Electron Ion Collider Accelerator Science and Technology – Designs, R&D and Synergies with European research in Accelerators – submission to European Strategy Update on particle physics

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Abstract

A U.S.-based Electron-Ion Collider (EIC) has recently been endorsed by the U.S. National Academies of Sciences, Engineering, and Medicine (NAS). This brings the realization of such a collider another step closer, after its earlier recommendation in the 2015 Long-Range Plan for U.S. nuclear science of the Nuclear Science Advisory Committee "as the highest priority for new facility construction following the completion of FRIB". The connections between the scientific questions addressed at CERN and at the EIC as well as the shared interest regarding detector R&D are addressed in a separate submitted document "Synergies between a U.S.-based Electron-Ion Collider and the European research in Particle Physics". There are, also, a large number of accelerator R&D topics that are associated with the US EIC that could be undertaken in collaboration that would be of enormous mutual benefit for European research centers and the US EIC.

An EIC will be an unprecedented collider that will need to maintain high luminosity ($10^{33-34}\text{cm}^{-2}\text{s}^{-1}$) over a very wide range of Center-of- Mass energies (20 GeV to ∼100 GeV, upgradable to ∼140 GeV), while accommodating highly polarized beams and many different ion species. Addressing the challenges of this machine requires R&D in areas such as crab cavities, energy-recovery linacs (for ion beam cooling), and high field magnets for the interaction points – areas in which U.S. and European centers are already investing in R&D, in many cases jointly.

A multi-laboratory collaboration is presently working on two site-specific EIC designs – eRHIC led by Brookhaven National Laboratory and JLEIC led by Jefferson Lab. While the designs are different, there are many common R&D issues on which eRHIC and JLEIC efforts are cooperating closely. The purpose of the present paper is to outline the status of the EIC accelerator designs and to discuss the most significant R&D subjects that have strong connection with developments in Europe, with the purpose of enlarging EIC collaboration both in physics and accelerator, to strengthen synergies with European accelerator projects, and – more generally – to maximize positive impact of fundamental science on society worldwide.

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1 The Physics Motivation of the Electron Ion Collider

Our understanding of protons and neutrons, or nucleons—the building blocks of atomic nuclei—has advanced dramatically, both theoretically and experimentally, in the past half century. It is known that nucleons are made of fractionally charged "valence" quarks, as well as dynamically produced quark-antiquark pairs, all bound together by gluons, the carrier of the strong force. A central goal of modern nuclear physics is to understand the structure of the proton and neutron directly from the dynamics of their quarks and gluons governed by the theory of their interactions, quantum chromodynamics. With deeper understanding of the quark-gluon structure of matter, scientists are poised to reach a deeper picture of these building blocks, and atomic nuclei themselves, as collective many-body systems with new emergent behavior. Viewing nucleons and nuclei as complex interacting many-body systems gives rise to profound questions about the nature of ordinary matter.

The Electron Ion Collider (EIC) – the instrument that can answer these fundamental questions – has been selected as the primary new facility construction priority in the U.S. Department of Energy Nuclear Physics Long Range Plans in 2007 [1] and 2015 [2]. Such a facility must be very flexible over a multi-decade operating lifetime, supporting exploration of nuclear physics over a wide range of center-of-mass energies and ion species with highly polarized electrons and light ions. These requirements are spelled out in the EIC White Paper [3], the 2015 Nuclear Science Advisory Committee Long Range Plan [2] as well as in the most recent National Academies of Science assessment of US-based Electron Ion Collider science [4].

The science questions that an EIC will answer are central to completing our understanding of nuclear matter as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would also benefit other fields of accelerator-based science and society, from medicine through materials science to elementary particle physics.

The requirements of an EIC as described in the White Paper [3] include:

- Highly polarized ($\sim$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 $\sim 10^{33-34}$ cm^{-2}s^{-1}
- Possibilities of having more than one interaction region.

The future EIC would be much more capable and much more challenging to build than earlier electron or polarized proton machines. The accelerator challenges are twofold: a high degree of polarization for both beams, and high luminosity. It would be the most sophisticated and challenging accelerator currently proposed for construction in the United States and would significantly advance accelerator science and technology in the US and around the world.

A multi-laboratory collaboration is presently working on two site-specific EIC designs – eRHIC led by Brookhaven National Laboratory and JLEIC led by Jefferson Lab. The physics community involved in this collaboration is making two coordinated submissions to the European Strategy Update for Particle Physics – the EIC Physics submission [5], and the presented EIC Accelerator Science and Technology submission, aiming to enlarge EIC collaboration both in physics and accelerator science, strengthen synergies with European accelerator projects, and—more generally—to maximize the positive impact of fundamental science on society worldwide.

Suggested recommendation: reinforced by *EIC Physics submission*, recognize the EIC physics to be synergistic with the European projects (HL-LHC, HE-LHC, FCC, etc.) which are discussed within the European Strategy update process. Encourage creating a global world-wide collaboration on EIC physics, detector, and accelerator R&D.

2 Lessons learned from previous/existing machines & path forward

HERA [6], the first lepton-hadron facility collided 27.5 GeV spin polarized leptons (e^+, e^-) with 920 GeV protons reaching a luminosity of 5×10^{31}cm^{-2}s^{-1}. It was operated from 1992 to 2007 at DESY in Hamburg, Germany. While the luminosity of HERA is much lower than the value anticipated in the EIC, HERA experience is quite relevant for the EIC. The HERA concept of choosing the beam-beam parameters of lepton and hadron as they would collide with their own species which is also adapted for EIC was very successful. The vertical beam-beam tune shift for leptons of ΔQ_y exceeds the values planned for the EIC and the horizontal value was similar. An important lesson from HERA is the necessity to minimize synchrotron radiation in the IR, IR vacuum pressure, and to avoid halo of the proton beam. The techniques developed to maximize the spin polarization in presence of three pairs of spin rotators and strong beam-beam forces can be successfully applied to the polarization of the EIC lepton beams.

The B-factories demonstrated ampere-class electron beams and KEKB successfully demonstrated collisions under a large crossing angle compensated by a crab cavity thereby achieving record luminosity.

RHIC operation demonstrated that polarized proton beams can be produced and accelerated routinely to high energy and that polarization can be maintained over long storage periods with collisions, while CEBAF and Jefferson Lab FEL experience demonstrated acceleration and use of highly polarized electron beams as well as advanced energy recovery.

To achieve the requirements of the White Paper, both designs of EIC described later in this document aim to use ampere-scale beam currents, include ions as colliding species, rely on crossing angle collisions compensated by crab cavities, use beam cooling methods enabled by energy recovery techniques, as well as take advantage of many recent advances of detector technology developments. While the two EIC designs described below use these techniques in different configurations and implementations, there is much in common between them, which enables ongoing collaborative R&D, and there is also much in common and a lot of synergies with ongoing and planned European projects, which we hope will enable expansion of the EIC collaboration.

In summary, previous collider experience is quite relevant for the EIC and provides encouragement and confidence that the EIC design, construction, and operation can be mastered.

3 The JLEIC design of the EIC

Jefferson Lab proposes to build an EIC facility called the Jefferson Lab Electron-Ion Collider (JLEIC), having a peak luminosity over $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, and a collider center-of-mass energy range ~ 20 GeV to ~ 100 GeV upgradeable to ~ 140 GeV. The design is featuring innovative approaches which allow achieving high average luminosity and high polarization for protons, light ions and deuterons, and features re-use of existing facilities to minimize construction cost as well as to provide low operating cost.

Jefferson Lab, in collaboration with Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Stanford National Accelerator Laboratory, and collaborating universities, has developed a pre-conceptual design for an EIC that meets, and in many cases exceeds the stringent requirements detailed in the White Paper. The design integrates the experience of high-luminosity operations from recent accelerators with the innovations developed by the JLEIC team to produce a diverse array of collisions between polarized electrons and polarized nucleons.

The JLEIC Pre-Conceptual Design Report (October 2018, unpublished) has been developed, primarily focusing on an optimized 65 GeV center of mass (CM) energy design, with higher-energy options described in an Appendix. This design and the Pre-CDR are now undergoing an update, to fully meet the 100 GeV CM goals, including 140 GeV upgrade capabilities. Plots shown below will illustrate capabilities of both versions.

The JLEIC ion ring is based on an innovative figure-8 synchrotron layout (Figure 1) that has high spin transparency built into the design and will therefore guarantee high polarization of protons, deuterons, and other light ion beams. This novel topology, which has been extensively simulated, ensures that polarized ions can be accelerated, manipulated and spin-flipped without losing polarization. This includes polarized deuterium, which has never been available in any collider. A new, fully modern ion complex will be assembled that utilizes this figure-8 topology for polarization control. This complex will use state of the art magnets and ion sources to transport ion beams, including polarized deuterons, to the figure-8 collider ring for high luminosity collisions.

JLEIC is designed to take advantage of the existing CEBAF at Jefferson Lab. This electron superconducting RF (SRF) linac was recently successfully upgraded to 12 GeV for driving a fixed target nuclear science program. It will be used to provide an electron beam for JLEIC.

JLEIC will be a ring-ring collider in which both colliding beams are stored in two figure-8 shaped collider rings. The electron ring is made of normal conducting magnets and stores an electron beam of 3 GeV to 12 GeV energy and with up to 3 A average current. The CEBAF linac will serve as a full-energy injector into the electron ring, and requires no upgrade for energy, beam current or polarization. The ion collider ring consists of $\cos\theta$ 6 T superconducting magnets (for 100 GeV CM) and stores a proton beam with 30 GeV to 200 GeV, or fully-stripped ion beam up to 80 GeV per nucleon. Proton and ion beams are generated and accelerated in a new ion complex. The two collider rings are stacked vertically and have nearly identical circumferences of 2.25 km, and are housed in the same underground tunnel next to the CEBAF facility, as illustrated in Fig. 1.

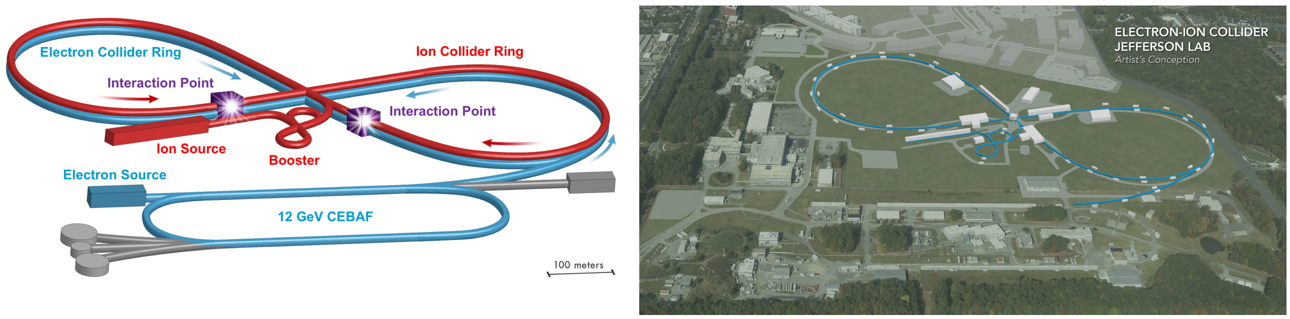

Figure 1: JLEIC Electron Ion Collider layout (left) and artist's concept of JLEIC on JLab site (right).

The unique figure-8 shape of the JLEIC collider rings was chosen for optimization and preservation of ion spin polarization during acceleration in the booster and collider rings as well as during beam store. There is a complete cancellation of spin precession in the left and right arc of the figure-8, thus the net spin tune is zero and energy independent. The spin tune will be moved away from zero by very low magnetic field spin rotators. The figure-8 also provides the only practical solution for acceleration and storage of polarized deuteron beam.

The crossing angle of the tunnels in the center of figure-8 collider is 77.4°. The electron and ion beamlines intersect at an angle of 50 mrad in two long straights of the figure-8 allowing to accommodate two detectors. The electrons execute a vertical excursion to the plane of the ion ring to realize electron-ion collisions. The two long straights also accommodate other components of the collider rings, including injection/ejection, RF system, electron cooling and polarimetry.

JLEIC takes advantage of two design features for delivering high luminosities: an existing highly polarized electron beam with up to 1.5 GHz bunch repetition rate from CEBAF, and a new ion complex. In particular, this new green field ion complex is designed to deliver colliding ion beams that match the phase-space structure and high bunch repetition rate of the colliding electron beam for implementing a novel luminosity scheme. The ion injector consists of sources for polarized light ions and non-polarized light to heavy ions; a 285 MeV linac with a RFQ and a warm DTL-type section followed by a SRF linac; and a figure-8 compact booster ring with an extraction energy of 8 GeV for protons, and corresponding energies for partially stripped heavy ions.

CEBAF will be used as a full-energy injector to the electron collider ring. The filling time of this collider ring is short, of the order of a few seconds. This leads to two consequences. First, the stored beam in the electron ring will be easily replaced or "topped-off" when needed, e.g. when the beam emittance or polarization become unsatisfactory. The CEBAF fixed target program can run simultaneously with JLEIC, with only a negligible loss of the duty factor. Secondly, the ring-ring collider design also enables collisions of polarized positrons and ions since the CEBAF linac can accelerate positrons as efficiently as electrons. The luminosity of positron-ion collisions will be low due to limitations of the polarized e^+ source. However this will further expand the JLEIC physics reach.

Building upon achievements of HERA and advanced beam manipulation techniques, the JLEIC design focuses on maximizing the luminosity, both peak and integrated. The peak luminosity is achieved using DC magnetized electron cooling of the ions at low energy. This is a well-developed technique, pioneered by the Budker Institute in Novosibirsk [7]. The highest energy DC electron cooling beam was at 4 MeV in the Fermilab Recycler [8]; this is the maximum energy proposed for DC cooling in JLEIC. Following acceleration of the ions, the initial luminosity is determined by this low energy cooling, reaching $2 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, more than 400 times the HERA luminosity as shown in Fig. 2.

An advantage of incorporating electron cooling throughout the ion complex is that ion bunches will be short; they will in fact be similar in length to the electron bunches. Therefore, the experience of the B-Factories (PEP-II in the USA and KEKB in Japan) can be applied directly to the JLEIC design. This optimization leads to a large number of bunches (>3000), each with a relatively small number of particles ($\sim 10^{10}$), reducing many of the problems of collective effects that tend to enlarge the beam size and reduce luminosity.

Intra-beam scattering, residual gas scattering, and beam-beam interactions all increase the ion emittance, causing the luminosity to decrease during the beam store. The JLEIC design includes high-energy bunched electron cooling to combat this effect, as well as the use of magnetized electron beams to improve the cooling rate. This system involves a bunched electron beam which is accelerated in a superconducting linac before being

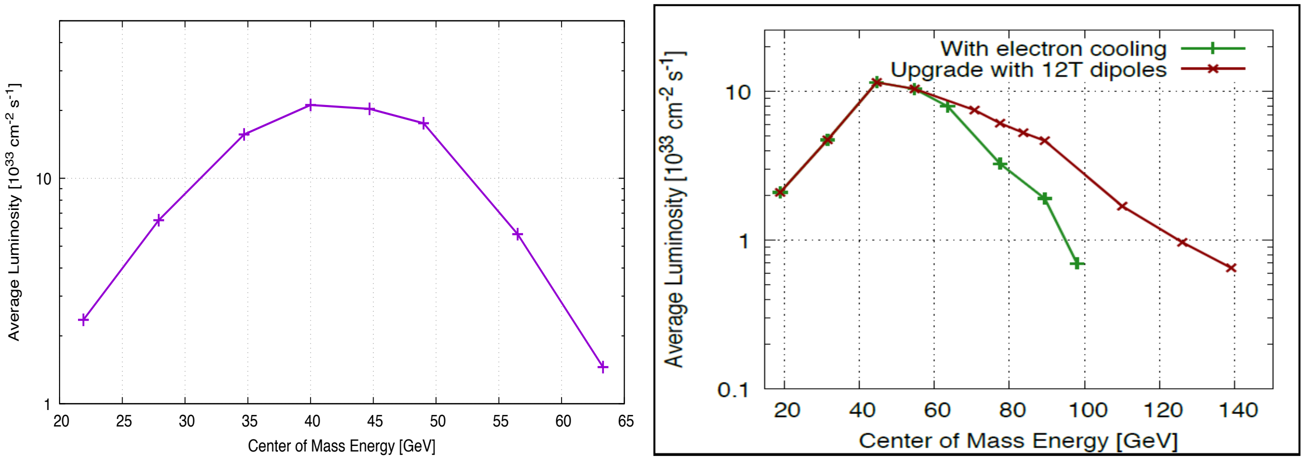

Figure 2: JLEIC e-p luminosity. Left – the average luminosity (average is ∼95% of the peak luminosity in this case) for the 65 GeV CM optimized design. Right – the average luminosity for 100 GeV CM collider design and its 140 GeV CM upgrade, in case with all electron cooling systems (DC and bunched beam) included. (The designs represented in these figures are different, in particular the 65 GeV design has an optimized electron ring, while the 100/140 GeV design is based on re-use of existing hardware for e-ring. Design of the 100/140 GeV version is undergoing further optimization.)

injected into a circulator-cooler ring. Each injection replaces every eleventh bunch, so the circulating current that cools the ions is eleven times the current from the gun. The cooling electrons are then decelerated in the energy-recovery linac for energy efficiency, a technique refined in the Jefferson Lab FEL [9] and now used world-wide.

Maintaining small ion emittance with bunched-beam cooling during the store results in a significant improvement in integrated luminosity. After a luminosity upgrade in 2000–2003, HERA reached a steady-state integrated luminosity delivery of $\sim 5 \times 10^{-3}\,\mathrm{fb}^{-1}$/week at a CM energy of 318 GeV. As designed, JLEIC will be able to surpass the integrated luminosity of the HERA physics program after a few days of running. Table 1 lists some of the key design parameters of JLEIC.

The IBS growth time (Table 1) at the maximum luminosity point is about a minute in horizontal direction, and longer in other directions. In the JLEIC baseline design the IBS effect is fully compensated by an on-energy electron cooling. The design is under optimization to achieve a balanced electron cooling by reducing horizontal IBS effect with an optimized lattice, by enhancing cooling effectiveness with advanced techniques, and by repartitions of cooling decrements in three dimensions through introducing dispersion inside cooler.

Electrons and ions in the two rings are brought into collision in the interaction region. The JLEIC design prioritizes full acceptance for the detector to ensure that all interactions can be fully identified. Construction of a new kind of interaction region also allows integration and optimization of the detector to realize the full range of physics goals detailed in [3]. The two beams are brought into collision with a crossing angle, which enables clean separation of the final-state particles and therefore full reconstruction of all events. This detector includes ultra-forward hadron detection for maximum acceptance of the forward scattered collision products.

The superconducting final focusing magnets in the interaction region are within the state-of-the-art and are staggered in the two rings to avoid beams passing through the yoke of the magnets in the other ring. Minimizing the complexities of these magnets is another advantage of a crossing angle.

Since the bunches are pencil-shaped, a crossing angle implies that most of the particles in a bunch would not interact directly with most of the particles in the other bunch during a collision. This luminosity reduction can be avoided by "twisting" the bunches with so-called "crab cavities" causing the bunches to collide head-on. Crab cavities were installed successfully at KEKB and allowed to surpass the world record in luminosity for a collider. The high luminosity upgrade of the LHC at CERN will also feature crab cavities. JLEIC is designed with complete crab cavity systems for both electron and ion beams.

The present JLEIC design was developed in close collaboration with future users and prioritizes high luminosity in the 20 GeV to 60 GeV center-of-mass energy range where high luminosity is paramount and where the detector acceptance is optimally matched to the collision kinematics. Use of 6 T dipoles results in an extension of the JLEIC center of mass energy reach to 100 GeV. This choice results in a luminosity of $\sim 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at a center-of-mass energy of ∼100 GeV (about 20 times the HERA luminosity) as shown in Figure 2. With a further upgrade of the dipole magnets of the ion ring, the maximum center-of-mass energy would be 140 GeV, still with a luminosity of $\sim 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

The JLEIC design maximally leverages the existing CEBAF capability for production of polarized electron beams, and leverages the innovative figure-8 rings to achieve higher values of beam polarization than required by the White Paper [3]. The polarization measurement statistical precision in nuclear femtography is proportional to the square of the polarization in each beam. The high polarization in JLEIC (>80% in the electron ring and >85% in the ion ring) compared with the minimum requirement [3] (>70% for both beams) decreases the time needed for an experiment by 52%. This is equivalent to an increase in luminosity by about a factor of two.

The JLEIC design has matured over the last decade with the fundamental design remaining unchanged. It has been extensively reviewed and simulated, while the key design elements were being prototyped. However, there are still areas where the technology needs further R&D – the JLEIC team is looking forward for expanding the collaborative R&D efforts as well as aiming to increase impact of these R&D activities on synergistic European and worldwide projects.

4 The eRHIC design of the EIC

Brookhaven National Laboratory proposes eRHIC, an implementation of an electron-ion collider that meets all requirements listed in the EIC White Paper [3] and which can be constructed at low cost. The design takes full advantage of the existing accelerator infrastructure of the RHIC complex, using the Yellow Ring of the RHIC heavy ion collider together with the entire hadron beam injector chain. A new electron storage ring in the RHIC tunnel will provide polarized electron beams for collisions between electrons and polarized protons or heavy ions. The center-of-mass energy in electron-proton collisions ranges from 29 to 141 GeV, accomplished by colliding 5 to 18 GeV electrons with 41 to 275 GeV protons. The peak luminosity is $1.05 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, as shown in Figure 3.

Polarized electrons are provided by a full-energy spin transparent injector synchrotron located in the RHIC tunnel, specifically designed to be free of intrinsic resonances over its entire acceleration range from 400 MeV at injection to 18 GeV. The beams collide in one or two interaction regions. A dedicated fill pattern ensures that each bunch collides only once per turn. This way, the luminosity is shared equally between the two detectors without exceeding the beam-beam limit. To maximize the luminosity, flat beams with unequal emittances $\epsilon_x \gg \epsilon_y$ in the two planes are focused to flat cross sections $\sigma_x \gg \sigma_y$ at the IP using different β-functions $\beta_x \gg \beta_y$. The hadron beam parameters are similar to what has been achieved in RHIC, with the exception that the number of bunches will be increased from 110 at RHIC up to 1320 in eRHIC thereby increasing the total hadron beam current by a factor of three. The total electron beam intensity is limited by the superconducting RF system which will provide up to 10 MW of power to restore synchrotron radiation losses. Table 1 lists some of the key design parameters of eRHIC. A comprehensive and consistent pre-conceptual design has been completed in July 2018 (eRHIC Pre-Conceptual Design Report, eRHIC PCDR, July 2018, unpublished). The eRHIC design continues to be developed and improved.

Interaction region: Beams collide under a 25 mrad crossing angle. The interaction region design meets several requirements:

- Strong focusing of the electron and hadron beams to equal, small spot sizes at the interaction point. This is accomplished using superconducting low-β quadrupoles located right outside the central detector which extends to ±4.5 m from the interaction point (IP), thereby providing a superb acceptance for the colliding beam detectors. On the forward side, electron and hadron quadrupoles are arranged in an interleaved scheme, while on the rear side the magnets for the two beams share a common yoke (Fig. 4).
- Quick separation of the electron and hadron beams. Rather than using separator dipoles that would generate large amounts of synchrotron radiation near the detector, this is realized with a 25 mrad crossing angle. The geometric and beam dynamics effects of this crossing angle are compensated by crab cavities for both beams.
- Separation of the hadron beam from the forward-scattered 4 mrad neutron cone.
- Separation of the electron beam from the Bethe-Heitler photons used for luminosity monitoring.

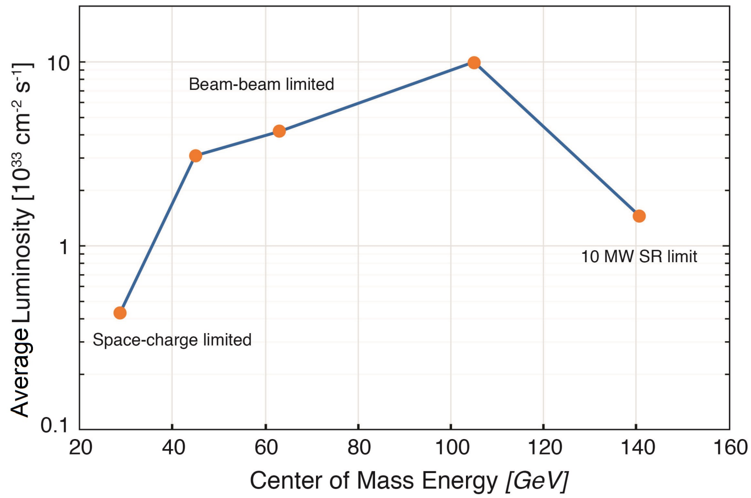

Figure 3: eRHIC electron-proton average luminosity vs. center-of-mass energy with strong hadron cooling. The luminosity averaged over the data taking period is ~ 95 % of the peak luminosity.

Electron storage ring: The electron storage ring is comprised of 16 FODO cells in each of the six arcs. To achieve the required design emittance of $20 - 22$ nm over the entire energy range from 5 to 18 GeV, it is operated with different phase advances per FODO cell - 90 degrees at 18 GeV, and 60 degrees at 10 GeV and below. The arc dipoles are realized as super-bends, each consisting of two 2.66 m long dipoles with a short, 0.44 m long dipole in-between. At energies of 10 GeV and above, all dipoles are powered uniformly, resulting in the maximum possible bending radius, which minimizes the emitted synchrotron radiation. Below 10 GeV the field of the short central dipole is reversed in order to create additional synchrotron radiation damping due to the small bending radius and therefore permitting large beam-beam parameters. At the same time, this reverse bend also helps to achieve the desired emittance. The vertical emittance is controlled by a long vertical dispersion bump.

Modifications to the hadron storage ring: Some moderate modifications of the hadron ring are necessary, mostly to accommodate the increased beam current and larger number of bunches. It is planned to inject and ramp 330 bunches, and then split these into 1320 bunches once store energy is reached. This three-fold increase in the number of bunches at injection reduces the bunch spacing by a factor of three compared to RHIC, which requires injection kickers with a faster rise time. Since the available space in the present injection kicker location is not sufficient for these new, longer kicker sections, the existing transfer line from the AGS to RHIC will be extended to IR 4 by means of the otherwise obsolete second RHIC ring (Blue Ring). There is sufficient warm space in IR 4 to install the new injection kickers.

The increased beam current and peak bunch current would cause unacceptable heating of the cryogenic stainless-steel beam pipes. To improve the surface conductivity of the vacuum pipes, a thin layer of copper will be applied in-situ. A layer of amorphous carbon will then be applied on top of the copper coating to reduce the secondary electron yield and therefore suppress the formation of electron clouds. In addition, all BPMs will need to be replaced to allow for the large number of short, intense bunches.

The large energy range of the hadron beams requires adjustment of the ring circumference in order to keep the electron and hadron bunches synchronized. This is accomplished by two methods. Between 100 and 275 GeV proton energy, a ± 14 mm radial shift is sufficient to account for the variation in velocity of the hadron beam. For proton beam operation at 41 GeV, the beam will travel through the (inner) Blue arc between IRs 12 and 2 instead of the (outer) Yellow arc, thus reducing the circumference by 93 cm, which corresponds to a proton beam energy of 41 GeV.

The RF system will be replaced to allow operation with up to 1320 bunches.

eRHIC beam dynamics: Both, the large number of bunches and high bunch current, are challenging features of eRHIC, especially in the electron storage ring. Simulations including the appropriate impedance values, short range resistive wall and coherent synchrotron radiation indicate that the beam-beam force is sufficient to damp transverse coupled bunch modes, while longitudinal coupled bunch oscillations can suppressed with a longitudinal damper with gain $g_z = 5 \times 10^{-3}$. To overcome the longitudinal microwave instability an RMS momentum spread

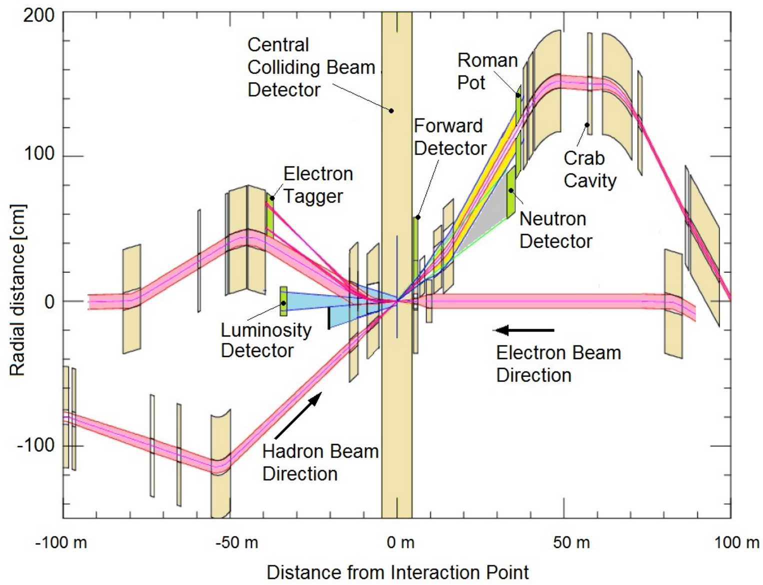

Figure 4: Layout of the eRHIC interaction region, shown is the PCDR version with 22 mrad crossing angle.

of $\sigma_p/p = 8.2 \times 10^{-4}$ is required.

Both, weak-strong and strong-strong beam-beam simulations, were performed to study the feasibility of the proposed high beam-beam parameters, $\xi_e = 0.1$ for electrons and $\xi_p = 0.015$ for protons.The threshold for coherent beam-beam oscillations was found to be about a factor two beyond the proposed bunch intensities in both beams, and therefore is not considered a concern. Tune scans were performed in weak-strong simulations to determine the optimum tune space for the electrons, which was found to be around $(Q_x, Q_y) = (.08/.06)$ to $(.12/.10)$.

The dynamic aperture in both the hadron and the electron ring has been assessed in tracking studies. The dynamic aperture in the hadron ring was found to be very similar to present RHIC, and therefore sufficient. Lattice work in the electron ring has so far focused on the 10 GeV lattice, which corresponds to the highest luminosity (see Table 1). The dynamic aperture of this 60-degree FODO lattice was found to be greater than 10σ in all dimensions. While this is sufficient, the effect of misalignments and multipole errors still need to be assessed, as does the dynamic aperture of the 90 degrees lattice at 18 GeV.

eRHIC polarization: The eRHIC physics program requires polarization levels of 70% in both electron and proton beams, as well as arbitrary spin patterns. RHIC has routinely provided proton-proton collisions with approximately 60% polarization in arbitrary spin patterns. Upgrading the Yellow ring by installing four additional Siberian snakes for a total of six snakes is expected to increase the store polarization to the required levels, as well as allow operation with polarized ^{3}He beams.

The required spin patterns in the electron storage ring are achieved by injecting polarized electron bunches with the desired spin orientation at full storage energy. Since the Sokolov-Ternov effect will lead to depolarization of bunches with spins parallel to the main dipole field, frequent bunch replacement of entire single bunches at about 20% of the Sokolov-Ternov time constant $\tau_{\mathrm{S-T}}$ is required to keep the time-averaged polarization sufficiently high. The effect of this replacement on the emittance of the stored proton beam has been studied experimentally in RHIC and was found to be tolerable. To minimize depolarization due to spin diffusion, spin matching must be employed. Simulation studies confirm that the spin performance of the storage ring is sufficient.

Strong hadron cooling: Operation with a luminosity of $10^{34}\,\mathrm{cm^{-2}s^{-1}}$ can only be accomplished using strong hadron cooling due to the short IBS growth time of 2 h. Two cooling schemes are currently under consideration, namely bunched-beam electron-cooling and coherent electron-cooling (CeC) The required high beam intensities for a bunched beam electron cooler exceed the capabilities of present-day electron guns by far. To overcome this limitation, a scheme where the electron beam is stored in a small storage ring equipped with strong damping wigglers is being evaluated. A coherent electron cooling test facility has been installed in RHIC, and is being experimentally studied.

Strong hadron cooling is very challenging and therefore considered a design risk. To mitigate this risk we have developed a parameter set that has a minimum IBS growth time of 8 h, comparable to present RHIC. With these parameters, eRHIC reaches a peak luminosity of $4.4 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$ without any cooling.

eRHIC electron injector: A purpose-built rapid-cycling synchrotron (RCS) with high periodicity will serve as cost-effective full-energy polarized electron injector using normal-conducting RF cavities. The high periodicity together with the appropriate choice of tunes ensures that intrinsic spin resonances occur outside the ramp energy range of the RCS. Simulation studies have shown that even in the presence of magnet misalignments as large as 0.5 mm RMS the polarization transmission efficiency is still 97%.

Table 1: eRHIC and JLEIC key design parameters for highest luminosity. Assumptions on integrated luminosity are as follows: We assume that the accelerator is 75% of the time in colliding beam mode; 25% of the time is needed for injection, acceleration, run preparation as well as maintainance, machine development, and failures. The average luminosity within a luminosity run is very close to the peak luminosity (>95%) due to strong hadron cooling.

design	eRHIC		JLEIC	
parameter	proton	electron	proton	electron
center-of-mass energy [GeV]	105		44.7	
energy [GeV]	275	10	100	5
number of bunches	1320		3228	
particles per bunch [10^{10}]	6.0	15.1	0.98	3.7
beam current [A]	1.0	2.5	0.75	2.8
horizontal emittance [nm]	9.2	20.0	4.7	5.5
vertical emittance [nm]	1.3	1.0	0.94	1.1
β_x^* [cm]	90	42	6	5.1
β_y^* [cm]	4.0	5.0	1.2	1
tunes (Q_x, Q_y)	.315/.305	.08/.06	.081/.132	.53/.567
hor. beam-beam parameter	0.013	0.064	0.015	0.068
vert. beam-beam parameter	0.007	0.1	0.015	0.068
IBS growth time hor./long. [min]	126/120	n/a	0.7/2.3	n/a
synchrotron radiation power [MW]	n/a	9.2	n/a	2.7
bunch length [cm]	5	1.9	1	1
hourglass and crab reduction factor	0.87		0.87	
peak luminosity [$10^{34}\,\mathrm{cm^{-2}s^{-1}}$]	1.05		2.1	
integrated luminosity/week [$\mathrm{fb^{-1}}$]	4.51		9.0	

5 Research and development for the electron ion collider

While there are two different solutions for the EIC, the research and development programs for these two designs have many elements in common. The common part of the R&D pursues the following topics:

- Design and feasibility study of novel superconducting quadrupole and dipole magnets for the EIC interaction regions: The IR quadrupole magnets are needed to focus both ion and electron beam in a short distance from the interaction point. This requires high field gradients > 100 T/m which might imply to use coils made of Nb_3Sn. The complicated EIC IR collision geometry and tight space constraints add to the challenge of using the Nb_3Sn technology. The stray fields of the magnets seen by the other beam must be small. There are some magnets that require active shield coils. The combination of all these requirements make the EIC IR magnets a prominent item of the list of R&D items.
- Development of strong hadron cooling: The high luminosity envisioned for electron-ion colliders requires intense hadron beams with small emittance. The beam emittance is subject to growth by several mechanisms. The most important one is Intrabeam Scattering caused by Coulomb scattering of ion/protons inside the particle bunch in presence of coupling between transverse and longitudinal oscillations. The well understood mechanism for electron cooling becomes inefficient at high hadron beam energies and would require unreasonably large electron currents which cannot be provided by an electron gun. Therefore, novel

cooling techniques must be developed. R&D is being carried out to overcome this difficulty studying the re-use of the electron beam several times for cooling before returning the electron beam to the linac for energy recovery. There are several R&D activities to consider an alternative electron cooling scheme called coherent electron cooling, all based on the concept of the electrons as pick-ups and after amplification of the signal as kickers in a way resembling stochastic cooling. Various amplification mechanisms are being studied, either using an FEL to amplify the signal, or using the mechanism of micro-bunch instability or dynamical plasma effects.

- Electron acceleration to enable strong hadron cooling: The hadron beam energies in the electron ion collider are too large for classical electron cooling with DC electron beams. The cooling rates that can be achieved by stochastic cooling fall short by several orders of magnitudes. A first step towards cooling of high energy hadron beams is the use of bunched beams instead of DC beams. This allows to accelerate the electron beams to the large required energies with the same relativistic factors as the high energy hadron beam by using RF fields in a superconducting linac. To limit the total power needed to provide such beams, the electron beam has to return after the cooling interaction with the hadron beam to the linac for recovery of the beam energy. Thus, an important ingredient of hadron cooling research is the development of energy recovery linacs. To limit the investment cost in superconducting RF, it is desirable to recirculate the electron beam several times through the linac to reach the full required beam energy while preserving the required high quality of the electron beam. There are also R&D activities that study whether an electron storage ring could replace the ERL as source of the electron beam.
- Fast kicker R&D: The short distance between bunches in the EIC requires fast kicker magnets for injection and extraction of the beams. This is particularly challenging for hadron beams for which the kickers must not only be fast, but also must have large amplitude. R&D aimed at developing strong and fast kicker magnets is needed.
- Superconducting RF for electron storage ring: At large electron beam energy, the particles lose considerable energy by emitting synchrotron radiation. A powerful RF system is required to provide the RF voltage and RF power to make up for these losses. Since the diverse EIC physics program requires a large variation in the electron beam parameters, the input coupler must provide variable coupling between RF transmitters and the cavities to ensure good beam stability and limited reflection to avoid waste of RF power. To limit the number of RF cavities, the input couplers need to have a very high power rating. Higher order modes (HOM) cannot be completely suppressed by the RF design, and thus efficient HOM dampers are required as well. An important part of the R&D program is devoted to the development of superconducting RF systems with high-power variable coupling input couplers and efficient HOM damping.
- Beam dynamics assessment and computer simulation code development and benchmarking: The EIC has many beam dynamics challenges, the assessment of which requires a suite of sophisticated codes which need to be compared among themselves and need to be benchmarked with experimental results on existing accelerators. This constitutes an important part of the EIC R&D program.
- Crab cavity development: A crossing angle geometry is required to achieve high luminosity in any EIC design. The crossing angles need to be compensated by crab cavities. The development of a suitable RF resonator is part of the EIC R&D program.

6 EIC R&D synergies with European projects

Many of the common R&D topics described above have strong synergies with ongoing R&D in Europe or with planned or developing European projects. We reiterate on some examples along these lines below.

- The High Luminosity LHC crab cavity system is an example of synergy between EIC and LHC. The efforts in the US toward crab cavity for LHC goes back to around 2007. Two different designs of crab cavities, developed with strong participation of US labs and universities have been installed and are being tested in the CERN SPS. This is a global effort that involved BNL, FNAL, JLab, LBNL, Old Dominion University, SLAC, UK labs and CERN. Crab cavities are essential for EIC.
- PERLE is a project suggested by LAL & IPN Orsay as energy recovery demonstrator for LHeC/FCC_eh ERLs, while also having a self-standing low energy nuclear physics potential. Positioned as a “Stepping Stone” for 100 MW ERLs, PERLE with 10 MW beam power would be a unique “test bed” for the next generation of high power ERLs. A number of research topics have synergies with many projects planned worldwide, such as CBETA at Cornell and many others:

  - Developing techniques and pushing limits for multi-pass transport and diagnostics of non-equilibrium beams with high ratio of beam power to installed RF power.
  - Mitigation of longitudinal phase-space distortion due to wakes, including CSR and longitudinal space-charge effects. Preservation of beam quality/stability in presence of collective effects, errors and imperfections.
  - Development of SRF cavities suitable for high power beams. Developing further the prototype 802 MHz Nb SRF cavity built for PERLE and for the LHeC / FCC-ep version.
- Muon Collider design (e^+e^- threshold version) suggested by INFN and relying on FFAG optics with fixed field multi-pass RLA based on SRF linac suitable for multi GeV acceleration of fast decaying muons.
- New high voltage (turbine) technology for 8 MeV magnetized DC cooler at HESR/FAIR, GSI.
- R&D on Nb3Sn and thin film cavities aiming to develop cost-effective SRF technology.
- Highly HOM-damped SRF cavities for next generation colliders and ERLs.
- Interaction Region SC magnets for HE-LHC, FCC and future colliders.
- General accelerator beam dynamics and simulations development.

The above list shows just a fraction of mutually beneficial synergistic R&D.

Suggested recommendation: recognize the EIC accelerator technology development to be synergistic with the projects (HL-LHC, HE-LHC, FCC, etc.) discussed within the European Strategy update process. Encourage creating a global world-wide collaboration on EIC accelerator and machine-detector interface R&D.

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