Report from the EIC Detector Proposal Advisory Panel

March 21, 2022

1. Introduction and Overview

The Electron Ion Collider (EIC), an accelerator facility to be constructed at the Brookhaven National Laboratory (BNL), will enable the detailed study of protons, neutrons and atomic nuclei. The EIC complex is expected to have two interaction regions with the potential to host two large scale detectors. The science case for the EIC has been explored in a National Academy of Sciences (NAS) report [1], in an EIC White Paper [2] and more recently in the EIC Yellow Report [3]. The Yellow Report also describes the performance requirements for the detector systems and the fundamental concepts for EIC detectors that meet the performance requirements. A comprehensive generic EIC-related detector R&D program has guided the advancement of the detector technologies over the past 10 years.

The EIC is an official project of the U.S. Department of Energy and will be preparing for CD-2 within the year. The program is managed through a partnership between Brookhaven National Laboratory (BNL) and the Thomas Jefferson National Accelerator Facility (JLab), and the two laboratories will jointly host the experimental program. The DOE project includes significant funding for the construction of one EIC detector, one interaction region located at IR6, and a conceptual design for a second interaction region. It is expected that the detector system will have components that are funded or contributed from sources outside the DOE project. Currently the EIC user community, as represented by the EIC Users Group [4], counts over 1300 members from 267 institutions in 36 countries worldwide.

BNL and JLab management charged the Detector Proposal Advisory Panel to advise on the optimal approach to realize the EIC physics program. The panel's membership and charge are given in Appendix 1. The first priority is to identify the approach for realizing the first detector system – Detector 1. This detector system would be primarily funded by the DOE EIC Project and is expected to address the science outlined in the EIC White Paper and NAS Report. In addition, the Panel was asked to assess options for an additional detector system that could address science beyond the White Paper and NAS Report and/or enable some complementarity to the first detector. Due to currently foreseen resource constraints, a second detector could only begin operations 3 - 5 years after the start of operations of the first EIC detector (Detector 1).

The Panel reviewed proposals from three proto-collaborations: ATHENA, CORE, and ECCE. The panel was charged to consider scientific performance, technical risk, cost, schedule, the strength of the collaboration, and the availability of resources. As stated in the charge to the Panel (App. 1), the EIC Detector Advisory Committee (DAC), a standing committee for the EIC Project that has been following progress of the development of detector technologies, did an independent technical and cost evaluation of the proposals. The DAC membership is given in Appendix 2.

The proto-collaborations submitted their proposals in early December 2021 and made presentations at a public meeting of the panel that took place December 13-15, 2021 [5]. Answers to follow-up questions from the Panel were submitted and reviewed at a subsequent executive meeting, January 19-21, 2022. The panel reviewed the proposals in 5 main areas: 1) Physics Performance, 2) Detector Concept and Feasibility, 3) Electronics, DAQ and Offline 4) Infrastructure, Magnet and Machine Detector Interface, and 5) Collaboration and Management. This report contains a summary of the evaluations in these areas, some general comments and observations, and the panel's conclusions and recommendations. The findings are based on the proposals, presentations, discussions between the panel and the proponents, as well as individual discussion with the management of the proto-collaborations.

The science case is described in several publications, in particular the White Paper [2], the NAS Report [1] and the Yellow Report [3]:
The Electron-Ion Collider (EIC) is a new, innovative, large-scale particle accelerator facility which will allow the study of protons, neutrons and atomic nuclei with the most powerful electron microscope, in terms of versatility, resolving power and intensity, ever built. The resolution and intensity are achieved by colliding high-energy electrons with high-energy protons or (a range of different) ion beams. The EIC provides the capability of colliding beams of polarized electrons with polarized beams of light ions, and this all at high intensity. The EIC was established as the highest priority for new construction in the 2015 US Nuclear Physics Long Range Plan [6] and was favorably endorsed by a committee established by the National Academy of Sciences in 2018 [1].

Key science questions that the EIC will address are:

- How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?
- How are partons inside the nucleon distributed in both momentum and position space?
- How do color-charged quarks and gluons, and jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

The accelerator design foresees two interaction regions, IR6 and IR8. The interaction region IR6 is designed to meet the physics requirements of, e.g., the White Paper and will host Detector 1. A pre-conceptual layout exists for IR8, with a larger crossing angle compared to IR6 and possibly using a 2nd, downstream focus, if feasible. It is supposed to host Detector 2.

The 2nd focus option would expand the physics capability, thereby adding to the complementarity between the two detectors, as discussed in Section 2.1 below.

1.1 Constraints

The call for proposals, issued early in 2021 [7], outlines important requirements for the design and construction of the proposed detectors:

Detector 1 is within the scope of the EIC project and must be ready for data taking by CD-4A. Project funds are expected to cover most but not all of the cost of Detector 1. The call stipulated that it should be based on the "reference" detector described in the Yellow Report [3] and included in the EIC Conceptual Design Report [8].

Resources for Detector 2 are not included in the scope of the project, nor is the construction of the second interaction region (IR8). Detector 2 is supposed to be ready for data taking several years after the start of data taking in IR6. It could be a complementary detector e.g. by using different technologies, by optimization for particular science topics or by addressing science topics beyond those described in the White Paper.

2. Evaluation of the Submitted Proposals

2.1 Physics Performance

Evaluation criteria

Detector 1 must be fully capable of addressing the science case laid out in the EIC White Paper [2] and the 2018 NAS report [1]. For brevity, this is referred to as the 'baseline physics case' in the following. Key measurements for this science case are presented in sections 1.3, 2, 3, and 4 of the White paper (and summarized in tables 2.1 to 3.2 therein). The NAS report adds the production of heavy quarkonium (J/Ψ or Upsilon) near threshold to this set of measurements.

The following assessment is based in the projections of physics performance in the proposals, on the presentations and discussions during the panel meetings in December and January, and on a set of performance estimates requested from all proposals by the panel.

Characterization of the proposals

All three proposals have taken important steps forward towards a realistic estimate of detector performance. The ATHENA and ECCE proposals include full GEANT4 simulations of the detector, including the models of the material of supports and services. In the physics projections of the CORE proposal, detector effects are parameterized and implemented in the DELPHES Monte Carlo, except for a simplified treatment of PID using cuts. The effects of noise in the readout electronics are in general not included in the simulations of any proposal. With some exceptions, the same holds for physics background processes. For many of the more complex analyses, such as charm tagging and jet reconstruction, the proposals emphasize that the presented results reflect work in progress and are to be refined in future studies.

The ATHENA and ECCE proposals give projections for a wide array of physics processes. In both cases, these cover nearly the full range of key measurements of the baseline physics case specified above. A few important observables were not studied (the inclusive longitudinal structure function F_L and inclusive diffraction for nuclei, as well as electroweak structure functions of a polarized nucleon), but this is not regarded as critical by the panel.

Both proposals also present projections for measurements beyond the baseline case. ATHENA considers in particular jet, dijet, and jet substructure observables for different processes in *ep* and *eA* collisions. Additional physics topics studied by ECCE include pion structure, electroweak measurements (see section 4 of the White Paper), spectroscopy of *XYZ* states, and DVCS in the far backward region.

The CORE proposal gives detailed projections for exclusive processes in *ep* and *eA* collisions, which will be discussed further below. For measurements in inclusive and semi-inclusive DIS, the proposal presents predictions for the relevant aspects of the detector performance and refers to the studies in the White Paper and the Yellow Report for their impact on specific processes. Noteworthy is the very fine resolution in the inelasticity *y* predicted for DIS at very high Q^2.

Assessment of physics capabilities

Based on the projections presented by ATHENA and by ECCE proposals, the panel expects that either detector will be able to fully realize the baseline physics case and to make significant contributions in areas beyond. The panel estimates the same to be true for the CORE detector, with the proviso that the corresponding performance studies are in part less detailed compared with the other two proposals.

Comparing the expected physics performance among the three proposals, the panel did not find any striking differences that could clearly be traced back to the detector design, given the differences in simulation details and analysis methods. An example of visible differences is the predicted resolution for jets in the region $\eta < 1$, which is clearly best in the ECCE projections. The panel feels, however, that no strong conclusion about the detector performance can be drawn from this, given that a different jet algorithm is chosen in the ECCE study, and given the preliminary nature of the jets studied emphasized by the proponents.

The CORE studies for DVCS and exclusive meson production find that the reaction kinematics can be reconstructed from the central detector alone. This allows the extension of the parton imaging program from the proton to nuclei, and it may increase the precision of measuring *t* in *ep* collisions. The panel regards this as a good example of specialization/optimization to enhance the complementarity between two detectors, discussed below.

The CORE proposal makes a convincing case for the significant gain in physics reach achievable with a secondary focus:

- increased acceptance in the invariant momentum transfer *t* of the scattered proton in *ep* collisions, which directly translates into an increased resolution power for imaging partons in the transverse plane,
- significantly improved abilities to detect nuclear breakup in exclusive and diffractive scattering on light and heavy nuclei. The distinction between coherent and incoherent scattering is essential for the physics interpretation of these processes,
- prospects for a program of low-background γ gamma spectroscopy with rare isotopes in the beam fragments.

The possibility to use a second focus requires appropriate design of the IR and the far forward instrumentation but is largely independent of the design of the central detector. It is understood that the implementation of a second focus should not lead to a significant degradation of the beam quality parameters, in particular, not at the other IR.

2.2 Detector Concept and Feasibility

Our assessment has been aided by the EIC Project Detector Advisory Committee (DAC), which includes a team of experts in detector technologies and cost and risk evaluation, providing an independent review of the detector proposals.

Common strengths and R&D

The generic detector R&D program administered by the BNL Physics Department and supported by the DOE Office of Nuclear Physics since 2011, created 24 eRD projects to address the scientific requirements for measurements at a future Electron Ion Collider (EIC) and to develop the necessary technologies. The eRD program covered software and hardware activities leading to consortia on tracking, particle identification (PID), calorimetry, software and simulations. The eRDs have enabled the three proto-collaborations to present very compelling detector concepts.

The panel found that the performances of all three detector concepts match well the standard set by the generic EIC detector presented in the Yellow Report, except in limited phase space regions. All detectors have a solenoidal superconducting magnet leading to a barrel and endcap configuration and providing excellent tracking and vertexing, particle identification, and calorimetry. The asymmetric nature of collisions at the EIC leads to different optimization of the forward and backward endcaps.

All detectors extensively use high-precision low-mass Monolithic Active Pixel Sensor (MAPS) based silicon to provide vertex/tracking complemented by gaseous detectors. A combination of technologies provides PID over different momentum ranges. The technologies include dual radiation RICH (dRICH), modular RICH (mRICH), high-performance DIRC (hpDIRC), and AC coupled LGADs for Time-of-Flight Information. ATHENA uses a large-gap proximity focusing RICH for PID in the backward region. Calorimeter systems include crystals (PbWO4 and Sciglass), W/SciFibers or W-Shashlyk for the electromagnetic part. In the barrel region ATHENA employs a hybrid of imaging calorimetry with silicon pixel sensors combined with Scintillating Fibers (SciFi) embedded in lead. Iron or steel-scintillators are used for hadron calorimeter. ECCE is reusing the sPHENIX hadron calorimeter in the barrel. CORE has adopted a neutral hadron detection and muon ID system, which is integrated with the flux return of the solenoid. The preferred photosensors for many devices (Calorimeters and PID) are SiPMs.

Common Risk Factors

Because of the joint generic detector R&D, all detector concepts share some risks since they all plan to use technologies such as 65 nm MAPS and the AC-LGAD technology, which need further development. Delays in the AC-LGADS impact only the PID in ATHENA and CORE, while in ECCE they also affect the outer tracker performance. The production and performance of SciGlass and the production of large foils for the μ-RWell detectors are also not yet fully mature.

Similarly, all detector concepts use SiPMs, which after irradiation become noisier and thus potentially problematic for the chosen streaming readout architecture.

Comparative Strengths and Risks of the Detectors

One of the main differences among the three detector concepts is the magnetic field strength. ATHENA and CORE use a 3 T magnet, while ECCE plans to reuse the 1.5 T BABAR magnet, which has been moved from SLAC to BNL for use in the sPHENIX experiment at RHIC. The panel could not find a clear example where the lower field used by ECCE would lead to a physics loss. The reuse of the BABAR solenoid is a risk that was already the subject of an extensive engineering study. ECCE has also put in place a risk mitigation plan that includes the design of a replacement magnet and a decision point in 2023. The panel was also concerned about the axial asymmetry in ECCE's field because of the differences in the configuration between forward and backward endcaps. The stronger field in ATHENA and CORE also leads to risks. The magnetic field lines in the region covered by the RICH must be optimized to minimize distortions due to track bending in the gaseous volume. This optimization of the field configuration leads to non-uniformity in the field of about 25%. The large magnetic field can also lead to stray fields affecting the accelerator components.

All three detector concepts use gaseous detectors. ATHENA exploits μ-RWell, Micromegas, and GEM chambers. The use of more technologies, even if they have been already implemented in other experiments, can still lead to possible delays in the construction of the detector. ECCE and CORE propose using only μ-RWell chambers. CORE and ATHENA utilize planar μ-RWell, while ECCE also employs more complex cylindrical μ-RWell trackers to optimize performance.

The production of readout chips and monolithic sensors is also a risk to the schedule and cost. The costs of chips have risen, and some companies are closing their lines to particle physics experiments characterized by smaller orders compared to industry. ATHENA and CORE are slightly more exposed to this risk than ECCE since they use more ASICs with a larger fraction still requiring some further development. For example, the imaging calorimetry is based on AstroPix monolithic silicon sensors, built in the High Voltage CMOS process developed for MUPix and ATLASPix. In the case of the MUPix chip used in the Mu3e experiment at PSI, the foundry where the original development was carried on is already no longer accessible.

All three proto-collaborations provided cost estimates for the detector, including the costs to complete the R&D and the savings due to possible in-kind contributions and reuse. The analysis performed by the DAC concluded that ATHENA is using many state-of-the-art technologies and "in development" technologies that require a more costly R&D program. Compared with the cost estimates for the reference detector provided by the EIC project, ATHENA costs are higher for calorimetry and PID. For ECCE, the costs of the HCAL and Magnet are lower, given the absence of a backward endcap HCAL and the reuse of the BABAR magnet. The cost of CORE is lower than the reference detector but the panel’s assessment is that it may be somewhat underestimated. Both ECCE and ATHENA expect significant in-kind contributions from foreign funding agencies. DAC evaluated the cost and schedule provided by the three proto-collaborations according to the quality of the estimates and concluded that the information provided by ECCE and ATHENA was very accurate for this level of design; the estimates from CORE were ranked as more uncertain.

Conclusions for Detector Concept and Feasibility

Based on the careful study by the DAC and the information provided by the three proto-collaborations, the panel finds that ATHENA and ECCE satisfy the requirements to fulfil EIC's "mission need" statement based on the EIC community White Paper and the National Academies of Science (NAS) 2018 report. The more limited range of new technologies and the reuse of the BABAR Magnet and the sPHENIX HCAL make ECCE less expensive and more likely to be ready for data taking on time for Critical Decision 4A (CD-4A), the start of EIC accelerator operations, and therefore suitable as Detector 1. Core has provided a more conceptual, less fully developed design.

2.3 Electronics, DAQ, Offline

The detector readout electronics, Data Acquisition (DAQ) and offline computing systems are essential components of a future EIC detector. Together, they must provide the ability to carry out the full breadth of the EIC physics program as described in the EIC community White Paper [2] and the 2018 NAS report [1]. Design choices for these systems should aim to optimize the use of resources and time-to-analysis in order to maximize scientific output. An architecture providing the flexibility and scalability to adapt to unforeseen data taking challenges, new ideas, and physics explorations beyond those described in the White Paper and the NAS report is desirable.

The following assessment is based on the detector proposals and auxiliary material made available to the panel, on presentations and discussions during the Panel meetings in December and January, and on a technical evaluation of the detector proposals carried out by the EIC Detector Advisory Committee (DAC).

Common strengths and R&D needs

Following the concept outlined in the Yellow Report [3], all three proposals put forward an electronics readout system and DAQ architecture designed for streaming readout. This provides clear advantages over a triggered architecture: it provides the ability to fully optimize the physics reach of the experiment, it facilitates the future evolution and extensions of the EIC physics program, it minimizes data loss due to inefficiency in trigger selections, and it offers the possibility of a more streamlined workflow and combined online/offline software effort.

This choice is in line with the general trend in the field, exploiting innovations in high-speed communication, microelectronics, and FPGA technologies.

The design of the readout/DAQ systems described in all three proposals was informed by activities undertaken as part of the eRD23 project (Streaming readout for EIC detectors) and shows many design commonalities. Data from detector-specific Front-End Electronics (FEE) will be sent via optical fibers to a system providing a common interface between FEE and a backend commodity computing farm. This common interface module will be based on the design of the Front-End Link eXchange board (FELIX) used by LHC experiments, and it will also perform some data aggregation. The commodity DAQ computing farm is typically assumed to be split into different layers according to different functions (readout, online filtering, buffering).

Current estimates of EIC data transfer rates to IT facilities are expected to be below those of sPHENIX, and technology that provides the required rate capabilities of data transfer to IT facilities (both on and off-site) during data taking is commercially available.

The FEEs must be adapted to the characteristics and needs of each subdetector technology. In addition to the development of detector-specific front-end boards, specialized ASICs need to be developed on a timescale compatible with the EIC project. Notable examples of required further R&D work include the development of readout electronics for a EIC Silicon tracker, which is the focus of the eRD104/eRD111 R&D projects and the EIC Silicon Consortium, and the ASIC development for AC-LGAD detector systems, which is the focus of the eRD112 R&D project.

Common Risks and Challenges

The implementation of a streaming readout comes with a certain number of challenges and uncertainties. Within such an architecture, bad/noisy detector channels or unexpected backgrounds will lead to a significant increase in data rate that could potentially exceed the data transfer capability between the FEEs and readout computers. Both ATHENA and ECCE have pointed out the particular importance of having the ability to monitor for bad/noisy channels or modules and reset/disable them, of excellent control of FEE level detector calibration related to zero suppression, and of having the ability to implement common mode noise removal. Risks are further mitigated by both ATHENA and ECCE by optimizing the scale of data aggregation for each subdetector system in such a way as to ensure a reasonable throughput safety margin between the FEE and the readout computer farm, and by the possible implementation of software event filtering and/or software triggers. Further risk mitigation strategies specific to individual proposals include, for ECCE, a detector design relying as much as possible on low-noise detectors (e.g. avoiding SiPM for mRICH), and for ATHENA, the possibility to retain the capability for operating with a hardware trigger via the timing system.

For all three proposals, one of the challenges to a streaming readout is expected to come from the dark currents from the SiPM that will gradually increase with accumulated radiation dose. Both ATHENA and ECCE explicitly plan to have an additional throughput safety margin between the FEE and readout computer farm to account for this effect. We note that the ATHENA proposal foresees a number of readout channels from SiPM that is a factor of about 3 to 5 times larger than that of ECCE and CORE proposals, likely requiring the need for additional mitigation strategies to maintain the ability to operate a streaming readout as function of time. Additional mitigation strategies put forward and studied by ATHENA include the undertaking of an annealing cycle of the SiPM to partially restore initial dark current conditions, the implementation of timing selection cuts in the FEE, and the possible further downstream data reduction based on algorithms implemented in the FPGAs of the FELIX-like boards and/or in software. We note that the in-situ thermal annealing of SiPM, proposed for the RICH detectors present in all proposals, still requires further R&D work for its successful implementation.

In general, the development and production of specialized chips is a risk to the schedule and cost of the project. For all three proposals, the highest risk is associated with the development of the MAPS and the ASICs for the AC-LGAD sensors.

Comparative strengths and risks

The readout/DAQ/offline computing model presented as part of the CORE proposal is far less developed than that of the other two proposals, limiting the ability for a full comparative assessment across all three proposals. This is reflected in the further comments in this section.

The larger number of subdetector systems in ATHENA, with different readout technologies, comes at the cost of additional readout development work (e.g. FEEs). This additional complexity carries additional risk both in terms of schedule and costs.

Another difference among all three proposals is in the number of different readout ASICs to be used and to be developed. The ECCE readout is assessed to carry a slightly lower risk, as it is based on a smaller number of ASICs of which most are already available. The ATHENA proposal depends on a slightly larger number of different ASICs, with a larger fraction still requiring some level of further development.

ATHENA has approximately 20% more detector channels than ECCE, which makes it the proposal with the highest number of detector channels. The estimated cost of the ATHENA DAQ system scales with this difference in the number of channels.

The offline software environment of ATHENA, demonstrated in the detailed simulations, is already quite mature, while ECCE has a well-developed offline computing model. For both ATHENA and ECCE, the development of the DAQ/Offline systems is supported by a substantial team.

Additional comment

It is important to understand and monitor the long-term availability of different chip technology nodes on which a detector default baseline and fallback ASICs depend.

2.4 Infrastructure, Magnet, and Machine Detector Interface

Infrastructure

No major concerns regarding the infrastructure needed for the detectors were raised in our discussions with the experiments and with the EIC experimental program team. BNL has a longstanding experience in managing large experimental setups, providing the needed services and technical support for the installation, and operation of the experiments (power, cryogenics, cooling and ventilation, lifting, communication networks, etc.) as well as assuring their ESH compliancy. We were pleased to note that already at this relatively early stage of the proposals, the proto-collaborations are already engaged in a fruitful discussion with the host lab and we encourage them to keep doing so as the technical design matures.

Magnets and Machine Detector Interface

All the proposed experiments deploy superconducting solenoids, which have different Bdl integrals, field homogeneity and stray field strength outside their iron yokes. ATHENA and CORE propose to deploy newly built 3T solenoids, while ECCE is planning to reuse the 1.5 T BABAR magnet which will be used by the sPHENIX experiment.

The panel doesn't see any particular concern in the construction of the new magnets, which fall comfortably within the nowadays established technologies. In the case of ATHENA, the design is already rather advanced and shows no critical problems.

Concerning the reuse of the BABAR magnet, the ECCE proto-collaboration has presented a plan to assess its long-term reliability, together with a plan B, i.e. building a replacement magnet. The panel noted also that the yoke endcaps in the ECCE design have different thickness, which will result in asymmetric stray fields at the two ends, with a potential adverse impact on the beams.

In general, considering the complex layout of the EIC interaction region (crossing at an angle, beam crabbing), the perturbation introduced by the coupling with the solenoidal field will affects the orbits and the dynamics of the beams, and it will need to be compensated in order not to spoil the machine performances.

In our discussion with the accelerator physicists, we were reassured that the appropriate corrections (“knobs”) in the beam optics have been studied to compensate for the effect, with the caveat that simulations, even the more sophisticated ones, assume often a perfect knowledge of the boundary conditions and do not account for non-linear effects.
It is, therefore, crucial that the recommended experiment provide high quality maps of the magnetic field over all the IR space, which will allow one to precisely align the less stiff electron beam with the magnetic axis of the solenoid (thus cancelling the coupling) and to implement the appropriate knobs on the proton beam trajectory and crabbing.

The panel also noted that for all the experiments, the design of the forward region was less mature in comparison to the central detector. In consideration of the importance of this region for the physics and its proximity with the machine, we encourage the recommended proto-collaboration to further develop the design in close concert with the accelerator group.

2.5 Management and Collaboration

Detector 1 must be developed and constructed within a very demanding schedule and within a tightly constrained budget. The time until CD-2, when Detector 1 must be baselined, is particularly short considering the work to be accomplished in order to be ready to be baselined.

Collaboration planning and composition at this time must account not only for the expertise and effort necessary for construction of the detector; it must also account for future needs to commission the detector and then to operate and maintain the experiment.

In order to ensure that the EIC has a maximally optimal Detector 1, the proto-collaboration for a concept selected for Detector 1 must be open to: (1) integrating new collaborators in a manner that enables them to make contributions that impact the capabilities and success of the experiment in significant ways, including some new collaborating individuals and groups into positions of responsibility and leadership; and (2) integrating new experimental concepts and technologies if appropriate to best meet the goals and requirements of Detector 1, without introducing undue risk.

One can naturally anticipate considerable evolution and maturity of concepts on project organization and technical coordination as the collaboration for Detector 1 moves toward CD-2 and its technical design report. A fully mature organizational structure need not be expected at this time.

Although the detector project is embedded in the overall EIC project, where top-level project management and systems engineering are provided, the detector project will need appropriate project management and engineering throughout its organization in order to be successful, particularly within the DOE Office of Science (SC) system.

Common strengths of proto-collaborations

The three proto-collaborations are led by experienced, strong leadership teams. ATHENA and ECCE also have expert and experienced international collaborators, as demonstrated by the well-developed state of the proposed conceptual designs prepared in a relatively short period of time, and by the organization of the effort to produce these designs and of the proposals. This accomplishment is truly impressive. Nevertheless, none of the three proto-collaborations is yet large enough or strong enough for successful development of a detector for Day 1 of the EIC. In particular, the CORE proto-collaboration and conceptual design have not reached a stage that CORE can demonstrably achieve the level of maturity necessary for CD-2 on the timescale required of Detector 1.

The proto-collaborations recognize the need for organization and development of critical activities beyond construction of their experiments, for instance commissioning, monitoring tools, data processing, and analysis.

Consideration of diversity, equity, and inclusion has been thoughtfully incorporated into the conception and structure of all three proto-collaborations.

Comparative strengths *vis a vis* Detector 1

CORE is not at the same stage of collaboration and organizational development as ATHENA or ECCE, and is judged by the panel not to be in a position to be ready as Detector 1. Consequently, the following discussion of comparative strengths focuses on ATHENA and ECCE.

ECCE emphasizes capability to “evolve” and “realign” after proposal review. While comprised of a large number of experienced and expert groups and individuals from the U.S. and abroad, it presents itself as a “consortium” at this point in time, a consortium that will evolve into a collaboration as new groups join. It presents a tentative, initial organizational structure, one that is quite thoughtful and reasonable, with the expectation that the collaboration will eventually determine its organizational structure. ECCE puts emphasis on capability to integrate new groups with maximum benefit, and expressed openness and flexibility regarding incorporation of newcomers and their ideas into its plans. Thus, ECCE appears to be well positioned to make use of the talents and resources of the full community.

ECCE is a bit more advanced with respect to project planning and its concepts of project management in the DOE Office of Science system. Moreover, ECCE recognizes the importance and roles of project management, of technical coordination, and of engineering (*e.g.* systems engineering), as exemplified by its incorporation of professional project managers in its costing activity and its inclusion of a technical coordinator in its organizational structure, and as illustrated in its response to the panel’s question about incorporation of engineering into its project organization.

Concluding remarks

The managements and collaborations of both ATHENA and ECCE are capable of becoming a solid basis for the full development and implementation of a successful Detector 1. On balance, the Panel finds that the more flexible organizational structure and outlook of ECCE puts it in a better position to become the organizational basis for Detector 1. As noted, the proto-collaborations are not yet at the strength necessary to prepare a detector for Day 1 of the EIC. Consequently, successful collaboration on Detector 1 by members of all three proto-collaborations will be critical for the EIC.

3. Physics Impact of a second detector

A strong case for two complementary general-purpose detectors has been made during the panel review, in line with the arguments given in chapter 12 of the Yellow Report [3]. Such a scenario will allow independent confirmation of scientific results on a broad scale, thus addressing the basic requirement of reproducibility of measurements. In particular, results obtained with two different detectors will have different systematic uncertainties and offer possibilities for strong cross checks.

- Even the first years of EIC running may yield surprising results and discoveries. A possible example are nuclear cross section ratios in so far unexplored kinematics, which require relatively low integrated luminosity and beam conditions that could be realized early on. The time lag for the startup of a second detector is somewhat of a disadvantage in this respect, but this does not diminish the need of independent confirmation for any discovery measurement.
- A large part of the EIC physics case requires measurements with high accuracy, which necessitate accelerator and detector performance close to the final design parameters, as well as high accumulated luminosity. Examples are various polarization asymmetries at low Bjorken *x*, which are expected to be very small, and exclusive processes with high demands on background suppression and kinematic resolution. For such measurements, the time lag of a second detector is less critical, and complementarity in systematics and acceptance can be a significant advantage for maximizing the physics output of the EIC.
- On a longer term, combined analyses of the measurements from both detectors will allow for minimizing experimental uncertainties well beyond the reduction of statistical errors. This expectation is based on the positive experience from experiments at past and present facilities, such as LEP, HERA, and the LHC.

For the above scenario to be compelling, it is essential to have two detectors with a sufficient degree of complementarity in layout and detector technologies. This requires a well-chosen balance between optimization as general-purpose detector versus partial specialization and the ability to cross check the other detector for a broad range of measurements. The design of a second detector should be chosen with these criteria in mind. The time required for its design and construction may offer opportunities for benefiting from technological progress.

All three proposals have shown that their respective detector designs are capable of performing measurements that go beyond the baseline physics case. As studies for such measurements are pursued and extended, additional detector capabilities may become desirable. The second detector will offer a chance to take such developments into account.

As laid out in the section 2.1 on physics performance, an IR with a secondary focus can significantly broaden the physics scope and output of the EIC. A second detector could also be more specialized towards a particular physics area. This can be an attractive scenario if corresponding physics opportunities arise.

Having two independent detector collaborations offers further benefits at the scientific level and beyond:

- the development and use of different and independent analysis methods,
- the incentives due to a friendly competition between two collaborations,
- the increased number of scientific leadership positions, with considerable benefits for attracting talented scientists to the EIC and for the training of a highly skilled workforce.

While these goals could also be partly achieved by segmentation within a single collaboration, experience strongly suggests that having distinct collaborations offers clear advantages in this respect. Furthermore, the additional R&D required for a second detector will bring additional benefits in developing technologies and in training the associated workforce.

4. General comments and observations:

The panel is impressed with the quality of the proposals and the strength of the expected physics performance of the three proposals. The detector systems are well matched to the reference detector, and the technologies are well advanced. CORE presented a conceptual design for a detector that could be realized in either interaction region. ATHENA's detector system includes more technologies with more risks and more channels and overall is more expensive than ECCE. The proposed data acquisition systems are similar and face similar challenges. The infrastructure needed for each of the three proposals seems feasible. Staging options do not seem to gain significant advantage.

There is significant support in the community and from the panel for a second general-purpose detector system to be installed in IR8 when resources are available. This detector should take advantage of the delayed start to explore opportunities for some complementarity in the physics reach and/or in the technologies used.

A significant number of collaborating institutes signed two or even three proposals. A strong push for two detectors at this time would likely require additional person power and expertise to complete successfully.

The panel explored various scenarios for realizing an EIC optimal science program taking into consideration the constraints of the project. The panel was informed that a secondary focus is excluded in IR6, and not yet fully confirmed for IR8. The use of IR8, without the secondary focus, for Detector 1, would mean a delay of 6-12 months for the project and would likely incur additional costs for the Project.

5. Conclusions:

The panel finds that ECCE and ATHENA fulfill all requirements for a Detector 1. ECCE has several advantages, in particular reduced risk and cost, and qualifies best for Detector 1. CORE presented a more conceptual design and given the tight timeline for CD2/3a would generate a schedule risk for the EIC Project as Detector 1.

The panel supports the case for a second EIC detector. While resources needed for the development and construction of Detector 1 and IR6 are included in the DOE EIC project envelope, DOE resources to start a Detector 2 project will most likely be delayed for several years, or the resources would have to found from other sources. There is significant international participation in the proto-collaborations, however, the panel found the overall resources were insufficient to proceed with a second detector effort at this time.

The EIC's project planning for Detector 1 should incorporate a period for integrating new collaborators and re-optimizing experiment conceptual design in advance of CD-2.

6. Recommendations:

The panel unanimously recommends ECCE as Detector 1. The proto-collaboration is urged to openly accept additional collaborators and quickly consolidate its design so that the Project Detector can advance to CD2/3a in a timely way.

The panel supports the case for a second EIC detector, however, given the current funding and available resources, the committee finds that a decision on Detector 2 should be delayed until the resources and schedule for the Project detector (Detector 1) are more fully realized.

References

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[2] A. Accardi et al., "Electron Collider: The Next QCD Frontier", Eur. Phys. J., vol. A52, no. 9, p. 268, 2016. https://arxiv.org/pdf/1212.1701.pdf

[3] "Science Requirements and Detector Concepts for the Electron Ion Collider", BNL-220990-2021-FORE, JLAB-PHY-21-3198, LA-UR-21-20953 http://www.eicug.org/web/sites/default/files/Yellow_Report_v1.1.pdf

[4] EIC Users Group home page: www.eicug.org

[5] EIC Detector Proposal Advisory Committee Meeting, Dec. 13-15, 2021 https://www.bnl.gov/dpapanelmeeting/

[6] A. Aprahamian *et al.*, "Reaching for the Horizon: The 2015 long range plan for nuclear science". DOE/NSF Nuclear Science Advisory Panel (NSAC) Report, 2015.

[7] "Call for Collaboration Proposals for Detectors at the Electron-Ion Collider" https://www.bnl.gov/eic/cfc.php

[8] EIC Conceptual Design Report: https://www.bnl.gov/ec/files/eic_cdr_final.pdf

Appendix 1: Panel Membership and Charge

EIC Detector Proposal Advisory Panel

Patricia McBride, Co-Chair	Fermilab
Rolf Heuer, Co-Chair	CERN
Sergio Bertolucci	INFN Sezione di Bologna
Daniela Bortoletto	Oxford Univ.
Markus Diehl	DESY
Ed Kinney	Univ. Colorado
Fabienne Kunne	Paris-Saclay
Andrew Lankford	UC Irvine
Naohito Saito	KEK
Brigitte Vachon	McGill Univ.
Tom Ludlam, Scientific Secretary	BNL

Charge to the EIC Detector Collaboration Proposals Advisory Panel

Brookhaven National Laboratory (BNL) and the Thomas Jefferson National Accelerator Facility (JLab) announced a Call for Collaboration Proposals for Detectors to be located at the Electron-Ion Collider (EIC), see https://www.bnl.gov/eic/CFC.php. The EIC will have the capacity to host two interaction regions, each with a corresponding detector. It is expected that each of these two detectors would be represented by a Collaboration.

The primary goal of the EIC Detector Proposal Advisory Panel is to advise BNL and JLab on how to realize an optimal set of experimental equipment at the EIC utilizing the resources and expertise of the EIC user community. This advice should address the following:

1. The first priority is to identify the optimal approach to realize a detector system, designated Detector 1, to be primarily funded by the EIC project and capable of addressing the science case in the EIC White Paper and NAS Report.

2. The second priority is to assess options for an alternate detector system, designated Detector 2, possibly addressing science beyond the White Paper and NAS Report and/or enabling some complementarity to Detector 1. Such a second detector could be envisioned to be realized up to 3-5 years after Detector 1. Currently, the EIC project scope does not include the construction of Detector 2 or the accelerator components needed for the second interaction region.

Based on the proposals submitted, the Panel should evaluate the scientific merit, the expected scientific performance, technical risk, cost, and schedule of the experiment proposed as well as the strength of the collaboration and the availability of resources.

We welcome your guidance and advice on the following topics:

1. What are the strengths and weaknesses of the submitted collaboration proposals for detectors at the EIC, including the criteria listed above?
2. How can the resources and expertise of the EIC user community be best utilized?
3. Comment on the complementary science reach of two potential EIC detectors to be located at Interaction Points 6 (IP6) and 8 (IP8).

BNL and JLab will provide technical and administrative support to the Panel. To aid the Panel in its assessment, the EIC Project Detector Advisory Committee (DAC) will provide an independent evaluation of each of the detector proposals, based on the DAC's expertise in detector technologies and related cost and risk assessment.

Appendix 2: EIC Detector Advisory Committee (DAC)

Name	Institution	Expertise
Ed Kinney, Chair	Univ. Colorado	EIC Science, general
Ewa Rondio	NCBJ, Warsaw	EIC Science, general
Werner Riegler	CERN	Integration
Greg Rakness	Fermilab	Integration
Peter Krizan	Univ. Ljubljana	Particle Identification
Ana Amelia Machado	U. Campinas, Brazil	Particle ID, sensors
Heidi Schellman	Oregon State Univ.	Computing
Brigitte Vachon	McGill Univ.	Electronics
Glenn Young	BNL	Calorimetry
Etiennette Auffray	CERN	Calorimetry
Andrew White	U. Texas Arlington	Tracking
Chi Yang	SDU, China	Tracking

Ex-Officio members added to provide expertise in Project Management, risk evaluation, and Cost Estimating:
James Fast (JLab), Cathy Lavelle (BNL)