SPIN PHYSICS AT THE ELECTRON–ION COLLIDER (EIC)*

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Spin physics and the 3D structure of nucleons and nuclei is a cornerstone of the science program of the EIC, which will be the world's only polarized collider. These proceedings summarize the capabilities of the EIC in the context of spin physics, outline a few key measurements envisioned for the ePIC detector, and briefly discuss additional opportunities that could be provided by a 2nd detector.

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1. The EIC

The EIC will collide polarized electrons and protons (both at 70% polarization), as well as light ions such as ^{3}He, which will be available as a part of the baseline EIC project. The proton (ion) polarization can be longitudinal or transverse. Additional source development may, for instance, add ^{7}Li, which is complementary to ^{3}He due to its strong $^3\mathrm{H} + {}^4\mathrm{He}$ component in the wave function. It is also possible to polarize deuterium, but aside from a few discrete energies, acceleration and storage are challenging. Vector-polarized deuterium would thus likely not be available until later in the program. In addition, the EIC can accelerate unpolarized ions over the full mass range from deuterium to uranium.

As the name suggests, the EIC is primarily intended to operate with electron beams, but HERA successfully used positrons and this could also be an option for the EIC. The polarity of the magnets in the lepton ring would have to be reversed, but accumulating unpolarized positrons would in principle be straightforward. However, since the EIC lepton energy is lower than it was in HERA, one cannot rely on self-polarization of the beam (Sokolov–Ternov). Reaching high levels of polarization would thus require a high-intensity polarized source, which could, for instance, be developed in collaboration with JLab.

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The beam energies presented in the conceptual design report (CDR) [1] are 5–18 GeV for electrons and 100–275 GeV for protons, with an additional discrete energy at 41 GeV (requiring the construction of a bypass to achieve synchronization). The minimum energies for ions would be the same as for protons (*i.e.*, 41 and 100 GeV/A, respectively), but the maximum energy, which is limited by magnet strength, would be $(Z/A) \times 275$ GeV/A (*e.g.*, 183 GeV/A for ^{3}He and 108 GeV/A for ^{208}Pb). The maximum luminosity of 10^{34} cm^{-2}s^{-1} for proton beams will be reached in the 10×275 configuration, and drop off at the highest electron energy (synchrotron radiation power limit) and lowest proton energy (space charge limit). Except for these extreme settings, the EIC will eventually collect about 100 fb^{-1} per year. For ions, the luminosity per nucleon is generally similar for all nuclei, and only slightly lower than for the proton. The current plan for the EIC is to start taking data before the nominal CDR parameters are reached. The 41 GeV bypass will not be available during early running and the maximum electron energy will be limited to 10 GeV. The luminosity will grow over time, starting at about 10 fb^{-1} per year for protons. However, it should be noted that this value was used for many of the simulations shown in the Yellow Report [2] and subsequent studies.

An important aspect of the EIC design is also the level of integration of the detector into the interaction region of the accelerator, resulting in an acceptance for the far-forward near-beam detectors that is much better than in HERA. For some processes, like DVCS shown in figure 1, this means that despite a lower center-of-mass (c.m.) energy, the EIC actually will have a greater kinematic coverage than HERA did.

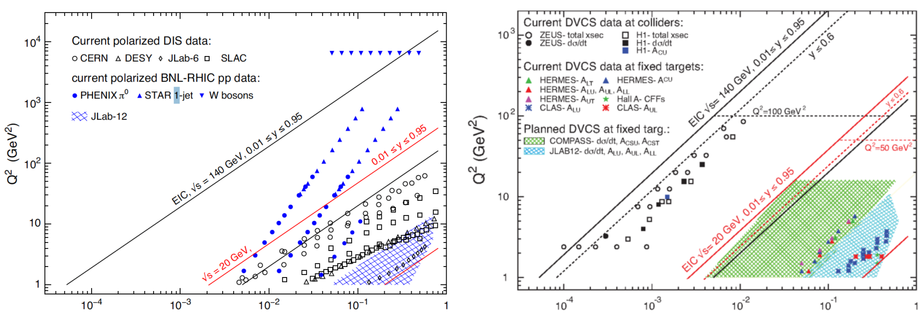

Fig. 1. Kinematic coverage for the world's polarized experiments (left) and specifically for measurements of deeply virtual Compton scattering (right) [2].

The ePIC detector [3] is hermetic (4π acceptance) and includes a full suite of subsystems for tracking, calorimetry, and hadron identification. A combination of EM calorimeters and Cherenkov detectors provide excellent identification of the scattered electron. The detailed layout of the detector is optimized for the asymmetric beam-energy configurations of the EIC, and its overall length is kept compact (9.5 m in total) to make it easier for the accelerator to reach its luminosity goals. The ePIC detector and the near-beam instrumentation fulfill the requirements laid out in the Yellow Report [2].

2. Spin physics at the EIC

Nucleon "femtography", and spin physics in general, is a cornerstone of the EIC science program, and exclusive and semi-inclusive processes related to the 3D structure of nucleons drive most of the accelerator and detector requirements. Theory results and detailed simulations of many spin-related processes have been published in the White Paper [4], Yellow Report [2], and as a part of the three collaboration proposals for detectors at the EIC [5–7]. In addition, there have been topical publications such as the recent review on quarkonium production [8], and a technical design report (TDR) is currently in preparation. While it is not possible to summarize all aspects of the EIC spin program here, a few highlights follow below.

The EIC will allow us to study the transverse spatial structure of the proton by measurements of generalized parton distributions (GPDs) using different complementary exclusive channels. Deeply virtual Compton scattering can, for instance, tell us about the distribution of quarks, while J/ψ production is sensitive to gluons. The EIC will, for the first time, be able to map out the size of these two distributions across a broad range of x, allowing us to answer the question of whether the gluons are always more concentrated toward the center of the proton than the quarks, or if the two distributions become more similar as the proton grows in impact parameter space at lower values of x. Do they change in a bound proton, which can be studied by, for instance, detecting both the struck proton and spectator deuteron from ^{3}He? One can also measure the nuclear GPDs though coherent processes on deuterium or ^{3}He.

A corresponding mapping of the proton in momentum space can be done using transverse-momentum-dependent (TMD) PDFs. A recent study shows that already with 10 fb^{-1}, the Sivers asymmetry A_{UT} for pions can be measured with good precision in fine bins of z, x, and Q^2 [9]. This is, in large part, due to the high figure of merit for EIC measurements with a transverse "target", as the hadron beam is always polarized and there are none of the complications typically associated with transversely polarized targets (dilution, orientation of the holding field, luminosity restrictions, *etc.*). It also suggests that the results from early running will already be quite interesting, and that very precise measurements of TMD PDFs, with full flavor tagging, can be performed across a wide range of kinematics once the EIC reaches its nominal luminosity.

Longitudinally polarized beams are required for measuring the gluon (ΔG) and quark ($\Delta\Sigma$) contributions to the proton spin. Studies in the Yellow Report [2], where EIC pseudodata were added to DSSV fits, show the great precision with which it can be done. Indirectly, this also constrains the contributions from orbital angular momentum (OAM), although not to the point where direct measurements of OAM would not be of interest (GTMDs?).

The availability of deuteron and polarized ^{3}He beams, where the spectator proton(s) can be measured in the forward detectors, also makes it possible to study neutron structure (*e.g.*, A_1^n). Since the spectator tagging procedure is largely process-independent, it can be applied to any reaction of interest such as DVCS or VM production.

The ePIC detector will also be suitable for detection of jets, which can be a useful tool for spin physics (*e.g.*, diffractive dijets).

3. A second detector for the EIC

In the past, most colliders had more than one general-purpose detector to allow for a mutual confirmation of results. Examples include CERN, Fermilab, and RHIC. In some cases (*e.g.*, Belle and BaBar), the two detectors were located at different but generally similar facilities. The EIC will be unique and its capabilities will in many ways go far beyond those of its predecessor (HERA). Having a second detector would thus greatly improve the discovery potential of the EIC.

The H1 and ZEUS experiments at HERA have also shown that if two detectors are a little different, but not too different, and the analyses are coordinated (*e.g.*, use similar binning), then data can be combined in such a way that the overall systematic uncertainties are reduced. This technique would be even more impactful at the EIC, which will have more than two orders of magnitude higher luminosity than HERA, and a large fraction of EIC measurements will be limited by systematics.

There are also important lessons from Fermilab which adopted a staggered approach to detector construction. Even though D0 came 7 years after CDF, both made comparable contributions to the science program, which greatly benefited from having two detectors [10]. If a 2$^{\text{nd}}$ EIC detector had been built 5–7 years after ePIC, the machine would already have reached its nominal parameters, and in the meantime, there would have been opportunities for additional R&D.

A 2nd detector can also expand the science of the EIC. The details of the 2nd detector are not yet fully defined, and users will have a significant impact on its design. There are, however, some natural avenues for the 2nd detector to expand the capabilities of the EIC.

One major opportunity is to greatly improve the ability to study nuclear targets and exclusive processes on the proton. Interaction region 6 (IR6), where the ePIC detector will be located, will have a comprehensive suite of near-beam instrumentation. However, by introducing optics with a second focus at a location with a large dispersion, the Roman Pots can catch particles that otherwise would fall into the 10σ exclusion zone around the beam, extending the acceptance even down to $p_{\mathrm{T}} = 0$. This novel arrangement would greatly improve the detection of low-x/low-t protons and light nuclei from coherent diffractive processes, as well as all fragments from the breakup of nuclei, making it possible to measure the complete nuclear final state. For reactions on a bound nucleon, it would extend the mass range over which the spectator A-1 system could be detected. The fragment-detection capability could also be used to cleanly separate coherent and incoherent processes. It would also allow for studies of the fragments themselves, for instance enabling the detection of hypernuclei (in coincidence with a K^+ in the central detector) or rare isotopes. In the latter two cases, it would be possible to do gamma spectroscopy by measuring the Lorentz-boosted photons in coincidence with the detected nucleus. The Detector Proposal Advisory Panel that was reviewing the three proposals that were submitted in response to the Call for Collaboration Proposals for Detectors at the EIC, highlighted in its report "the significant gain in physics reach achievable with a secondary focus".

The design of the 2nd detector should be complementary to ePIC, and strive to maximize synergies with the forward detection. For instance, a high-resolution EM calorimeter in the barrel would improve the ability to study DVCS on nuclei, while a higher magnetic field could improve the resolution in t for coherent diffraction on heavy nuclei and the invariant-mass resolution for hadron spectroscopy. Additional R&D could improve the performance of various subsystems, including the momentum reach of PID detectors such as the DIRC in the barrel, which would be important for semi-inclusive measurements (including, *e.g.*, TMDs), jet substructure, and hadron spectroscopy. It would also be possible to use an Hcal design in the barrel and (outgoing) electron endcap that would be optimized for high-purity muon identification in the relevant momentum range. While muon ID has many uses, including jets and BSM physics, it is of particular interest for exclusive di-lepton production, which is an essential part of the EIC spin program and synergistic with a second focus. It includes processes such as exclusive quarkonium (*e.g.*, J/ψ) production, timelike Compton scattering (TCS), and double DVCS (DDVCS).

Double DVCS is important for the 3D structure as it provides a unique opportunity for measuring GPDs outside of the $x = \xi$ line, thereby reducing the model dependence in 3D imaging due to the extrapolation to $\xi = 0$. It is challenging to measure since the virtuality of both the incoming and outgoing photons (the latter decaying into a lepton pair) results in a lower event rate than for other Compton processes. However, since the main interest is the dependence on ξ rather than t, the measurements can take full advantage of the near-perfect low-t proton acceptance provided by a second focus. The cross sections also rise at lower x [11], and in collider kinematics, the detector has a uniform acceptance in the lepton c.m. angles (in fixed-target experiments, the gap around the beam translates into a limited and complicated acceptance). All di-lepton measurements benefit from the muon ID, but DDVCS critically relies on the muon decay channel to differentiate between the scattered electron and the decay leptons. It also strongly benefits from electron acceptance for $Q^2 > 0.1$ GeV^2. Thus, overall, the EIC and the 2$^{\mathrm{nd}}$ detector could provide the best opportunity for measuring DDVCS, and conversely DDVCS illustrates several of its potential features.

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