PROCEEDINGS OF SCIENCE

A Second Detector for the Electron-Ion Collider

Pawel Nadel-Turonski[a,b,*]

[a] *University of South Carolina,*
Columbia, SC 29208, USA
[b] *CFNS Stony Brook University,*
Stony Brook, NY 11794, USA

E-mail: turonski@sc.edu

The Electron-Ion Collider (EIC) is the next-generation US-based project for QCD and nuclear science. It will collide polarized electrons with polarized protons and light ions, as well as unpolarized ions of any mass, and will provide a high luminosity over a wide range of c.m. energies. The first EIC detector (ePIC) will support a broad science program, but having two detectors would significantly expand the capabilities of the EIC. The possibility to independently cross check results between the two detectors will greatly enhance the discovery potential. And as demonstrated by H1 and ZEUS, combining data from two detectors can also reduce the overall systematic uncertainties, which will be even more impactful at the EIC than at HERA since the luminosity will be a hundred times higher. A second detector can also provide new capabilities that would expand the EIC program. In particular, the interaction region in which it would be located (IR8) can support ion beam optics with a second focus that would greatly improve the far-forward near-beam acceptance for low-x protons and light nuclei, and make it possible to detect almost all nuclear fragments in reactions where the nucleus breaks up, significantly enhancing the nuclear part of the EIC program. The central detector could also provide complementary capabilities, such as a solenoid with a higher magnetic field and improved muon identification. And if a second EIC detector would be built up to five years after ePIC, this would provide ample time for additional R&D. It could, for instance, make it possible to extend the momentum coverage for hadron identification in the barrel region.

31st International Workshop on Deep Inelastic Scattering (DIS2024)
8–12 April 2024
Grenoble, France

---

[*] Speaker

PoS(DIS2024)283

1. Introduction

The science of the EIC [1] was endorsed by the National Academy of Sciences (NAS) [2]. It included fundamental questions about the origin of the nucleon's spin and mass, the characteristics of the "glue" that binds quarks inside of nucleons, the emergent properties of dense systems of gluons, and how nucleons are assembled to form nuclei.

While the ePIC Detector [3], located at interaction region 6 (IR6) at the EIC, is designed to address the science program described in the NAS report, a second detector will allow for enhanced capabilities in selected sectors, creating new physics opportunities. And a second general-purpose detector would allow for mutual confirmation of results - a crucial component of discovery science at a facility that is unique worldwide.

Since the EIC will be a high-luminosity collider (two orders of magnitude higher than HERA), and many key results will be limited by systematic uncertainties. However, as demonstrated by H1 and ZEUS, a combined analysis of data from two detectors can significantly reduce the final uncertainties. A second detector can thus leverage the capabilities of the EIC in a way that a single one cannot. In addition, since luminosity hungry processes (*e.g.*, 3D structure of nucleons and nuclei measured through exclusive reactions) will benefit the most from the new capabilities of a second detector, the latter will have a large impact on all aspects of the EIC science program.

Two detectors will also expand the opportunities for a new generation of scientists and encourage technological development and innovation by fostering healthy and friendly competition between the two collaborations, which provides the most fertile ground for the emergence of the best new ideas.

It should also be noted that while colliders are usually built from the outset with two or more detector (*e.g.*, ATLAS and CMS at the LHC), the Tevatron at Fermilab successfully followed a staggered timeline, where CDF started taking data in 1985, while D0 followed in 1992. Yet, at the end of operations, both detectors had collected comparable amounts of data. In a similar way, the second detector at the EIC could hopefully follow ePIC within five years, during which time there would be additional opportunities for detector R&D. And while the construction of a second detector would require additional funding, it would have a modest impact on the overall operations costs of the facility.

2. New detector capabilities and physics opportunities

The technical requirements of the second detector are not yet fully defined, and users who join the effort will be able to make a significant impact. Nevertheless, there are some natural ways for a second detector to expand the capabilities of the EIC.

Perhaps the most important of these is a near-beam far-forward detection system incorporating a second focus into the accelerator optics, which will greatly improve the detection of low-x protons and light nuclei from exclusive and coherent diffractive processes, and nuclear fragments from the breakup of heavier nuclei that will make it possible to measure the complete nuclear final state. This can be used to efficiently veto nuclear breakup, but also to study the final state itself. Examples of the latter even include gamma spectroscopy of rare isotopes and hypernuclei.

There are also measurements that greatly benefit from a combination of synergetic capabilities in the forward and central detectors. An example of this is deeply virtual Compton scattering (DVCS) on nuclei, where the far-forward detectors would select exclusive coherent events, while a high-resolution EM calorimeter in the barrel would improve the measurement of the momentum transfer t, the Fourier transform of which gives access to the transverse spatial distribution of partons in the nucleus. In a similar way, the much better proton acceptance at low t would in combination with a high-purity muon identification system be very helpful for the elusive Double-DVCS process, which may be best studied at the EIC second detector.

Muon identification is also an example of a capability that would be complementary to ePIC, which has opted for a traditional hadronic calorimeter (Hcal) in the barrel rather than a system prioritizing muons, which would be advantageous for exclusive and semi-inclusive charmonium production as well as physics beyond the Standard Model. Another way of achieving complementarity with ePIC is through additional R&D. For instance, the high-performance DIRC that was developed for ePIC was a big step forward compared with BaBar, Belle II, and PANDA. But it could be improved further, and the corresponding improvement in performance would impact measurements of jets, semi-inclusive DIS, and hadron spectroscopy. A solenoid with a higher magnetic field that could improve the tracking resolution would also have a broad impact, for instance on the invariant mass resolution for spectroscopy or t-resolution in coherent diffraction on heavy nuclei (which also benefits from the improved vetoing of nuclear breakup using the second focus).

The second detector working group of the EIC UG [4] is playing an important role in carrying out studies that will be part of the science case for a second detector, and investigating the feasibility of possible detector implementations that can guide simulations and future work.

2.1 Far-forward hadron and ion detection utilising a second focus

The interaction region of the ePIC detector (IR6) has a full suite of near-beam instrumentation, but this forward hadron "spectrometer" does not have standard optics (*e.g.*, point-to-point or point-to-parallel). It will, however, be possible to address this in IR8 where the second detector would be located. The final-focus quadrupole (FFQ) magnets, which create the focus at the collision point (IP), can act as an asymmetric lens creating a weaker second focus (in both planes) further away on the other side. The spot size and shape on both ends can be different - round (in coordinate space) at the second focus and optimized for max luminosity at the IP. This arrangement not only creates point-to-point focusing, but more importantly, the second focus coincides with the maximum dispersion (generated by dipole magnets before and after the FFQs). Thus, the beam is the smallest at the location where off-momentum particles are pushed out the furthest from the beam center. This allows Roman Pot detectors at the second focus location to catch particles that would otherwise remain within the inaccessible 10 σ beam envelope. This arrangement makes it possible to even detect particles with $p_T = 0$ if they experience a small change in rigidity (longitudinal momentum or mass-to-charge ratio). In contrast, without the second focus, forward detection is largely limited to particles that fall outside of the angular momentum spread of the beam particles at the IP.

Overall, an optics with a second focus offer an order-of-magnitude improvement for the detection of low-p_T particles. For protons, this is particularly helpful for exclusive reactions at lower x, and generally at higher proton beam energies. For coherent scattering on light ions, the ability to reach $p_T = 0$ is crucial, since most of the cross section is in the first diffractive maximum, and being able to detect the recoiling ion enables a clean measurement without incoherent background. The second focus also opens up new possibilities for the detection of nuclei and nuclear fragments. Almost any nucleus that loses a single nucleon or changes its charge by one unit, or nuclear fragments with similar or larger changes in the mass-to-charge ratio, will reach the focal-plane detectors. With the addition of a second detector in an IR with a second focus, the EIC would thus truly become an electron-*ion* collider.

A second focus has been used in the past in fixed-target storage rings. In particular, the inspiration for the EIC implementation came from the CELSIUS ring at The Svedberg Lab in Uppsala, Sweden, where it worked very well and was used for the study of low-energy ultra-peripheral heavy-ion collisions [5]. The adaptation of the idea to a collider environment was done in 2010-2015, and we now have good understanding of how it works. In particular, it is worth noting that since the focal length of the second focus is much longer and the focus is shallower than the one at the IP, it does not impose any additional constraints on the strength of the FFQs. The main question is rather how to create an appropriate x-y focus at the dispersion maximum in a location that can accommodate Roman pot detectors within the available space, and to do so while meeting other accelerator constraints.

2.2 Central detector

A first step in defining the boundary conditions for the second detector was to explore the possible solenoid configurations that would meet the requirements of IR8 and be compatible with features such as a higher magnetic field and integrated muon identification. And although the final detector subsystem configuration may differ, a guideline was also to be able to accommodate subsystems similar to those in ePIC, scaled to the appropriate internal geometry (with a shorter solenoid, endcap detectors can be moved in closer to the IP, either covering a larger solid angle or being radially smaller, where the latter is more relevant as a benchmark). Given that aluminum-stabilized superconductors are unlikely to be available in the foreseeable future, we further assumed the use of Cu as in ePIC. To reduce coil forces, and hence the material budget in the cryostat, we tried to minimize the longitudinal asymmetry in the distribution of the flux return iron.

The outer transverse dimension of the solenoid is limited by the rapid cycling synchrotron (RCS) line that is used to inject electrons into the ring. This runs 3 m to the side of the IP, and requires a very low fringe field. While it could be possible to have a shielded RCS line go through the detector, this would create significant complications. As a baseline we thus assumed that all the magnetic flux would be contained within 3 m. A second detector would not need to have a solenoid similar to the one used in BaBar, which was originally intended for re-use in ePIC. Reducing the coil length by 30% gives a better match to the length of the tracker and creates more space in the endcaps for detector subsystems and services. This assumption allowed us to revert to the original EIC detector proposal advisory panel (DPAP) specification of ± 4.5 m longitudinal detector space. The inner radius of the cryostat is determined by the magnetic field at the center, since higher fields require a larger fraction of the 3 m outer radius to be allocated to the flux return iron. Since two [6] [7] of the three detector proposals reviewed by the DPAP had a 3 T field at the center, we used this as a starting point. In this configuration, the inner cryostat radius can be up to 1.2 m (0.2 m less than in ePIC) while fully containing the flux within an instrumented flux return. But with a shorter solenoid the inner detector radius outside of the cryostat can be larger than in ePIC, making detector integration easier. The solenoid parameters in this configuration are moderate (stored energy of 7.9 MJ and a current density of 3250 A/cm^2).

The assumption for the flux return was that it would be instrumented using a system similar to the K_L and muon (KLM) detector from Belle II. This differs from a traditional Hcal in that it has fewer layers, but each one is read out individually. In addition, each layer has two sub-layers with crossed scintillator strips, providing a very good position resolution. This not only gives excellent muon identification, down to low momenta, but also precise neutral hadron detection. This is a combination that matches the EIC very well since most mid-rapidity jets are best reconstructed from tracking, EM calorimetry, and PID, and one thus only needs to add information on the neutral hadrons. At Belle II the energy sum of the layers is not used, but R&D is ongoing to see how well this could be done for the EIC. The R&D is also investigating the possibility to use time-of-flight to determine the momenta of low-energy neutral hadrons. Work on the EIC KLM, DIRC, and other subsystems relevant for the second detector was supported by the generic detector R&D for the EIC.

References

[1] Electron Ion Collider Conceptual Design Report, 2021, https://doi.org/10.2172/1765663.

[2] An Assessment of U.S.-Based Electron-Ion Collider Science, 2018, https://doi.org/10.17226/25171.

[3] The electron-Proton and Ion Collider (ePIC) Experiment, https://www.epic-eic.org/.

[4] The EIC User Group, https://www.eicug.org/.

[5] A. Ringbom *et al.*, A facility for studies of giant multipole resonances by fast heavy-ion scattering, Nucl. Instrum. Methods Phys. Res. A 373 (1996) 57-64, https://doi.org/10.1016/0168-9002(95)01494-2.

[6] ATHENA Detector Proposal, ATHENA Collaboration, arXiv:2210.09048, 2022.

[7] CORE – a COmpact detectoR for the EIC, CORE Collaboration, arXiv:2209.00496, 2022.