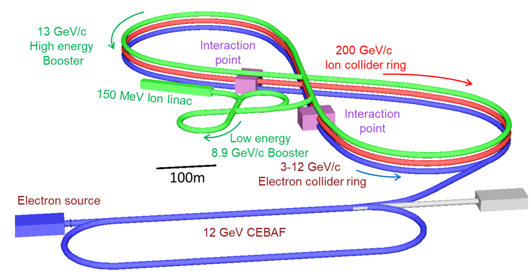

Figure 1: A schematic layout of JLEIC

The JLEIC ion complex shown schematically in Fig. 2 is a green-field design utilizing several advanced concepts and accelerator technologies for performance optimization. It includes polarized and unpolarized ion sources; two RFQs for ions with low and high charge-to-mass ratio respectively; an ion linac made of both warm DTL-type apparatus and a set of SRF cavities [8]; two warm booster synchrotrons, and a collider ring made of cos-theta type high field (up to 6 T) SC magnets. The low and high energy boosters [9] accelerate proton from 150 MeV (the linac energy) to 7.9 GeV and then to 12.1 GeV kinetic energy respectively. The collider ring can accelerate and store protons with energy up to 200 GeV [6]. The complex accelerates and store any ions interested as well to the energies with the same magnetic rigidity as protons.

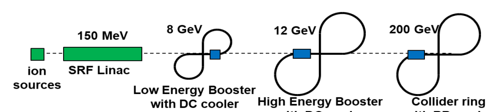

Figure 2: A schematic layout of JLEIC ion complex

The two collider rings and the full-size high energy booster (HEB) have nearly identical footprints so they are stacked vertically and housed inside a common underground tunnel of approximately 2.3 km length. The electrons take a vertical excursion to the plane of the ion collider ring for horizontal crab crossing at each IP, then travel back to the plane of the electron ring.

Table 1 summarizes the JLEIC main design parameters at four representative points, from low to high CM energy. Estimation of the average luminosity assumes 1 or 2 hour beam store either without or with hadron cooling during collisions respectively. The full size high energy

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booster permits a new ion beam being made while another one is in collision in the collider ring. This could reduce the ion collider ring refill time (including detector overhead) to as low as 5 min, critical for a short beam store operation mode, thus boost the machine duty factor. The average luminosity in Table 1 also includes a 75% operational duty factor, most relevant to operation of the facility. To derive these performance, certain limits are imposed on several machine and beam parameters based largely on previous experiences of lepton and hadron colliders and state-of-the-art technologies.

- **Stored beam current**: up to 0.75 A for protons or ions, up to 3.6 A for electrons
- **Synchrotron radiation power**: up to 10 kW/m linearly, thus total 10 MW for the whole electron ring
- **Ion beam space-charge tune-shift**: below 0.06
- **Beam-beam tune-shift at each IP**: not to exceed 0.015 for protons or ions, and 0.15 for electrons

Table 1: JLEIC Design Parameters at Four Representative Design Points

CM energy	GeV	21.9		44.7		63.3		89.4	
		p	e	p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	200	5	200	10
Collision frequency	MHz	476		476		476/4=119		476/4=119	
Particles/bunch	10^{10}	0.59	3.9	0.98	4.7	3	8.9	3.93	4.2
Beam current	A	0.45	3	0.75	3.6	0.57	1.7	0.75	0.8
Polarization	%	85	>85	85	>80	85	>80	85	~80
Bunch length	cm	2.5	1	2.5	1	3.2	1	3.2	1
Norm. emittance, x/y	µm	0.5/0.2	18/3.6	0.65/0.13	83/16.6	1.26/0.5	83/16.6	1.5/0.5	664/133
β*, horiz. / vert.	cm	8/1.3	30/9.8	8/1.3	5.72/0.97	21/1.6	14.5/2.2	19.2/2.3	4/0.8
Beam-beam, x		0.015	0.12	0.015	0.045	0.015	0.136	0.006	0.022
Beam-beam, y		0.01	0.15	0.014	0.041	0.0065	0.120	0.003	0.022
Laslett tune-shift		0.055	small	0.018	Small	0.0039	Small	0.005	Small
Peak luminosity	10^{33}/cm^{2}s	3.2		14.6		9.84		3.8	
Average luminosity	10^{33}/cm^{2}s	2.3		10.5		8.2		1.9	

The JLEIC luminosity is shown in Fig. 3. The plot also shows luminosity for a potential future upgrade to 140 GeV CM energy by increasing proton energy to 400 GeV with new 12 T superconducting magnets installed.

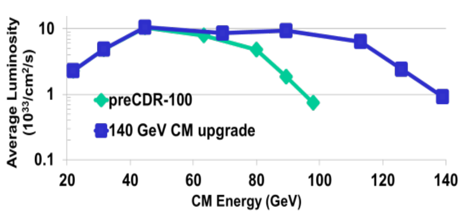

Figure 3: Luminosity performance of JLEIC baseline and its future energy upgrade

CONCEPTS FOR HIGH PERFORMANCE

High Luminosity

JLEIC takes advantage of two design features for delivering high luminosity: a highly polarized electron beam with up to 1.497 GHz bunch repetition rate from CEBAF and a green field ion complex based on modern technologies. The ion complex can be specially designed to deliver beams matching phase-space structure (bunch length and transverse emittance) and time structure (bunch frequency) of the electron beam for implementing a novel three-tier luminosity concept which includes the following ingredients [10]:

- **Colliding beam design**: high bunch repetition rate, low bunch intensity, short bunch, and small transverse emittances
- **Interaction region (IR) design**: very strong final focusing (low beta-star), crab crossing of colliding beams with crab cavities, large attainable beam-beam tune shift
- **Beam damping design**: synchrotron radiation (SR) damping for electrons, strong cooling of hadron beams

JLEIC colliding beams are designed to have short bunch length and small transverse emittance such that strong final focusing can be applied to reduce beam spot sizes to a few µm at IPs, thus increases luminosity. A high bunch frequency ensures very low bunch intensity, which could be up to 20 times less than these traditional hadron colliders, while maintaining high average current. Low bunch intensity leads to much weaker collective beam effects, therefore, short bunch length and small transverse emittance can be achieved.

With high bunch frequency, the bunch spacing is very small; crab crossing of colliding beams must be implemented to quickly separate two beams and avoid parasitic collisions. To prevent luminosity loss caused from the crossing angle, SRF crab cavities will be installed on both sides of an IP for both beams for restoring head-on collisions in the CM frame.

This novel luminosity concept was successful implemented in several *e+e-* colliders and led to highest luminosity at the KEK-B factory. By adopting this concept, JLEIC is designed like a lepton-lepton collider for achieving a same success of high luminosity.

High Polarization

The unique figure-8 shape of the four JLEIC rings was chosen for superior ion beam polarization. The idea behind a figure-8 ring concept [11] is simple: spin precessions in two half arcs are exactly cancelled, thus the spin tune in the ring is zero, therefore energy independent. This automatically prevents depolarization during acceleration, thus superior to the conventional race-track synchrotrons. The spin tune can be further moved away from

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zero by spin rotators of very low integrated magnetic field. The figure-8 design also provides the only practical solution to accelerate and store a polarized deuteron beam in the medium to high energy range, given the present accelerator technology. Simulation studies already demonstrated the JLEIC proton and deuteron polarization could be as high as 85% [6].

Full Acceptance Detection

The key process in EIC is deep inelastic scatterings. Due to a large asymmetry in the electron and ion momenta, particles that are interested to be detected tend to go at very small forwarding angles related to the direction of ion motion. Design of the JLEIC detector and interaction region (IR) was geared for supporting such forwarding detection. Particularly, these particles with extremely small angles will pass through apertures of the ion final focusing quadrupoles (FFQ), and be captured in the detectors further down-stream. Therefore, apertures of the ion FFQs must be sufficiently large to provide the acceptance required by experiments. On the other hand, the FFQs should be placed as close to IPs as possible to maximize the luminosity. The JLEIC IR design shown in Fig. 4 has found a balance of these conflict requirements, thus overcomes the serious detection, optics and engineering design challenges [12].

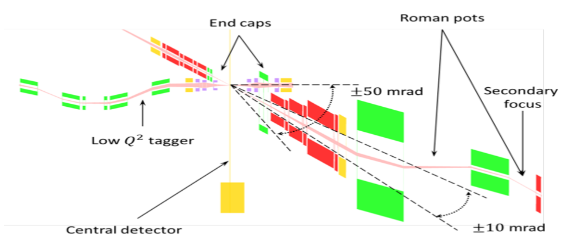

Figure 4: Layout of the full-acceptance detector region.

MULTISTAGED ELECTRON COOLING

Cooling of hadron beams is essential for achieving a reduction of the proton and ion beam emittance up to an order of magnitude in all directions, thus delivering a very short bunch with a very small beam spot at collisions. It could also counteract the IBS induced emittance growth during beam store, thus extending the luminosity lifetime.

The JLEIC choice is conventional electron cooling, a proven technology at low energies. JLEIC has also adopted a multi-staged scheme [13] which utilizes cooling during formation of ion beams, particularly including an initial pre-cooling at low energy, and also during collision for enhancing the cooling efficiency. This scheme is based on a simple fact that the cooling time is proportional to ion beam 6D emittances and roughly square of beam energy. Therefore, cooling is more efficient when ion energy is low. At collision energies, the cooling time also sees a reduction due to a much smaller emittance as a result of the pre-cooling at low energy. Combining both cooling phases, it is expected the total cooling time could be orders of magnitude shorter than that of performing cooling only at high (collision) energy. This is critical to reach high integrated luminosity

Table 2 summarizes the multiple cooling phases for both proton and lead ion beams [4]. Pre-cooling is done by a DC cooler in the high energy booster after stacking is completed. In the collider ring, the beams are boosted to collision energies and promptly cooled by a high energy electron beam for conditioning and maintaining the ion beam emittance. Providing a high current cooling beam is a significant technical challenge. Design study of such a cooler based on energy recovery linac (ERL) and circulator ring is in progress. Figure 5 illustrates the design of this type of cooler [14].

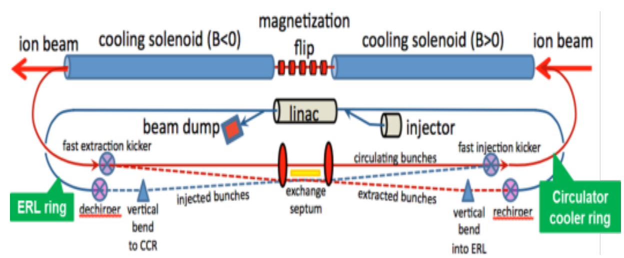

Figure 4: Layout of the JLEIC ERL-circulator cooler.

A critical R&D is proof of cooling of ions by a bunched electron beam which had never been done before. A proof-of-principle experiment was performed utilizing a DC electron cooler at the Institute of Modern Physics in China. A bunched beam was generated by modulating the gate voltage of the thermionic cathode. The experiment successful demonstrated for the first time both longitudinal and transfer cooling of ions [15-16]. This retires one technical risk of the JLEIC design.

CONCLUSIONS

JLEIC will deliver superior performance essential for the QCD frontier, preeminent in nuclear physics for decades to come. Accelerator R&D will be continuously carried out for further improvement of the design for performance enhancement and cost efficiency, and for technology readiness.

Table 2: Multi-Staged Electron Cooling at JLEIC

Ring	Functions	Kinetic energy (GeV / MeV)			Cooler type
		Proton	Lead ion (Pb)	Electron	
LE Booster	Accumulation of positive ions		0.1 (injection)	0.054	DC
HE booster	Maintain emitt. during stacking	7.9 (injection)	2 (injection)	4.3 (p) or 1.1 (Pb)	DC
	Pre-cooling for emitt. reduction	7.9 (injection)	7.9 (ramp to)	4.3	
Collider ring	Maintain emitt. during collision	Up to 150	Up to 60	Up to 81.8	ERL

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