1 The Emerging Science Frontier: The Electron Ion Collider

Much of the focus in contemporary nuclear physics research is on mapping and understanding the emergent phenomena from QCD that determine the unique properties of strongly interacting matter: the breaking of chiral symmetry that gives light-quark hadrons most of their mass; the spin, flavor, space and momentum structure of hadrons; the nearly perfect liquid behavior of the hot matter created in RHIC collisions; possible color superconductivity in the dense interior of compact stars. A key to understanding the rich panoply of QCD phenomena is identifying conditions under which the theory is amenable to controlled solution. Numerical solutions on a space-time lattice have made impressive advances in the treatment of strongly interacting matter in equilibrium at both low and high temperatures. A perturbative expansion in powers of the running QCD coupling constant α_s is successful in describing hadron dynamics in high-energy processes involving large momentum transfer. Interactions of pions and nucleons at low momentum have been successfully analyzed via chiral effective field theories.

Recent theoretical advances have introduced a new QCD regime amenable to a quite different effective field theory approach. This new interpretability frontier occurs in matter probed at moderate momentum transfers, where the QCD coupling is still relatively weak, but at gluon densities high enough to produce extremely strong fields that can be treated by classical field theory. This regime is dominated by direct manifestations of the defining feature of QCD: the self-interaction of gluons. Gluon splitting and gluon recombination are predicted to reach a competitive balance, leading to a saturation of gluon density that should be universal to all strongly interacting matter probed under suitable conditions. Hints of this saturation have been extracted from measurements of electron-proton collisions at HERA and of deuteron-nucleus and nucleus-nucleus collisions at RHIC. Saturated gluon densities would have a profound influence on heavy-ion collisions at the LHC, and may well be the source of certain general features of high-energy hadron cross sections. In order to tie these phenomena together and map the universal properties of gluon-dominated matter, one needs to probe partonic structure at very low values of Bjorken x, where individual partons carry $\lesssim 0.1\%$ of a nucleon's overall momentum, but within a "sweet spot" in momentum transfer (Q^2) that is neither too low nor too high.

The ideal accelerator to test this new effective field theory well into the gluon saturation regime with an *a priori* understood probe is an Electron-Ion Collider, EIC. Coherent contributions from many nucleons within a heavy-ion beam particle at such a collider amplify gluon densities, thereby broadening the Q^2 "sweet spot" and extending the effective reach to small x-values by at least two orders of magnitude, in comparison with e-p collisions at the same energy per nucleon.

The addition of polarized proton and light-ion beams to collide with polarized electrons and positrons at EIC would dramatically expand our understanding of the nucleon's internal wave function. It would greatly extend the kinematic reach and precision of deep inelastic scattering measurements of nucleon spin structure. The contribution of gluons and of sea quarks and antiquarks of different flavor to the nucleon's spin would be mapped well into the gluon-dominated region. The study of Generalized Parton Distributions (GPD's) in deep exclusive reactions will be pushed far beyond presently accessible energies at JLab, HERA and CERN, extending three-dimensional spatial maps of the nucleon's internal landscape from the valence quark region down into the region dominated by sea quarks, antiquarks and gluons. This extension may be critical for completing the picture of how the nucleon gets its spin, by providing sensitivity via GPD's to the orbital motion of partons associated with a pion "cloud".

High-energy scattering from nucleons in a collider environment lends itself specifically to study how Einstein's fundamental relation, allowing matter to be created from pure energy, is realized in QCD when an essentially massless (and colored) quark or gluon evolves into massive (and color-neutral) hadrons. Numerical solutions of QCD on a space-time lattice cannot provide guidance for the dynamical process by which the scattered parton picks up other colored partners from either the QCD vacuum or the debris of the high-energy collision. How are restoration of the color field within hadrons and hadronic mass generation affected in this process by quark spin, flavor and motion, or by surrounding nuclear matter? These questions can be answered at a high-energy, high-luminosity polarized electron-ion collider, using high-efficiency detectors capable of distinguishing different types of hadrons.

EIC will also vastly improve our knowledge of gluonic structure in atomic nuclei. In addition to amplifying gluon fields to provide precocious entry into the anticipated universal saturation regime, how does the nuclear environment affect the path to saturation? Do the momentum and space distributions of gluons in nuclei differ in non-trivial ways from those in nucleons, as has been found for quarks? Are there small clumps of gluons, or are they more uniformly distributed? These questions will be addressed by a combination of deep inelastic inclusive scattering and vector meson production from nucleons and nuclei.

In short, EIC is a machine that would expand the intellectual horizons of nuclear physics research into the heart of QCD, where gluon self-interactions dominate. It would address the following fundamental science questions:

- What are the strongest fields that QCD allows, and how does nuclear matter behave in the vicinity of this limit?
- What is the internal landscape of a nucleon in the region dominated by sea quarks and gluons?
- How do hadronic final-states form from massless quarks and gluons in QCD?
- How does the nuclear environment affect the distribution of gluons in momentum and space?

It would build on the scientific and technical expertise developed over decades at the nation's two premier QCD laboratories at Jefferson Lab and RHIC, but would add new state-of-the-art accelerator technology to reach its design goals.

In this section, we highlight only a few of the science programs that EIC would foster and outline two of the design options under consideration, referring the reader to the more detailed White Papers [refs] that have been written on EIC alone.

2 A New Era of Hadronic Physics with an Electron Ion Collider

The EIC will provide definitive answers to compelling physics questions essential for understanding the fundamental structure of hadronic matter. It will allow precise and detailed studies of the nucleon in the regime where its structure is overwhelmingly due to gluons and to sea quarks and anti-quarks. Some of the scientific highlights at the EIC in this area would be: (1) definitive answers to the question of how the proton's spin is carried by its constituents, (2) determination of the three-dimensional spatial quark and gluon structure of the proton, (3) precision study of the proton's gluon distribution over a wide range of momentum fractions. In the following we will briefly address the first two of these highlights of future research in hadronic physics.

The spin structure of the proton. Few discoveries made in the exploration of the structure of the nucleon have had a bigger impact on the field and its further development than the surprising finding by the EMC that the quarks and anti-quarks together carry only about a quarter of the nucleon's spin. To determine how the fundamental quarks, anti-quarks and gluons of QCD conspire to provide the spin-1/2 of the nucleon, presents the formidable challenge of understanding a complex composite system in nature and has by now developed into a world-wide quest central to nuclear physics. The proton spin sum-rule,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g \ ,$$

states that the proton spin is the sum of the quark and gluon intrinsic spin ($\Delta\Sigma$, ΔG) and orbital angular momentum (L_q, L_g) contributions. EIC with its unique high luminosity, highly polarized electron and nucleon capabilities, and its extensive range in center-of-mass energy, will allow to access the quark and gluon spin contributions through deep-inelastic scattering (DIS). Building on the results of the important current or forthcoming experiments at RHIC, DESY, CERN and JLab, the EIC will extend the measurements well beyond the reach of existing accelerators, in particular to lower momentum fractions x of the quarks and gluons where significant contributions to the proton spin could reside. A key measurement at the EIC would be of the spin-dependent proton structure function $g_1(x,Q^2)$ of the proton over a wide range in Q^2, and down to $x \sim 10^{-4}$. Studies of the scaling violations of $g_1(x,Q^2)$ prove to be a most powerful and clean tool to determine the spin contribution by gluons. This is demonstrated by Figure 1, which shows projections for EIC measurements of $g_1(x,Q^2)$ as a function of x in various Q^2-bins. Also shown are four theoretical model predictions that variously assume a positive or negative gluon contribution to the proton spin, and of different sizes. Each of these is compatible with the currently available polarized-DIS data, with RHIC data now starting to put significant constraints on the polarized gluon distribution at momentum fractions $x \geq 10^{-2}$ or so. The great power of the EIC in providing precise information on ΔG is evident. We note that measurements of g_1 at an EIC would also be possible off neutrons, which in combination with the proton results would allow a precision test of the famous Bjorken sum-rule, relating the proton and neutron spin structure. Furthermore, semi-inclusive DIS measurements, for which a specific hadron is detected in the hadronic final state, would provide information with unprecedented detail on the individual contributions by quark and anti-quark spins to the proton spin, hereby allowing tests of

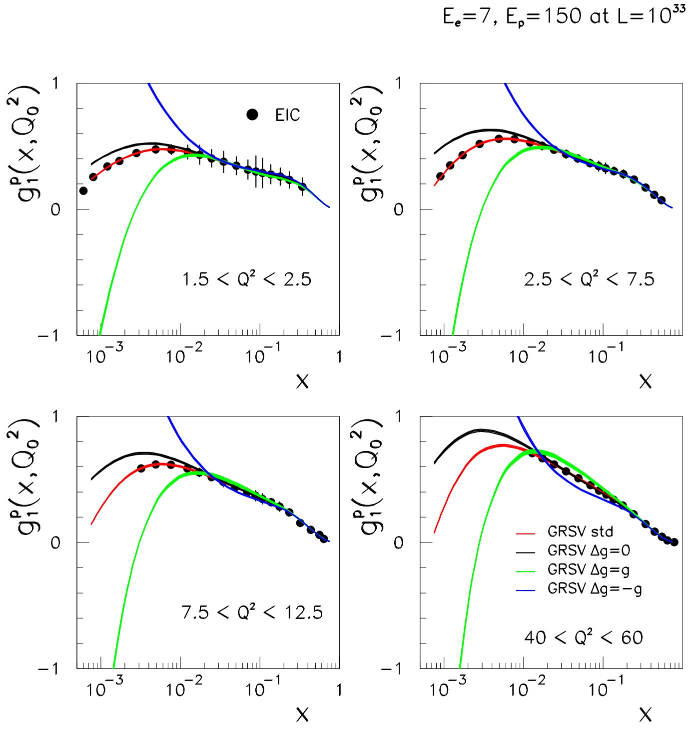

Fig. 1. Projected EIC data for the proton structure function $g_1(x, Q^2)$ as a function of x in four Q^2 bins, measured by colliding 7 GeV electrons with 150 GeV protons at an integrated luminosity of $5\,\text{fb}^{-1}$. The curves show the theoretical predictions based on different sets of spin-dependent parton distribution functions that mostly differ in the gluon distribution.

models of nucleon structure and comparisons with lattice-QCD results.

There are various avenues for investigating the role of orbital angular momenta in nucleon structure. One of them is the study of correlations of the transverse momentum of a parton in the nucleon with the nucleon spin. Such correlations are possible if the nucleon is polarized perpendicular to the direction of motion and give rise to certain patterns of azimuthal-angular dependences of final-state hadrons. There are initial experimental results from fixed-target DIS that indicate the presence of such correlations. Measurements at an EIC would allow precision studies of such orbital effects. Generalized parton distributions (GPDs), to which we turn now, provide unique access to the total, spin plus orbital, angular momentum contributions of quarks and gluons, as well as to many other important aspects of nucleon structure.

Measurements of Generalized Parton Distributions. GPDs may be viewed as the Wigner quantum phase space distributions of the nucleon's constituents – functions describing the simultaneous distribution of particles with respect to position and momentum in a quantum-mechanical system, representing the closest analog to a classical phase space density allowed by the uncertainty principle. In addition to the information about the spatial density (form factors) and momentum density (parton distribution), these functions reveal the correlation of the spatial and momentum distributions, i.e., how the spatial shape of the nucleon changes when one probes quarks and gluons of different wavelengths. The concept of GPDs has in many ways revolutionized the way scientists think about the structure of

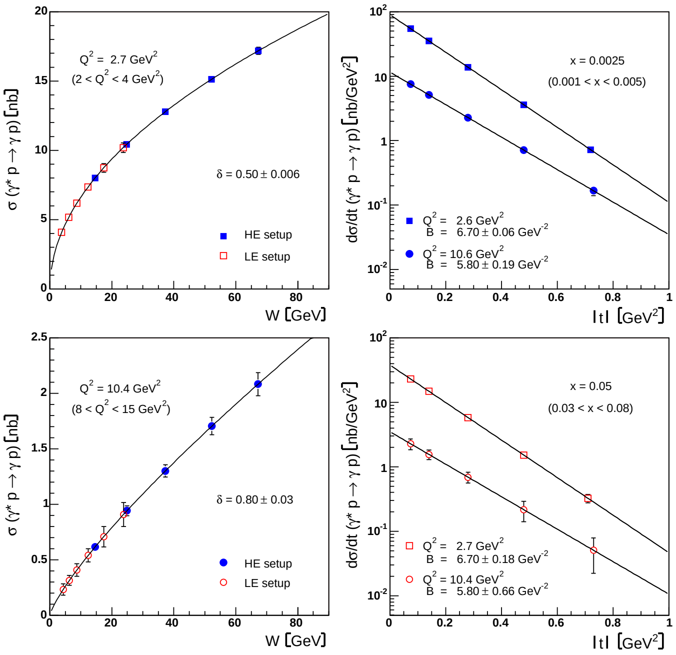

Fig. 2. Left: projected results for the total DVCS cross section with an EIC, as a function of W for two values of Q^2. Right: t differential DVCS cross section for two representative values of x and Q^2. The projections assume a high-energy setup (10 GeV on 250 GeV), with an integrated luminosity of $530\,\mathrm{pb}^{-1}$ for the smaller x-value, and a low-energy setup (5 GeV on 50 GeV) with $180\,\mathrm{pb}^{-1}$ for the larger x-value. The estimates of the event rates here assume 100% detector acceptance.

the nucleon. It has led to completely new methods of performing a "spatial imaging" of the nucleon, either in the form of two-dimensional tomographic images (analogous to CT scans in medical imaging), or in the form of genuinely three-dimensional images (Wigner distributions). In addition, GPDs allow us to quantify how the angular momenta of partons in the nucleon contribute to the nucleon spin.

Measurements of GPDs are possible in hard exclusive processes such as "Deeply-virtual Compton Scattering (DVCS)", $\gamma^* p \to \gamma p$. The experimental study of these processes is typically much more challenging than of traditional inclusive DIS. In addition to requiring substantially higher luminosities (because of small cross sections) and the need for differential measurements, the detectors and the interaction region have to be designed to permit full reconstruction of the final state. A properly designed collider is much better suited for this purpose than a fixed-target experiment. A collider also achieves momentum transfers of the order $Q^2 \sim 10$ GeV^2, where higher-twist corrections in the GPD analysis are under control. The EIC would allow unique access to the gluon and sea-quark and anti-quark GPDs, entirely complementary to what will be achieved by the 12-GeV upgrade program at JLab. This would be possible through study of a variety of exclusive final states, ranging from photons to pions, kaons and J/ψ. As an example of the potential of an EIC in this area, we show in Fig. 2 the expected uncertainties of measurements of the DVCS cross section. In particular, we show the cross section differential in t, the momentum transfer on the nucleon line. By a Fourier transform, the t-dependence encodes the information about the transverse spatial distribution of partons in the proton. One can see that excellent statistics can be obtained in fully differential measurements in x, Q^2 and t, and over a wide kinematic range. This will allow for precise extraction of information about the nucleon GPDs, and for numerous detailed studies for example of their Q^2-evolution.

3 Physics of Strong Color Fields with an Electron Ion Collider

With its wide range in energy, nuclear beams, high luminosity and clean collider environment, the EIC will offer an unprecedented opportunity for discovery and for the precision study of a novel universal regime of strong gluon fields in QCD. The EIC will measure, in a wide kinematic regime, the momentum and space-time distribution of gluons and sea-quarks in nuclei, the scattering of fast, compact probes in extended nuclear media and will elucidate the role of color neutral (Pomeron) excitations in scattering off nuclei. These measurements at the EIC will also deepen and corroborate our understanding of the formation and properties of the strongly interacting Quark Gluon Plasma (QGP) in high energy heavy ion collisions at RHIC and the LHC.

Strong color fields in nuclei. At high energies, the wave functions of hadrons and nuclei contain strong color fields – this is because the number of quarks and gluons increases as a power of energy due to QCD evolution. Since the transverse size of a hadron is constrained by unitarity and can grow only logarithmically, at sufficiently high energy the density of partons in the transverse plane becomes large. This density then becomes a new dimensionful parameter in the problem, and the related new momentum scale is called the saturation momentum Q_s. Because of the Lorentz contraction of a fast–moving nucleus, the saturation momentum grows linearly with the size of the nucleus: $Q_s^2 \sim A^{1/3}$. If the saturation momentum is large on a typical QCD scale, the dynamics of partons inside the nuclear wave functions can be described by using the weak coupling techniques. The occupation number of gluon field modes with transverse momenta below Q_s saturates at the value $\sim 1/\alpha_s(Q_s) \gg 1$, i.e., the gluons form a classical field frozen in time by Lorentz dilatation – often referred to as the "color glass condensate" (CGC). The wave functions of hadrons and nuclei are expected to become *universal* at high energies (small Bjorken x). There is a growing body of evidence that strong color fields are responsible for many phenomena observed at RHIC and will determine the dynamics of heavy ion collisions at the LHC.

Measurements of momentum distributions of gluons and sea quarks in nuclei. One of the major surprises of the last decade was the predominant role gluons play in the proton wave function when viewed with high resolution. Gluon momentum distributions overwhelm their quark counterparts in the proton, for $x < 0.01$. In sharp contrast, the gluonic structure of nuclei remains unknown in this region. DIS experiments have established that quark and gluon distributions in nuclei exhibit "shadowing": they are modified significantly relative to their distributions in the nucleon wavefunction. The nature of such gluon shadowing, however, is *terra incognita* in QCD at high energies. This physics can be fully studied in electron–nucleus scattering at the EIC, which will offer a wide kinematical coverage in the (x, Q^2) plane, as shown in Fig. 3.

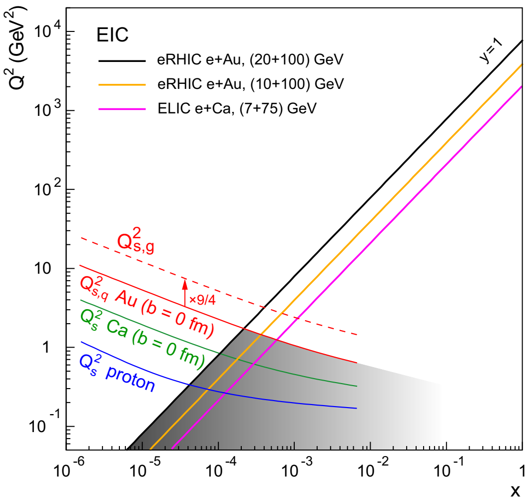

Fig. 3. Kinematic acceptance in the (x, Q^2) plane for the EIC. Shown are lines for two complementary concepts to realize EIC, eRHIC and ELIC. Lines showing the quark saturation scale Q_s^2 for protons, Ca, and Au nuclei are superposed on the kinematic acceptance. As indicated, the gluon saturation scale in Au nuclei is larger by the color factor 9/4.

The inclusive structure functions F_2^A and F_L^A offer the most precise determination of quark and gluon distributions in nuclei. Independent extraction of F_2^A and F_L^A is only possible through a range of center of mass energies, an essential requirement of the EIC. The F_2^A structure function is sensitive to the sum of quark and anti-quark momentum distributions in the nucleus; at small x, these are the sea quarks. Information on the gluon distribution in the nucleus, G^A, can be indirectly garnered from the well-known logarithmic scaling violations of F_2^A with Q^2, $\partial F_2^A/\partial \ln(Q^2)$. The longitudinal structure function F_L^A is at small x proportional to the gluon momentum distributions, and hence allows an independent direct determination of G^A. In Fig. 4 we show projections from perturbative QCD based models with differing amounts of shadowing and from a saturation (CGC) model for the normalized ratio of F_2^A in gold relative to deuterium, compared to the statistical precision expected for an integrated luminosity of 4/A fb^{-1} for 10 GeV electrons on 100 GeV Au nuclei. Fig. 4 suggests that data can indeed distinguish between differing model predictions.

Measurements of the charm structure functions F_2^C and F_L^C are sensitive to the photon-gluon fusion process at high energies. They them will provide the first data on nuclear charm quark distributions at $x < 0.1$. This would present a unique opportunity to select the effect of the nuclear medium on one quark flavor of choice. The high luminosities of EIC give estimates of 10^5 charm pairs for 5 fb^{-1} enabling precision charm studies.

The gluon space-time distribution. Beyond the momentum distributions of gluons (and sea quarks), we would like to also know how the glue is spatially distributed in nuclei. The nature of this glue spatial distribution, be it in small clumps or more uniformly distributed, provides a unique handle on the physics of strong color fields and has important ramifications for a wide range of final states in hadronic and nuclear collisions. Measurements of elastic vector meson production e+A $\longrightarrow$ $(\rho, \phi, J/\psi)$+A and Deeply Virtual Compton Scattering (DVCS) e+A $\longrightarrow$ e+A + γ are known to be extremely sensitive to the momentum

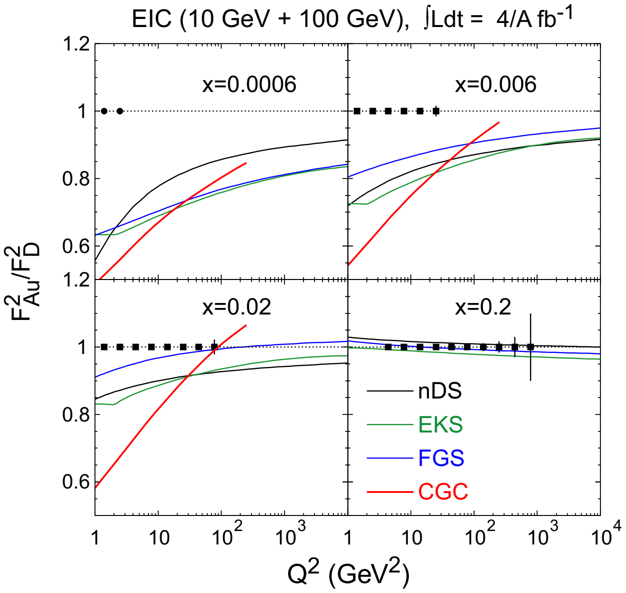

Fig. 4. The ratio of the structure function F_2^{Au} in Au nuclei relative to the structure function F_2^{D} in deuterium nuclei as a function of Q^2 for several bins in x. The filled circles and error bars correspond respectively to the estimated kinematic reach in F_2 and the statistical uncertainties for a luminosity of $4/\mathrm{A}\,\mathrm{fb}^{-1}$ with the EIC. Here the acronym nDS, EKS and FGS correspond to different parameterizations of parton distributions at the initial scale for pQCD evolution. The acronym CGC corresponds to a Color Glass Condensate model prediction applicable at small x.

distribution of gluons in nuclei. The ratio, in a nucleus relative to a nucleon, of the forward cross-section for longitudinally polarized photons, is then, in perturbative QCD, proportional to the corresponding ratio of gluon distributions *squared*. This large sensitivity to the glue allows through measurements of exclusive final states, also for extraction of the space–time distributions of glue in nuclei. This can then be correlated to a spatial imaging of glue in nuclei in the the context of the GPD framework described above.

Color neutral (Pomeron) excitations in scattering off nuclei. Diffractive interactions result when the electron probe in DIS interacts with a color neutral vacuum excitation. This vacuum excitation, which in QCD may be visualized as colorless combination of two or more gluons, is often called the Pomeron. At HERA, an unexpected discovery was that 15% of the $e{+}p$ cross-section is from diffractive final states. This is a striking result implying the proton at rest remains intact one seventh of the time when struck by a 25 TeV electron. The effect is even more dramatic in nuclei. Several models of strong gluon fields in nuclei suggest that large nuclei are intact $\sim$ 40% of the time, nearly saturating the quantum mechanical black disk limit of 50%. Measurements of coherent diffractive scattering on nuclei are a unique feature of the EIC collider environment, and will provide definitive tests of strong gluon field dynamics in QCD. For instance, saturation/strong gluon field models predict a weak x dependence and a strong Q^2 dependence of these ratios. They should be clearly distinguishable from non–perturbative ("soft" Pomeron) models of diffractive scattering.

Fast probes of an extended gluonic medium. In DIS experiments on nuclear targets one observes a suppression of hadron production analogous to, but weaker, than the quenching in

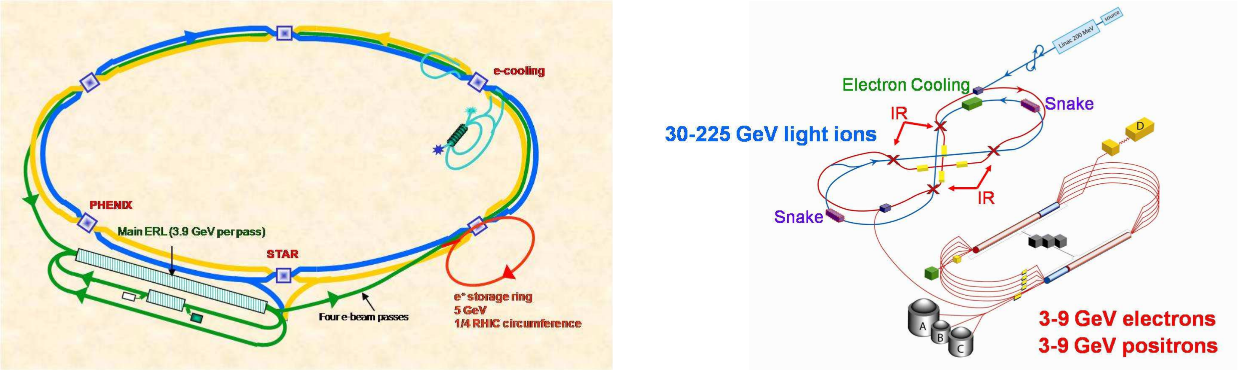

Fig. 5. Design layouts of the ERL-based eRHIC, and the CEBAF-based ELIC colliders.

the inclusive hadron spectrum observed in heavy-ion collision RHIC. An Electron Ion Collider allows a large range of ions to act as femtometer-scale detectors to experimentally study the propagation of quarks and gluons in this "cold nuclear matter" and their space-time evolution into the observed hadrons. The basic question to be answered here is on what time scale the color of the struck quark is neutralized, acquiring a large inelastic cross-section for interaction with the medium. Energy loss models assume long color neutralization times, with "pre-hadron" formation outside the medium and quark/gluon energy loss as the primary mecahnism for hadron suppression. Absorption models assume short color neutralization times with in-medium "pre-hadron" formation and absorption as the primary mechanism. There do exist indications for short formation times from HERMES data and JLAB preliminary data. At the EIC, the range of photon energies would be $10\,\mathrm{GeV} < \nu < 1600\,\mathrm{GeV}$ compared to HERMES (2–25 GeV). It therefore offers more channels to study hadronization inside and outside of the nucleus and reaches into a region relevant for the LHC.

4 Electron Ion Collider: Accelerator Designs

Presently there are two distinct design approaches that address the physics of the EIC: eRHIC, based on the RHIC ion complex, and ELIC, using CEBAF as a full energy injector into an electron storage ring.

eRHIC There are two accelerator design options for eRHIC which were developed in parallel and presented in detail in the 2004 Zeroth-Order Design Report[1]. Presently the most promising design option is based on the addition of a superconducting Energy Recovery Linac (ERL) to provide for the polarized electron beam. This ERL-based design option can achieve peak luminosity for electron-proton collisions at the 2.6×10^{33} cm^{-2}s^{-1} level and has the potential for even higher luminosities. The peak luminosity per nucleon for electron-Au collisions is 2.9×10^{33} cm^{-2}s^{-1} for 100 GeV/n gold ions colliding with 20 GeV electrons. R&D for a high-current polarized electron source and high energy and high current ERL is needed to achieve the design goals in this design. Another design option is based on the addition of an electron storage ring to provide for polarized electron or positron beam. This option is technologically more mature and promises peak luminosity for electron-proton collisions of 0.47×10^{33} cm^{-2}s^{-1}. The general layout of the ERL-based design option of the eRHIC collider is shown in Fig. 5. A polarized electron beam is generated in a photo-injector and accelerated to the energy of the experiment in the ERL. After colliding with the hadron beam in as many as four IP(s), the electron beam is decelerated to an energy of a few MeV and dumped. Positron beam is possible with the addition of a conversion system and a compact storage ring, at one quarter of the RHIC circumference, for positron accumulation, storage and self-polarization. In the present design, the ERL provides electrons in the energy range from 3 to 20 GeV, leading to a center-of-mass energy range from 25 to 140 GeV.

The main highlights of the ERL-based eRHIC design are:

- luminosity of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and higher in electron-hadron collisions.
- high electron beam polarization (∼80%).
- full polarization transparency at all energies for the electron beam.
- multiple electron-hadron interaction points (IPs) and detectors.
- ±3m “element-free” straight section(s) for detector(s).
- ability to take full advantage of electron cooling of the hadron beams.
- easy variation of the electron bunch frequency to match it with the ion bunch frequency at different ion energies.

ELIC ELIC is an electron-ion collider with center of mass energy of 20 to 90 GeV and luminosity up to 8×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is described in detail in the 2007 Zeroth Order Design Report[2]. This high luminosity collider is envisioned as a future upgrade of CEBAF, beyond the 12 GeV Upgrade, and compatible with simultaneous operation of the 12 GeV CEBAF (or a potential extension to 24 GeV) for fixed-target experiments. ELIC’s design features directly aim at addressing the science program outlined above. The CEBAF accelerator with polarized injector is used as a full energy injector into a 3-9 GeV electron storage ring. A positron source is envisioned as an addition to the CEBAF injector, for generating positrons that can be accelerated in CEBAF, accumulated and polarized in the electron storage ring, and collide with ions with luminosity similar to the electron/ion collisions. The ELIC facility is designed for a variety of polarized light ion species: p, d, ^{3}He and Li, and unpolarized light to heavy (up to A $\sim$ 200) ion species. To attain the required ion beams, an ion facility must be constructed, a major component of which is a 30-225 GeV collider ring located in the same tunnel and below the electron storage ring. A critical component of the ion complex is an ERL-based continuous electron cooling facility, anticipated to provide low emittance and simultaneously very short ion bunches. ELIC is designed to accommodate up to four IP’s, consistent with realistic detector designs. Longitudinal polarization is guaranteed for protons, electrons, and positrons in all four IP’s simultaneously and for deuterons in up to two IP’s simultaneously.

An alternate design approach for ELIC is based on the linac-ring concept, in which CEBAF operates as a single-pass ERL providing full energy electrons for collisions with the ions. Although this approach promises potentially higher luminosity than the ring-ring option, it requires significant technological advances and associated R&D. The main highlights of the ELIC design are:

- “Figure-8” ion and lepton storage rings ensure spin preservation and ease of spin manip-

ulation.
- spin transparency to energy for all species.
- unprecedented luminosity at the 10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ level.
- four interaction regions with ±2m element-free region.
- the present JLab DC polarized electron gun routinely delivers ∼85% polarization and meets the beam current requirements for filling the storage ring.
- the 12 GeV CEBAF accelerator can serve as an injector to the ring.
- collider operation remains compatible with 12 GeV CEBAF operation for a fixed-target program.

R&D Required

I. Common R&D Topics In order for either eRHIC or ELIC to reach luminosity at the 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ level, R&D on high energy electron cooling and on the production of polarized 3He beams is required. Electron cooling is required to achieve the design transverse emittances and to counteract the effects of intrabeam scattering during the course of a store. An electron cooling system based on ERL technology is presently under development for RHIC-II, intended to lead to an order of magnitude higher ion-ion luminosities in RHIC. The same system will be used for eRHIC. ^{3}He ions have not yet been used for experiments. EBIS, the new ion source under construction at BNL, will provide the ability to produce polarized ^{3}He beams, given a ^{3}He source. In addition, R&D will be required on a variety of detector and polarimetry items, such as the development of cost-effective and compact high rate tracking and associated readout systems, small angle detector instrumentations, multi-level triggers systems and precision ion polarimetry.

II. R&D Required for eRHIC R&D for the eRHIC ion beam, applicable to both ERL and Ring-Ring options for eRHIC, is required in order to increase the number of bunches in RHIC from 111 to 166, and for better understanding of the machine tolerances required for ^{3}He polarization preservation in RHIC (depolarization effects for ^{3}He beams are stronger than for protons due to the much larger anomalous magnetic moments) as well as in the pre-accelerators. In addition, the ERL eRHIC design requires R&D on high-current polarized electron source and on high energy and high current energy recovery. To achieve the design eRHIC luminosities, 260 mA average current is required from a polarized electron source. The best existing source, at JLab's CEBAF accelerator, operates at approximately 0.3 mA of average current (1 mA is expected to be reached shortly) with current densities of about 50 $\mathrm{mA/cm}^2$. The development of large cathode guns should provide a path to electron currents of tens to hundreds of milliamps. The eRHIC ERL is envisioned to employ state-of-art 703.75 MHz 5-cell SRF cavities. The cavity design was developed at BNL in the course of the electron cooling project and allows the minimization and efficient damping of the higher order modes, opening a way for higher electron currents. Simulations of multi-bunch and multi-pass breakup instabilities showed that the design eRHIC currents can be achieved in an ERL based on this cavity.

III. R&D Required for ELIC With the exception of electron cooling, no additional R&D is necessary for ELIC at the luminosity level of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. To achieve the ELIC design luminosity of 10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, R&D is critical in the areas of crab crossing and ion space charge at stacking in the pre-booster. For the former, R&D is required for the design of a 1500 MHz multi-cell crab cavity, for the understanding of beam dynamics with crab cavities, and for achieving phase and amplitude stability requirements. Overcoming space charge at injection also requires R&D. Stripping injection can be used to stack polarized proton and deuteron beams in the pre-booster after the 200 to 400 MeV linac. To minimize the space charge impact on the transverse emittance, a circular painting technique is suggested for stacking. Such a technique was originally proposed for stacking proton beam in the SNS. Lastly, the ELIC design requires a dedicated R&D effort to develope a high-speed data acquisition and trigger system, to allow for the high collision frequencies.

References

[1] eRHIC Zeroth-Order Design Report, Editors: M. Farkhondeh and V. Ptitsyn, BNL CA-D Note 142, 2004.

[2] Zeroth Order Design Report for the Electron-Ion Collider at CEBAF, Editors: Ya. Derbenev, L. Merminga, Y. Zhang, April 2007.