ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOOHC2

THE US ELECTRON-ION COLLIDER ACCELERATOR DESIGNS

A. Seryi*, Jefferson Lab, Newport News, VA; F. Willeke, BNL, Upton, NY
Z. Conway, M. Kelly, B. Mustapha, U. Wienands, A. Zholents, ANL, Lemont, IL
E. Aschenauer, G. Bassi, J. Beebe-Wang, J.S. Berg, M. Blaskiewicz, A. Blednykh, J.M. Brennan, S. Brooks, K.A. Brown, K.A. Drees, A.V. Fedotov, W. Fischer, D. Gassner, W. Guo, Y. Hao, A. Hershcovitch, H. Huang, W.A. Jackson, J. Kewisch, A. Kiselev, C. Liu, V. Litvinenko, H. Lovelace III, Y. Luo, F. Meot, M. Minty, C. Montag, R.B. Palmer, B. Parker, S. Peggs, V. Ptitsyn, V.H. Ranjbar, G. Robert-Demolaize, T. Roser, S. Seletskiy, V. Smaluk, K.S. Smith, S. Tepikian, P. Thieberger, D. Trbojevic, N. Tsoupas, E. Wang, W.-T. Weng, H. Witte, Q. Wu, W. Xu, A. Zaltsman, W. Zhang, BNL, Upton, NY; D. Barber, DESY, Hamburg, Germany
T. Mastoridis, California Polytechnic State University, San Luis Obispo, CA
I. Bazarov, K. Deitrick, G. Hoffstaetter, Cornell University, Ithaca, NY
D. Teytelman, Dimtel Inc., Redwood City, CA; Z. Zhao, Duke University, Durham, NC
S. Benson, A. Bogacz, P. Brindza, M. Bruker, A. Camsonne, E. Daly, P. Degtyarenko, Ya. Derbenev, M. Diefenthaler, J. Dolbeck, D. Douglas, R. Ent, R. Fair, D. Fazenbaker, Y. Furletova, R. Gamage, D. Gaskell, R. Geng, P. Ghoshal, J. Grames, J. Guo, F. Hannon, L. Harwood, S. Henderson, H. Huang, A. Hutton, K. Jordan, D. Kashy, A. Kimber, G. Krafft, R. Lassiter, R. Li, F. Lin, M. Mamun, F. Marhauser, R. McKeown, T. Michalski, V. Morozov, E. Nissen, G. Park, H. Park, M. Poelker, T. Powers, R. Rajput-Ghoshal, R. Rimmer, Y. Roblin, D. Romanov, P. Rossi, T. Satogata, M. Spata, R. Suleiman, A. Sy, C. Tennant, H. Wang, S. Wang, C. Weiss, M. Wiseman, W. Wittmer, R. Yoshida, H. Zhang, S. Zhang, Y. Zhang, Jefferson Lab, Newport News VA
E. Gianfelice-Wendt, S. Nagaitsev, Fermilab, Batavia, IL
J. Qiang, G. Sabbi, Lawrence Berkeley National Laboratory, Berkeley, CA
J. Maxwell, R. Milner, M. Musgrave, Massachussetts Institute of Technology, Cambridge, MA
Y. Hao, P. Ostroumov, A. Plastun, R. York, Michigan State University, East Lansing MI
V. Dudnikov, R. Johnson, Muons, Inc., IL
B. Erdelyi, P. Piot, Northern Illinois University, DeKalb, IL
S. De Silva, J. Delayen, C. Hyde, S. Sosa, B. Terzic, Old Dominion University, Norfolk, VA
D. Abell, D. Bruhwiler, I. Pogorelov, Radiasoft LLC, Boulder, CO
Y. Cai, Y. Nosochkov, A. Novokhatski, G. Stupakov, M. Sullivan, C. Tsai, SLAC, Menlo Park, CA
J. Fox, Stanford University, Menlo Park, CA; G. Bell, J. Cary, Tech-X Corp., Boulder, CO
P. Nadel-Turonski, Stony Brook University, Stony Brook, NY
J. Gerity, T. Mann, P. McIntyre, N. Pogue, A. Sattarov, Texas A&M University, College Station, TX

Abstract

With the completion of the National Academies of Sciences Assessment of a US Electron-Ion Collider, the prospects for construction of such a facility have taken a step forward. This paper provides an overview of the two site-specific EIC designs: JLEIC (Jefferson Lab) and eRHIC (BNL) as well as brief overview of ongoing EIC R&D.

EIC DESIGNS OVERVIEW

The Electron-Ion Collider – the instrument that will enable deeper understanding of quark-gluon structure of matter – was selected in the joint DOE-NSF U.S. Nuclear Physics Long Range plans of 2007 [1] and 2015 [2] as the top priority for R&D (2007) and new construction (2015). These recommendations were reinforced in 2018 by the National Academies of Science assessment of US-based EIC science [3]. The requirements of an EIC as described in the White Paper [4] include: "highly polarized (~70%) electron and nucleon beams; ion beams from deuteron to the heaviest nuclei (uranium or lead); variable center of mass energies from ~20 to ~100 GeV, upgradable to ~140 GeV; high collision luminosity of ~10^{33}-10^{34} $cm^{-2}s^{-1}$; possibilities of having more than one interaction region". A multi-laboratory collaboration is presently working on two site-specific EIC designs – eRHIC [5] and JLEIC [6]. Both designs are based on ring-ring approach and both benefit from existing Nuclear Physics infrastructure.

eRHIC design takes full advantage of the existing accelerator infrastructure of the RHIC complex at BNL, using the Yellow Ring of the RHIC heavy ion collider together with the entire hadron beam injector chain (Fig. 1). A new electron storage ring in the RHIC tunnel will provide polarized

* seryi@jlab.org

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOOHC2

electron beams for collisions between electrons and polarized protons or heavy ions. Polarized electrons are provided by a full-energy spin transparent rapid cycling synchrotron (RCS) located in the RHIC tunnel. RHIC hadron rings modifications aimed to accommodate the three-fold increased beam current and larger number of bunches include in-situ application of copper and amorphous carbon layers in the vacuum chamber to reduce the SEY and thus suppress the formation of electron clouds. The CM energy in e-p collisions ranges from 20 to 141 GeV, accomplished by colliding 2.5 to 18 GeV electrons with 41 to 275 GeV protons.

JLEIC takes full advantage of the 12 GeV CEBAF of JLab that will serve as high polarization full-energy electron beam injector for JLEIC (Fig. 2). The JLEIC boosters and collider rings are based on an innovative figure-8 layout that has high spin transparency built into the design. The CM energy in e-p collisions ranges from ~20 to ~100 GeV, accomplished by colliding ~3 to 12 GeV electrons with ~30 to 200 GeV protons. Upgrade to 140 GeV can be accomplished by doubling the energy of the ion ring. The two collider rings of JLEIC are stacked vertically and have nearly identical circumferences of ~2.3 km, housed in a cut-and-cover tunnel next to CEBAF. The electron beamline follows a vertical excursion to the plane of the ion ring to realize e-p collisions. The two long straight sections accommodate two IPs, injection/ejection, RF system, electron cooling and polarimetry.

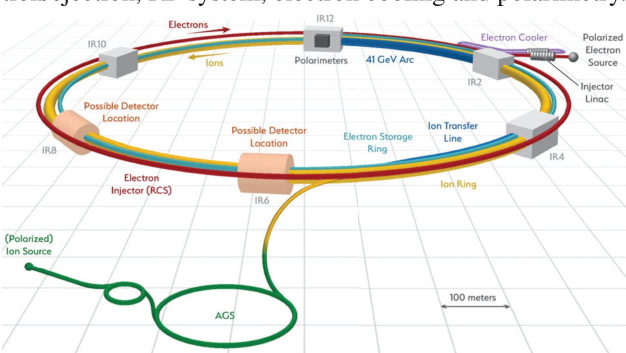

Figure 1: Layout of eRHIC.

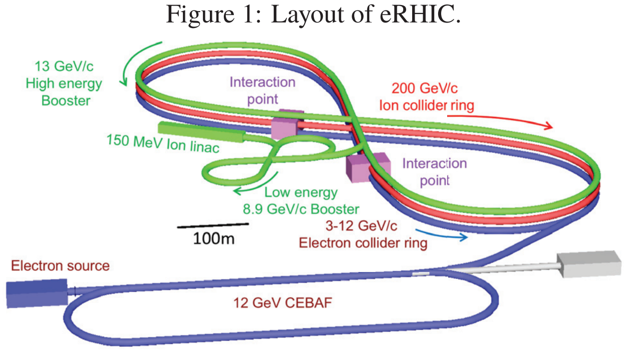

Figure 2: Layout of JLEIC.

LUMINOSITY AND GLOBAL PARAMETERS

The EIC accelerator challenges are twofold: a high degree of polarization for both beams, and high luminosity. Both designs were optimized [5, 6] to address these challenges and to meet requirements of the White Paper. Figure 3 shows the peak luminosity curves for baseline designs of JLEIC and eRHIC, for JLEIC 140 GeV CM upgrade, and for alternative optimization of eRHIC 2nd IP.

The relation of the peak luminosity to the average one varies with CM energy and operational assumptions. and is illustrated in Table 1, where key accelerator and MDI parameters of the designs are also shown for one selected energy from each of four curves of Fig. 3. The designs plan to operate in regimes when intra-beam scattering (IBS) effects define collider optimization. The IBS time ranges from 25 min to few hours for eRHIC and from 5 min to few tens of minutes for JLEIC. The IBS effects will typically be counteracted by beam cooling, strong coherent or strong incoherent cooling. JLEIC data in Table 1 rely on strong incoherent cooling. When proton beam energy is >150 GeV, the incoherent cooling is less effective but IBS is also weak, and the integrated luminosity can be optimized by a scheme of frequent replacement of the stored ion beams. Correspondingly, JLEIC-upgrade will not use strong cooling, and relies instead on DC cooling in a booster and hourly beam refills. Similarly, for eRHIC parameters shown in Tab. 1 strong hadron cooling is not required as there is an on-energy injector which provides a fresh hadron beam every hour. In this case, two options exist for pre-cooling, a DC cooler in the AGS injector or an ERL-based incoherent cooler at eRHIC ion injection energy. The IBS and cooling dynamics is one of many areas where the team is working on cross-comparison of calculations using various design codes.

The average luminosity shown in the Table 1 is calculated over one store-and-refill cycle. The average luminosity for extended running would typically be reduced to ~75% due to machine availability.

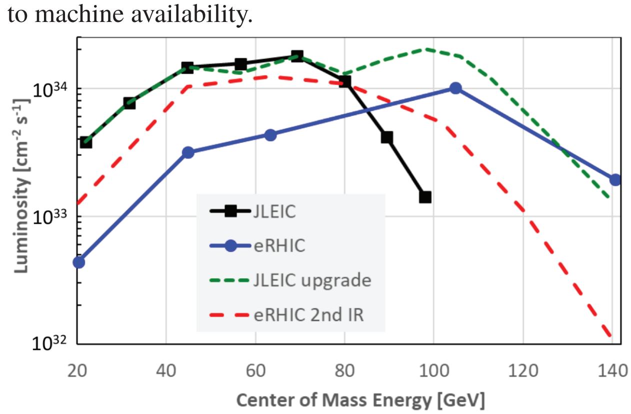

Figure 3: Peak luminosity.

MACHINE DETECTOR INTERFACE

The EIC physics requires nearly 100% acceptance, including stringent requirements on the detection of final state particles in the directions along the beamline. To address these requirements both designs use a crossing angle, compensated by crab cavities, and arrange the magnet apertures and locations of detectors to allow large forward coverage. In particular, Table 1 defines two acceptances: forward acceptance defined by the aperture of the first dipole, and far-forward

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOOHC2

Table 1: EIC Parameters for Selected Energies of Cases Shown in Fig. 3

design	eRHIC		JLEIC		eRHIC-opt.		JLEIC-upgrade	
parameter	proton	electron	proton	electron	proton	electron	proton	electron
center-of-mass energy [GeV]	104.9		44.7		63.3		105.8	
energy [GeV]	275	10	100	5	100	10	400	7
number of bunches	1160		3456		2320		864	
particles per bunch [10^{10}]	6.9	17.2	1.06	4.72	3.4	8.6	4.2	19.3
beam current [A]	1.0	2.5	0.75	3.35	1.0	2.5	0.75	3.4
beam polarization [%]	80	80	85	85	80	80	85	85
total crossing angle [mrad]	25		50		50		50	
ion forward acceptances [mrad]	±20/±4.5		±50/±10		±35/±8		±50/±5.6	
h./v. norm. emittance [μm]	2.8/0.45	391/24	0.65/0.13	83/16.6	1.5/0.15	391/24	3/0.5	228/45.6
bunch length [cm]	6	2	2.5	1	4	2	3.5	1
β_x^* / β_y^* [cm]	90 / 4.0	43 / 5.0	8 / 1.3	5.72 / 0.93	18 / 2	13 / 2.4	40 / 2.25	16.9 / 0.8
hor./vert. beam-beam param.	.014/.007	.073/.1	.015/.0135	.049/.044	.012/.013	.036/.062	.014/.008	.076/.037
peak lumi. [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1.01		1.46		1.24		1.78	
average lumi. [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	0.93*		1.4		0.95*		1.47*	

* L_{ave} numbers without strong cooling

acceptance defined by the apertures of the quadrupoles. The IR layouts of both designs and forward acceptances are illustrated in Fig. 4 and Fig. 5 and MDI designs are discussed in more detail in [7].

Similar techniques will be used to measure the electron and proton beam polarizations in both designs – Compton polarimetry for electrons and systems built on the RHIC successful multi prong approach for proton polarimetry. In the JLEIC the Compton polarimeter is located in a 4-dipole chicane just after the IR and will measure the longitudinal polarization of the beam, with an emphasis on detecting the Compton scattered electron. The eRHIC Compton Polarimeter will be located at a dedicated IR where the electron polarization is transverse. In both designs a polarized hydrogen jet target-based polarimeter will provide absolute measurements of the proton beam polarization on the time scale of several hours, while a p-Carbon polarimeter will be used to make fast, relative measurements of the polarization. The bremsstrahlung process $e + p \rightarrow e + p + \gamma$ will be used as reference process to measure luminosity [8] at EIC.

IR MAGNETS AND ENGINEERING DESIGN

The IR of both concepts is based on standard NbTi technology. The beam pipe for the hadron beam can be cold, whereas the electron beam pipe will be warm. The eRHIC IR [9] requires 15 new superconducting (SC) magnets: nine are anticipated to be made using BNL's direct wind technology [10–12] and four based on conventional collared coils with a Rutherford cable. The first magnet in the eRHIC hadron forward direction is a 1.3T large aperture super-ferric spectrometer dipole, inside of which is the first electron quadrupole, shielded from the dipole field with a bucking dipole and an iron shield.

The JLEIC IR requires 24 new SC magnets; 3 final focus quadrupoles on either side of the IP for both electrons and ions, anti-solenoids, as well as skew quads and ion beam

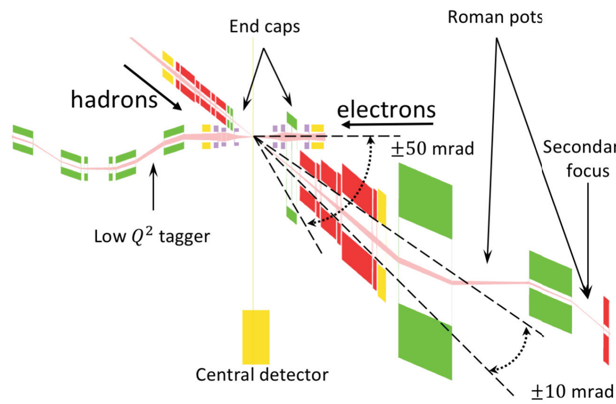

Figure 4: JLEIC IR layout.

correctors. All magnets are based on standard NbTi technology with a Rutherford cable. Additional to the individual beamline IR magnets are 3 SC spectrometer dipoles which steer particles to the detector system in the ion downstream portion of the IR [13–17].

COLLIDER RINGS

The JLEIC ion collider ring accelerates up to 0.75 A ion beams from 13 to 200 GeV/c. The ring design uses only conventional NbTi 6 T magnets operated at 4 K. Chromaticity is compensated locally using -I sextupole pairs. The JLEIC electron collider ring is designed [18, 19] to deliver an electron beam in an energy range of 3-12 GeV with high current (up to ~3A) and polarization (85%). PEP-II magnets and RF cavities are reused to reduce the project cost. The existing Yellow RHIC ring with its 4 T SC magnets will serve as the eRHIC hadron storage ring. An electron ring with a maximum energy of 18 GeV will be installed in the same 3.8 km tunnel. Super-bends will be utilized to achieve the required emittances and radiation damping rates at energies below 10 GeV. Dynamic aperture studies in the electron ring have resulted in 20σ transverse DA and a momentum acceptance of 12σ, while results for the hadron ring are very similar to present RHIC.

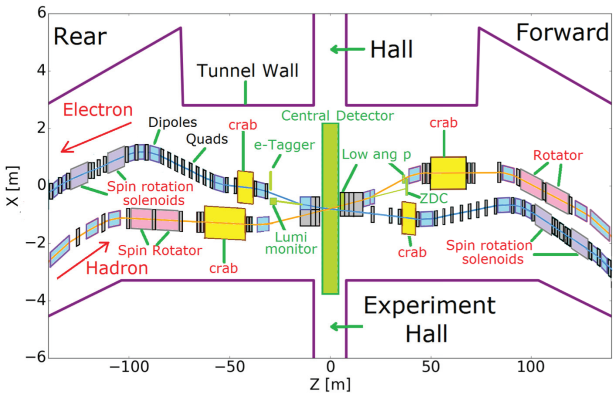

Figure 5: eRHIC IR layout.

INJECTION CHAIN

JLEIC uses CEBAF as a full energy electron injector, which operates in pulse mode for both injection and top-off with long bunch trains of ~3.6 μs and ~7 nC total charge [20]. JLEIC ion injector chain will contain a few ion sources, a 150 MeV ion linac with warm front ends, a figure-8 low energy booster of 8.9 GeV/c with a low voltage DC cooler, and a fullsize high energy booster/stacker [21] of 13.0 GeV/c with a 4.3 MV DC cooler. eRHIC will build a new 400 MeV linac plus an 18 GeV 1-2 Hz RCS in the existing RHIC tunnel as a polarized electron injector. Ion beam will be delivered using the existing RHIC ion accelerator chain. Minor upgrades are needed to accommodate higher bunch repetition rate and higher polarization transmission, including new RHIC injection line and kickers as well as upgraded polarization preservation in the AGS.

POLARIZATION

With JLEIC's figure-8 design, the primary effect of the ring arcs on the spin is compensated [22]. Our studies show efficient preservation, maintenance, control and manipulation of the polarization of any particle species (including protons, deuterons, $^3He^{++}$, $^6Li^{+++}$) using only weak magnetic field integrals not perturbing the beam. High polarization of JLEIC electron beam is provided by two design features, the CEBAF SRF linac as a full-energy injector of a highly polarized beam and vertical spin orientations alternatively parallel and antiparallel to the dipole fields in the two arcs of the figure-8 ring to neutralize the radiative Sokolov-Ternov effect on the polarization [23].

eRHIC will fully reuse the existing capabilities of RHIC accelerator complex for proton polarized beam, including spin harmonic control, partial snakes and tune jump system in injectors, and helical Siberian snakes and spin rotators in the hadron ring. The capability of accelerating polarized ^3He [24] and deuterons will be added and the number of Siberian snakes will be increased from two to six. Accelerating polarized deuterons will require use of a tune jump system and a partial snake. Both the electron and ion storage rings will simultaneously store bunches with ↑ and ↓ spin orientations. As the electron bunch polarization decays due to self-polarization and stochastic depolarization, the bunches will be replaced to maintain high average polarization, using 2 Hz injector based on a source similar to one used in SLC [25]. The RCS lattice employs high symmetry which moves all strong spin resonances out of the acceleration range [26], ensuring polarization preservation during acceleration.

COOLING

The need for small emittances and energy spreads required for the EIC suggests using electron beam cooling to maintain high luminosity ($L_{av} \approx 10^{34}$) during collisions. Since the cooling time is proportional to the square of the energy, it makes sense to cool beams initially at low energy. This can be done in the hadron boosters before the bunches are formed. If the bunches are then quickly formed and accelerated to full energy before IBS blows up the beam, the low emittance and energy spread from the cooling can be preserved at the collision energy [27]. This cooling can be done with conventional DC coolers [28, 29]. Using a magnetized beam can reduce the cooling time further. At the collision energy, both cooling rates and IBS are smaller and, if the emittance starts out small, cooling can hold it. If conventional incoherent cooling is used, very high current and magnetized cooling are required and the net cooling drops below the IBS heating for a proton energy over ~100 GeV [30]. Coherent electron Cooling (CeC) provides stronger cooling for a given current and can, in principle, be used for proton energies as high as 280 GeV, though the beam quality must be very high and the noise on the beam must be close to the shot noise minimum [31–34]. As noted above, this might not be needed at the highest proton energy if one swaps out fresh beams. The cooling rate is proportional to the square of the atomic number Z, so both incoherent and coherent electron cooling are very effective at reducing the emittance and increasing the beam lifetime. The electron beams themselves are provided by Energy Recovery Linacs (ERLs). While the ~100 mA beam required for a CeC cooler can be provided by an ERL directly, an incoherent high-energy cooler necessitates amplification of the current via a Circulating Cooler ring that uses the bunches multiple times before energy recovering them [35, 36].

RF SYSTEMS

Both EIC designs make luminosity through high average currents and many bunches and therefore have very similar RF challenges. A mixture of NCRF and SRF systems are foreseen covering beam capture, splitting, acceleration, bunching and crabbing. High currents in the electron rings will produce significant synchrotron radiation power, capped at 10 MW in both designs, and will require all cavities to be strongly HOM damped to ensure beam stability. Those cavity dampers will couple kWs of HOM power to room temperature absorbing loads. In the ion ring, high installed voltage will be provided by new SRF cavities to achieve the

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOOHC2

short bunch lengths. Given the high average current, these cavities will also need strong HOM damping. Since both designs use a crossing angle, strong crabbing is needed and will be provided by new SRF cavities similar to those being developed for the Hi-Lumi LHC. The high-current rings will need gaps for beam abort, e-cloud or ion clearing and will therefore experience strong transient beam loading. Fortunately the projects can draw on decades of experience from the B-Factories, RHIC and LHC in the design and operation of these devices and systems. While these installations are challenging and much detailed engineering work lies ahead, they are within the limits of previously demonstrated technology.

BEAM DYNAMICS AND IMPEDANCES

The collective effect studies for an EIC need to ensure beam stability for a wide range of beam collision energies and for the ion bunch formation process [37]. For both designs, broadband impedances have been estimated based on impedance budgets of existing machines, and narrowband impedances are due to RF cavities and wall resistance. The e-beam at low energies will require split dipoles (or damping wigglers), for enhancing energy spread to suppress the longitudinal microwave instability in JLEIC and for achieving the large beam-beam tune shifts in eRHIC. For the electron beam, feedback mitigates the longitudinal coupled bunch instability, and the beam-beam tune spread Landau damps the transverse coupled bunch instability as well as the ion induced instability. The ion beams feature high bunch number and high peak current. Measurements of coupled bunch growth rates in RHIC are planned and will be compared with the expected results, benefitting longitudinal damper designs for both machines. Beam image currents heat the vacuum chamber and add additional load to the cryogenic system. This is dealt with by coating the vacuum chamber with copper, retroactively in the case of RHIC. An additional coating of amorphous carbon, or perhaps some sort of engineered surface, will suppress electron cloud build-up.

HIGH LUMINOSITY ERHIC OPTIMIZATION FOR 63 GEV CM

The eRHIC parameters and the IR have been optimized to maximize the luminosity and the forward acceptance in 80-140 GeV CM energy range. Recognizing a potential need in the highest possible luminosity at lower CM energies (30-80 GeV), specific beam parameters and IR modifications have been developed leading to 10^{34} luminosity at the lower CM energies. Such an IR together with a dedicated detector can be allocated, e.g., in the second collision point of eRHIC. The modifications of the IR design with respect to the high-energy optimized one include increased crossing angle (up to 50 mrad) which would help to arrange closely spaced hadron and electron magnets and allow for larger number of bunches. Larger aperture hadron magnets are used to increase forward acceptance at lower energies and accommodate for increased beam size. The IR focusing electron quadrupoles are moved much closer to the IP, with the first quadrupole placed inside the detector enclosure. All this allows to implement lower IP beta-functions (down to 2 cm) in the electron and proton IR lattices. Also, the large divergence of electron beam in the collision point can be accommodated (up to 0.4 mrad). In addition the beam parameters modification for low energy optimized design involve smaller proton emittances and bunch length and increased number of bunches. The corresponding luminosity curve for this low E optimized design solution is shown in Fig. 3 and 63 GeV CM beam parameter set is listed in the Table 1. It should be noted that decreased IP beta-functions lead to increase of natural IR chromaticity, especially for protons. Thus, the managing the dynamic aperture becomes more critical. And increased bunch frequency will be more demanding for bunch-by-bunch proton polarization measurements.

JLEIC UPGRADE TO 140 GEV CM

The JLEIC-upgrade reaches 140 GeV CM energy by doubling the maximum energy of the ion collider ring from 200 GeV to 400 GeV, while keeping the electron complex and injector unchanged. The upgrade uses the same high luminosity and polarizations design concepts of JLEIC to deliver the same high performance (see Fig. 3 and Table 1). The final focusing quadrupoles will be reused, they are moved further away from IP. The secondary beam focus in both planes downstream of the forward final focusing block will be preserved as required by the physics measurements. The arc dipole magnets will be upgraded, entailing removal of all cryostats containing dipoles. The 6T NbTi dipoles will be directly replaced with new 12T Nb_3Sn dipoles, while the arc quadrupoles will be reused. The higher field magnets will be realigned in the existing cryostats, tested, and then reinstalled in the ion collider ring. The required level of dipole performance has been demonstrated in the LBNL D20 [38], EuCARD's FRESCA2 [39–41], and most recently the >14T dipole developed by FNAL as part of the US MDP (Magnet Development Program) [42, 43]. Each of these magnets has exceeded the performance requirements for the JLEIC ion collider ring at 400 GeV at 4.5K operation. The dipole design will be based on a graded multi-layer $\cos\theta$ coils wound from keystoned, Nb_3Sn SC Rutherford cable with a stainless steel shield layer [44], supported by a laminated cold steel yoke. A clamp assembly will secure the two halves of the yoke in place. Finally, a stainless steel outer shell will be welded around the yoke and acts as the helium vessel. The dipoles will be built as straight, 4m long magnets.

EIC R&D

Both proposed implementations for the EIC contain the same or similar design and technology elements (e.g. crab cavities, hadron beam cooling) and therefore share the associated risks and R&D. The pre-project R&D targeting the R&D items identified by the Jones Panel Report [45] is shared between BNL and Jefferson Lab as leads and includes

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOOHC2

collaborations from universities, industry and other national labs. This partnership is expected to grow further, once CD-0 is awarded, to play a significant role in the realization of the EIC. In addition there are R&D items specific to each design (eRHIC: electron storage ring extraction kickers; JLEIC: figure 8 spin transparency) that are perused independently by BNL and Jefferson Lab with partners. Through design optimizations and alternate technology choices, selected technology elements from the Jones Report (JLEIC: strong incoherent electron cooling, gear change; eRHIC: high current polarized electron sources, high peak current injector linac) are no longer required for achieving specified EIC performance [2]. The strong incoherent electron cooling effort for the JLEIC is continued, as it further increases the luminosity between 20 and 55 GeV CM reducing the time for dataset accumulation. Micro-bunched electron cooling is under active study as a FOA and is the baseline technique for achieving an eRHIC average luminosity of $L_{avg} = 1.0 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ at 100 GeV CM. Using the Blue ring as an on energy injector, with no cooling, reduces this by 5% while no mitigation yields $L_{avg} = 0.33 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$. This ongoing R&D and optimization effort has already significantly matured the targeted technology so that by the efforts completion the main technology elements will have sufficiently matured. R&D plans of both EIC concepts focus on efforts towards cost and/or schedule risk reduction as well as remaining activities for strong electron cooling.

CONCLUSION

The future EIC will be much more capable and much more challenging to build than earlier electron or polarized proton machines. It will be the most sophisticated and challenging accelerator currently proposed for construction in the United States and will significantly advance accelerator science and technology in the US and around the world. The EIC design team is working on optimization and analyzing the performance of both design concepts and is looking forward for collaborative efforts for making the EIC a reality.

ACKNOWLEDGMENTS

U.S. R&D efforts on EIC are supported by the DOE Office of Nuclear Physics. Authored and supported by Jefferson Science Associates LLC under U.S.DOE Contract DE-AC05-06OR23177. Supported by Brookhaven Science Associates LLC under U.S.DOE Contract DE-AC02-98CH10886. Supported by U.S.DOE under Contracts No. DE-AC02-06CH11357 (ANL), DE-AC05-06OR23177 (Fermilab), DEAC02-05CH11231 (LBNL), DE-AC02-76F00515 (SLAC).

REFERENCES

[1] R. Tribble *et al.*, "The frontiers of nuclear science: a long range plan", arXiv:0809.3137 [nucl-ex], December 2007.

[2] A. Aprahamian *et al.*, "Reaching for the horizon: the 2015 long range plan for nuclear science", October 2015.

[3] National Academies of Sciences, Engineering, and Medicine, "An assessment of U.S.-based electron-ion collider science". Washington, DC: The National Academies Press, 2018. doi:10.17226/25171

[4] A. Accardi *et al.*, "Electron ion collider: the next QCD frontier – understanding the glue that binds us all", *Eur. Phys. J. A*, vol. 52, p. 268, 2016.

[5] C. Montag *et al.*, "eRHIC design update", presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Sep. 2019, paper MOYBA4.

[6] Y. Zhang *et al.*, "JLEIC: a high luminosity polarized electron-ion collider at Jefferson Lab", presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Sep. 2019, paper MOYBA3.

[7] B. Parker *et al.*, "Electron ion collider machine detector interface", presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Sep. 2019, paper TUZBA2, this conference.

[8] L. Adamczyk *et al.*"Measurement of the luminosity in the ZEUS experiment at HERA II", *Nucl. Instrum. Meth. A*, vol. 744, p. 80, 2014.

[9] H. Witte, R.B. Palmer, and B. Parker, "Options for the spectrometer magnet of the eRHIC IR", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2401–2403. doi:10.18429/JACoW-IPAC2018-WEPMF017

[10] B. Parker *et al.*, "Superconducting corrector IR magnet production for SuperKEKB", in *Proc. North American Particle Accelerator Conf. (NAPAC'13)*, Pasadena, CA, USA, Sep.-Oct. 2013, paper THPBA07, pp. 1241–1243.

[11] H. Witte, B. Parker and R. Palmer, "Design of a ta ered final focusing magnet for eRHIC", *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, p. 4004105, Aug. 2019.

[12] B. Parker *et al.*, "BNL direct wind superconducting magnets", *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4101604, June 2012.

[13] M. Sullivan, "SR background update for JLEIC", talk presented at JLEIC Collaboration Meeting, March 2, 2018.

[14] R. Rajput-Ghoshal *et al.*, "Conceptual design of the IR magnets for future electron-ion collider at Jefferson Lab", *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, Aug. 2019.

[15] M. Wiseman *et al.*, "Preliminary design of the IR beam transport systems for JLEIC", *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, Aug. 2019.

[16] R. Rajput-Ghoshal *et al.*, "Interaction region magnets for future electron-ion collider at Jefferson Lab", presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Sep. 2019, paper TUZBA4.

[17] R. Rajput-Ghoshal *et al.*, "Optimization of an IR quadrupoles for future EIC at JLab", to be presented at International Conference on Magnet Technology, MT'26, 2019.

[18] F. Lin *et al.*, "Update on the JLEIC electron collider ring design", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2780–2782. doi:10.18429/JACoW-IPAC2019-WEPGW121

[19] Y. Nosochkov *et al.*, "Dynamica aperture of JLEIC electron collider ring with errors and correction", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1920–1923. doi:10.18429/JACoW-IPAC2019-TUPRB113

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-MOOHC2

[20] J. Guo *et al.*, "Pulsed operation of CEBAF for JLEIC injection", in *Proc. 29th Linear Accelerator Conf. (LINAC'18)*, Beijing, China, Sep. 2018, pp. 682–684. doi:10.18429/JACoW-LINAC2018-THPO004

[21] E.A. Nissen, "An increased extraction energy booster complex for the Jefferson Lab Electron Ion Collider", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 797–798. doi:10.18429/JACoW-IPAC2019-MOPRB098

[22] A.M. Kondratenko *et al.*, "Ion polarization Schemes for MEIC", arXiv:1604.05632 [phys.acc-ph], 2016. https://arxiv.org/abs/1604.05632

[23] F. Lin *et al.*, "JLEIC – the Jefferson Lab Electron-Ion Collider", presentation in 23rd International Spin Symposium (SPIN2018), Ferrara, Italy, 2018. https://agenda.infn.it/event/12464/contributions/14217/

[24] M. Musgrave *et al.*, "Polarized $^3He^{++}$ Ion Source for RHIC and an EIC", Proceeding of Science (PSTP2017), p. 20, 2017. https://doi.org/10.22323/1.324.0020

[25] D. Schultz *et al.*, "The high peak current polarized electron source of the Stanford Linear Collider", *Nucl. Instrum. Methods A*, vol. 340, p. 127, 1994.

[26] V.H. Ranjbar *et al.*, "Spin resonance free electron ring injector", *Phys. Rev. Accel. Beams*, vol. 21, p. 111003, 2018.

[27] Y.S. Derbenev, "Electron cooling for future Electron-Ion Collider at JLAB", in *Proc. 7th Workshop on Beam Cooling and Related Topics (COOL'09)*, Lanzhou, China, Aug.-Sep. 2009, paper FRM2MCCO01, pp. 181–184.

[28] S. Nagaitsev *et al.*, "Experimental demonstration of relativistic electron cooling", *Phys. Rev. Lett.*, vol. 96, p. 044801, 2006.

[29] V. Kamerdzhiev *et al.*, "2 MeV electron cooler for COSY and HESR – First Results", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, pp. 765–767. doi:10.18429/JACoW-IPAC2014-MOPRI070 .

[30] S.V. Benson *et al.*, "Development of a bunched beam electron cooler based on ERL and circulator ring technology for the Jefferson Lab Electron-Ion Collider", in *Proc. 11th Workshop on Beam Cooling and Related Topics (COOL'17)*, Bonn, Germany, Sep. 2017, pp. 72–76. doi:10.18429/JACoW-COOL2017-WEM12

[31] V. Litvinenko *et al.*, "Plasma-cascade instability – theory, simulations and experiment", arXiv:1902.10846 [physics.acc-ph], 2019.

[32] D. Ratner, "Microbunched electron cooling for high-energy hadron beams", *Phys. Rev. Lett.*, vol. 111, p. 084802, 2013.

[33] G. Stupakov, "Cooling rate for microbunched electron cooling without amplification", *Phys. Rev. Accel. Beams*, vol. 21, p. 114402, 2018.

[34] G. Stupakov and P. Baxevanis, "Microbunched electron cooling with amplification cascades", *Phys. Rev. Accel. Beams*, vol. 22, p. 034401, 2019.

[35] Y. Huang *et al.*, "Ultrafast harmonic rf kicker design and beam dynamics analysis for an energy recovery linac based electron circulator cooler ring", *Phys. Rev. Accel. Beams*, vol. 19, p. 084201, 2016.

[36] G.-T. Park *et al.*, "Status update of a harmonic kicker development for JLEIC", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 3047–3050. doi:10.18429/JACoW-IPAC2019-WEPRB099

[37] R. Li *et al.*, "Impedance and collective effects in JLEIC", in *Proc. of eeFACT2018*, Hong Kong, Feb. 2019, p. 90, https://doi.org/10.18429/JACoW-eeFACT2018-TUYAA03

[38] D. Dell'Orco, R. Scanlan, and C.E. Taylor, "Design of the Nb_3Sn dipole D20", *IEEE Trans. Appl. Supercond.*, vol. 3, no. 1, pp. 82-86, February 1993.

[39] G. Willering *et al.*, "Cold powering tests and protection studies of the FRESCA2 100 mm bore Nb_3Sn block-coil magnet", *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4005105, April 2018.

[40] Etienne Rochepault *et al.*, "Mechanical analysis of the FRESCA2 dipole during preload, cool-down, and powering", *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4002905, April 2018.

[41] P. Ferracin *et al.*, "Development of the EuCARD Nb_3Sn dipole magnet FRESCA2", CERN-ATS-2013-022 internal technical note.

[42] A. V. Zlobin *et al.*, "Design concept and parameters of a 15 T Nb_3Sn dipole demonstrator for a 100 TeV hadron collider", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 3365–3367. doi:10.18429/JACoW-IPAC2015-WEPTY041

[43] A.V. Zlobin, "Assembly and first test of the US-MDP Nb3Sn dipole demonstrator (MDPCT1)", FCC Week 2019, June 24-28, 2019, MDPCT1, https://indico.cern.ch/event/727555/contributions/3432217/

[44] E. Barzi, "Superconducting strand and cable development for the LHC upgrades and beyond", *IEEE Trans. Appl. Supercond.*, vol. 23, no. 3, p. 6001112, June 2013.

[45] "Report of the community review of EIC accelerator R&D for the Office of Nuclear Physics, (Jones Report)," Feb 2017, https://science.osti.gov/np/Community-Resources/Reports