IL NUOVO CIMENTO **47 C** (2024) 144
DOI 10.1393/ncc/i2024-24144-6

Colloquia: HADRON2023

The Electron-Ion Collider and the ePIC experiment

S. Dalla Torre

INFN, Sezione di Trieste - Trieste, Italy

received 21 December 2023

Summary. — The Electron-Ion Collider (EIC) will be the only new high-energy collider worldwide in the next twenty–thirty years. Electrons and ions, from p up to U, will collide at high luminosity to explore hadronic physics, making the ultimate understanding of QCD possible. Electron and light nucleus beams will be polarized to address fundamental questions as the origin of the nucleon spin. Other key questions addressed by the project are the origin of the hadron masses and the exploration of high-density gluonic matter. The approved project is successfully progressing at Brookhaven National Laboratory (BNL) in the USA. The project includes the ePIC experiment designed to cover the whole physics case at EIC. The main characteristics of the EIC project and of its accelerator as well as of the design of the ePIC experiment are discussed.

1. – Introduction

The need of a high-energy electron-hadron collider for the scientific progress in the field of hadronic physics and the comprehensive understanding of the nuclear matter and the nuclear force is widely recognized within the nuclear and subnuclear community. Following the pioneer and large successful experience of the electron-proton collider HERA at DESY, Germany, which concluded its activity cycle in 2007, up to six potential projects of electron-hadron collider were considered around the world. Presently, the US Electron-Ion Collider (EIC) project is the only one approved and it is moving towards the construction phase. The interested international community is clustering around it.

The EIC will be the only novel high-energy collider in the coming twenty to thirty years. Therefore, it offers unique opportunities of progress also in the technological sectors of the accelerators, the detector development and the read-out and data acquisition approach, which, in the project experiment ePIC, is highly integrated with the data analysis via the streaming readout approach.

2. – The EIC project

The EIC project has been approved in December 2019 by signing the Critical Decision 0 (CD0, mission needed). The project is progressing accordingly to its aggressive schedule: a second milestone, namely Critical Decision 1 (CD1, completion of the project definition phase) was reached in June 2021. The Technical Design Report (TDR) is in preparation in view of the construction phase, for which green light is expected in 2025 (CD2, approval of the performance baseline and requires the completion of preliminary design for all project; CD3, authorization to complete all procurement and construction and/or implementation activities). The project completion, that will be marked by the Critical Decision 4, is scheduled in the first years after 2030. An overview of the project timeline is provided in fig. 1. The project includes the electron-ion collider (sect. **3**) and a detector able to deliver the whole physics scope as presented in the white paper [1] and NAS report [2]. The ePIC Collaboration [3] is pursuing the project detector (sect. **4**). The design of the collider includes also a second interaction region, that can be instrumented later.

2˙1. *The project scope.* – The EIC scope is the comprehensive understanding of the nuclear matter and the nuclear force. Therefore its scientific goals cluster around the quest to understand the origin, evolution, and structure of the matter of the universe by answering to persistently key open questions: i) How do the properties of the proton

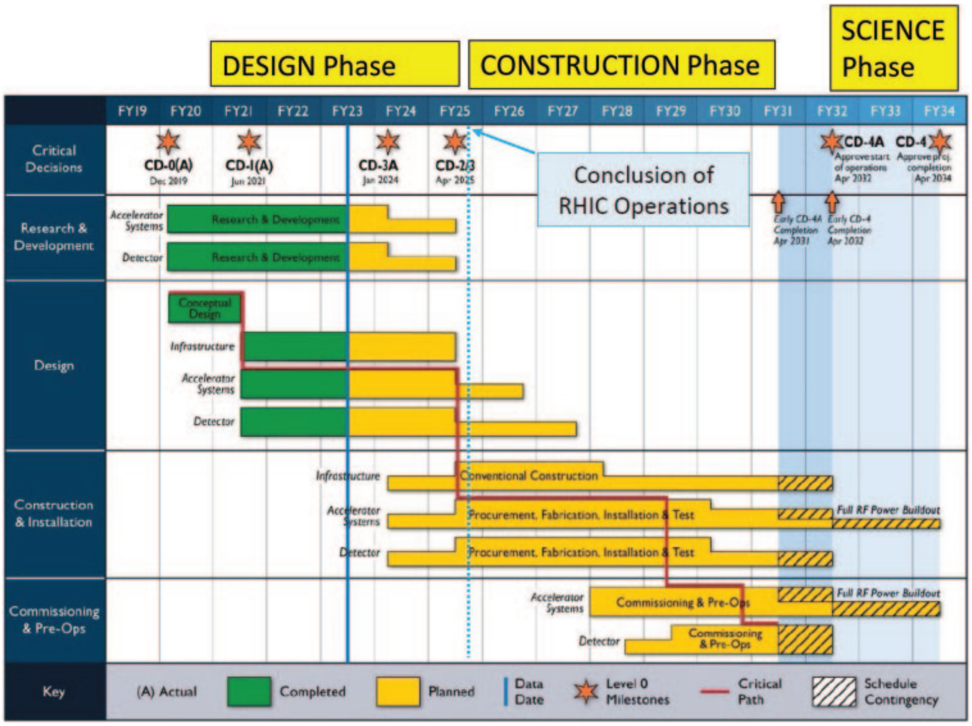


Fig. 1. – Project timelines as on June 2023. The accelerator and its infrastructure as well as the detector are included. A design phase (the current one), a construction phase and a phase of operation with scientific studies can be identified.

such as mass and spin emerge from the sea of quarks, gluons, and their underlying interactions? ii) What is the configuration and motion of quarks and gluons located within the nucleon? iii) What happens to the gluon density in nucleons and nuclei at small Bjorken-x? iv) How do quarks and gluons interact with a nuclear medium? v) How do the confined hadronic states emerge from quarks and gluons?

The unpolarized proton structure function is known with fine precision in an astonishing wide phase-space [4], even if specific kinematical regions are not deeply explored. For instance, the quark distribution functions are poorly known at very small Bjorken-x and the gluon distribution functions need further exploration both at small and large Bjorken-x. The polarization degrees of freedom enlarge the exploration domain and can be described with seven more independent structure functions. The measurements related to the longitudinal helicity have been performed since the eighties of the last century and the present picture is rich, even if it does not have the same fine resolution and completeness of that of the unpolarized structure function. These measurements have also initiated the so-called "spin crisis". In fact, following these measurements only about 30% of the proton spins is accounted for by the quarks. More recent semi-inclusive measurements indicate that about another 40% can be related to the gluon contribution. The remaining should arise from the dynamics, namely the orbital angular momentum, whose exploration is one of the goals of the EIC. The six structure functions related to the transverse polarization are in an initial explorative phase and they will largely benefit from the high luminosity and the polarized beams foreseen at the EIC.

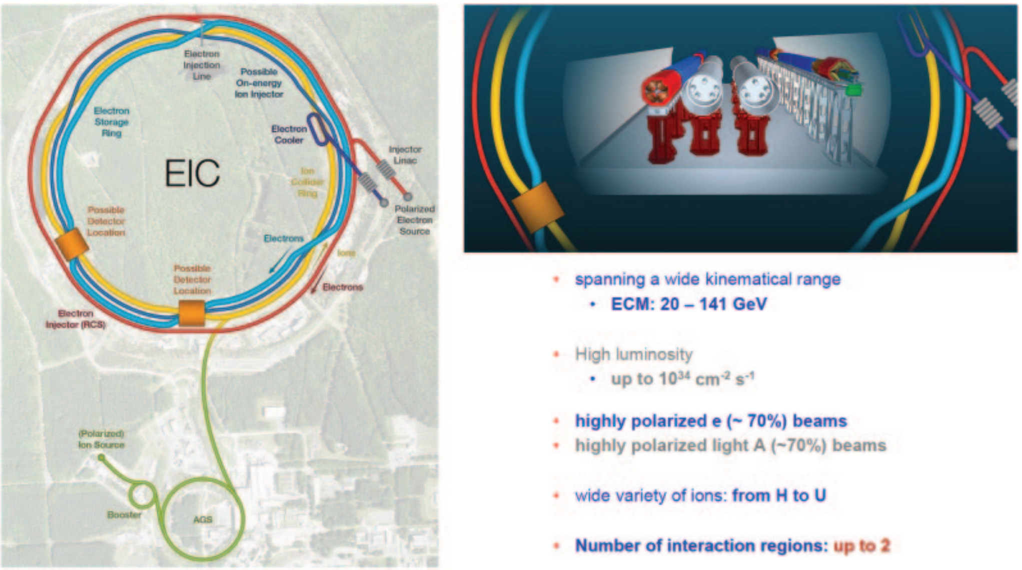
Another privileged field of studies at the EIC is the one related to the origin of the proton mass, where the quark mass contributes for only about 1% and the large majority of the mass is generated by the QCD dynamics via mechanisms to be understood and explained. The determination of the gravitational gluonic form factors through Deeply Virtual Meson Production (DVMP) on nucleons is one of the privileged approaches considered at the EIC.

In the nuclear sector, the first electron-ion collider will offer unique opportunities for the studies of gluons in nuclei, giving the concrete opportunity to study the collinear parton distributions in nuclei, the gluon saturation at small Bjorken-x, the properties of the cold nuclear matter and the description of the fragmentation and hadronization processes.

The takeaway messages of this overview of the EIC physics scope are self-evident. On one side, the ultimate exploration of the QCD world, aiming at revealing all its secrets, requires a collider offering a variety of center of mass energies up to substantially high ones, high luminosity, polarization degrees of freedom and scattering off a large variety of nuclear species. The EIC (sect. **3**) is designed to match all these requirements. On the other side, the detector should provide wide coverage of the scattered particle phase-space and perform precise measurement of inclusive, semi-inclusive and exclusive channels. The ePIC detector (sect. **4**) is conceived to match all these requirements.

3. – The Electron-Ion Collider

The EIC (fig. 2) will be the first collider with electron beams scattered off protons and nuclei up to the highest masses, namely up to uranium, and the first collider with highly polarized electron and light nucleus beams, where average polarization at the 70% level is expected. Its design is characterized by large luminosity, up to 10^{34} cm^{-2} s^{-1} for electron-proton scattering and the possibility to span a wide range of centre of mass energies, from 20 to 141 GeV. The EIC will take advantage of important elements of



- spanning a wide kinematical range
  - ECM: 20 – 141 GeV
- High luminosity
  - up to 10^{34} cm^{-2} s^{-1}
- highly polarized e (~ 70%) beams
- highly polarized light A (~70%) beams
- wide variety of ions: from H to U
- Number of interaction regions: up to 2

Fig. 2. – Left: the schematic overview of the EIC Collider; the yellow and light blue rings are the accelerating and storage rings of the present RHIC collider; the EIC storage rings will be the yellow one (from RHIC, to accelerated and storage ions) and the new dark blue (electron storage ring); the read ring is the rapid-cycling synchrotron for electron acceleration. The two interaction regions are also shown (courtesy of BNL Media & Communications). Right, top: the cut away of the EIC tunnel; in grey the existing RHIC storage rings, in colours the new electron storage ring and the synchrotron for electron acceleration (courtesy of BNL Media & Communications). Right, bottom: The main design parameters of the EIC.

the ion-ion collider RHIC in operation at BNL. In particular, the civil engineering including the tunnel, the ion acceleration and storage ring, being one of the two in use for RHIC, and of the whole complex of the hadron sources, including ions and polarized protons acceleration chain, are already available at BNL. The electron complex is new: this includes the polarized source, the pre-acceleration stages, a fast-cycling synchrotron for the electron acceleration with a dedicated designed in order to preserve the beam polarization.

The high luminosity is obtained with a variety of dedicated ingredients in the collider design, as the many bunches of both colliding beams, up to 1160 per beam, and the high current of the electron beam, resulting in a beam crossing every 10 ns. Two of them are frontier elements. The beam crab-crossing scheme will attempt a crossing angle never so large: 25 mrad. The phase-space of the ion beams will be reduced making use of the Coherent Electron Cooling (CEC, [5]), whose key technological element is a high-gain Free Electron Laser (FEL). The prove of principle is on-going at BNL.

Polarized beams require polarized electron and light-ion sources, acceleration complex capable of preserving the spin alignment, the preservation of the polarization in the storage rings and the possibility to rotate the spin alignment to obtain the needed orientation at the interaction point. The present RHIC collider provides polarized proton beams with the capability to preserve the stored beam polarization for hours and to provide any needed spin orientation at the interaction point. The related experience and expertise will largely contribute in establishing the polarized beams at EIC.

At EIC, the handling of the polarized ion beam and the beam polarization monitoring will largely rely on the experience gained operating the RHIC collider and will make use of the already available equipment. In particular, the reuse will include the spin rotators, which make any spin alignment at the interaction point possible, the Siberian snakes, which are the helicoidal superconducting dipoles aiming to preserve beam polarization during ion acceleration and storage, and the polarimeters measuring the polarization of the ion beam. The high polarization of the electron beam is preserved by the continuous bunch replacement injecting on energy from the accelerating synchrotron. Electron polarimetry is built-up onto the expertise present at Jefferson Laboratory.

Another specific characteristic of the accelerator complex is the high integration level between the accelerator and the detector, as needed for the request of hermeticity posed by the physics program.

4. – The ePIC detector

The ePIC detector is included in the EIC project and, as such, it must cope with the whole EIC physics scope by inclusive, semi-inclusive and exclusive measurements. The detection of the scattered electron, its identification and discrimination from hadrons, and the fine measurement of its kinematical parameters are the key for the pure inclusive measurements and central for semi-inclusive and exclusive studies. Semi-inclusive measurements need complete azimuthal coverage, excellent identification of the hadron species and excellent vertex resolution. Exclusive channels impose hermeticity with wide coverage in the Mandelstam t-variable and the detection of the fragments from the nuclear breakup, including neutral ones. These requirements, when translated to detector design, result in the need of a well-equipped central detector sitting in the interaction region, where a space approximately 10 m long is available, and in the instrumentation of the small angle regions, indicatively covering angles below 2°, in the forward and backward directions, with detectors situated along the collider beam lines (fig. 3). In the central detector (fig. 4), a 1.7 T superconducting solenoid provides the magnetic field for momentum analysis. As apparent in fig. 3, the central detector is organized in barrel, forward and backward regions. The detection system includes, for each of the three regions, tracking, particle identification devices and electromagnetic and hadron calorimetry. The far forward devices are dedicated to very small angle tracking and calorimetry with capabilities for gamma and neutron detection. The main installation of the far backward region is dedicated to luminosity measurement and monitoring by bremsstrahlung process measured with dedicated electromagnetic calorimeter devices. The ePIC detector is the evolution of a series of detectors proposed over time by the EIC User Group community and culminated with the detector presented in the EIC Yellow Report [6]. Further detector evolution was presented in the "Proposals for Detectors" at the Electron-Ion Collider submitted in December 2021. Since then, the ePIC Collaboration, formed in 2022, has been at work to evolve from the previously proposed detectors towards an optimized baseline detector. The ePIC Collaboration is formed by 171 Institutions from 26 countries and more than 500 scientists. 40% of the institutions are from the USA and 60% international.

In the following, some highlights of the proposed detector elements are illustrated, focusing on the most innovative approaches.

The tracking system includes detectors by monolithic Si trackers and MicroPattern Gaseous Detector (MPGD) technologies. Dedicated simulation exercises confirm that the tracking and, therefore, momentum and vertex resolution, is largely dependent on

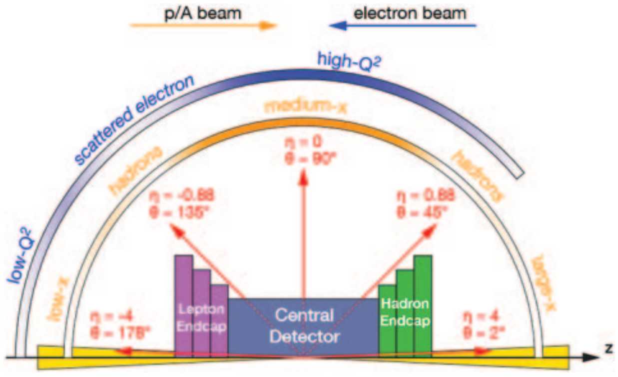


Fig. 3. – A schematic showing how hadrons and the scattered lepton for different Bjorken-x and Q^2 are distributed over the detector pseudorapidity and angular coverage. The central detector aims at an acceptance $-4 < \eta < 4$, while the far detectors, situated along the outgoing beam lines, cover as much as possible of the remaining forward and backward cones of about 2° aperture. The central detectors includes barrel, forward end-cap and backward end-cap components. (Courtesy of the EIC User Group).

the material budget. The sensors selected for the Si tracking are thin, low material and low power consumption MAPS in 65 nm technology, under development for the upgrade of the LHC experiment ALICE. The starting point are the MAPS sensors ALPIDE [7], while the path to the thinner flexible MAPS is ongoing [8]. The thin sensors, also allowing for curved arrangement virtually support-less, the very low power consumption and the possibility of large-size sensors make it possible to design the most inner layers, namely the vertex arrangement, with extremely low material of only 0.05% radiation length per layer for the three vertex layers. The same sensors arranged in a configuration with support are considered for the surrounding layers and the endcaps. The tracking systems is completed by large-size MPGDs adopting cylindrical MICROMEGAS and the novel μR-WELL technologies.

The high resolution required in measuring the backward scattered electrons is provided with a fine granularity crystal calorimeter by $PbWO_4$. A hybrid electromagnetic

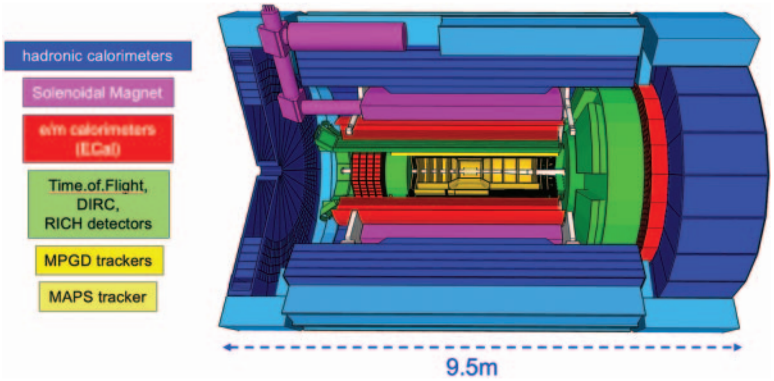


Fig. 4. – Crosscut view of the ePIC central detector. The color code identifies the different components of the detector (courtesy of the ePIC Collaboration).

calorimeter with imaging layers instruments the barrel. Its design uses light-collecting calorimetry based on SciFi embedded in Pb and imaging calorimetry based on the monolithic silicon sensors AstroPix. The imaging of particle showers is achieved by four layers of imaging silicon sensors interleaved with five SciFi/Pb layers, followed by a thick layer of SciFi/Pb calorimeter resulting in a total radiation thickness of about 20 radiation lengths. It is a design with the capability of detecting scattered and secondary electrons and separating them from pions, of detecting and reconstructing full kinematic information for photons, and provides sufficient spatial resolution to identify, up to high-momenta, neutral pions from neutral pion decays.

Particle identification requires multiple technologies to address the physics goals because of the globally wide momentum range to be covered. Measurements of Cherenkov radiation provide the greatest momentum reach, but they are limited in their low-momentum reach. Therefore, at the lowest momenta, a time-of-flight approach is foreseen based on AC-LGAD sensors. The set of Cherenkov devices includes a focusing dual radiator RICH in the forward region utilizing aerogel and gas radiators, a high-performance DIRC in the central region, and an aerogel proximity focusing RICH with long proximity gap to increase the resolution in the backward region. The photosensors, sitting in regions where there is intense magnetic field, represent a major challenge. Moreover, fine time resolution is requested. Two families of sensors are considered. SiPMs, so far, have never been used in a Cherenkov counter in experiments because of the high dark count rate, that increases with radiation damage and can only be partially limited operating at low temperature. This feature can represent a severe limitation for Cherenkov applications because, on one hand, single photons have to be detected and, on the other hand, the dark signals are indistinguishable from the single photon ones. The effects of the radiation damage can be reduced with thermal annealing protocols. A robust R&D program is ongoing to access the performances of SiPMs in single photon detection including irradiation and recovery by annealing. The option of *in situ* annealing by reversed bias is also part of these studies. SiPMs are the baseline choice for the dual RICH and the aerogel RICH. Commercially available MCP-PMTs are the baseline sensors for the DIRC. Larger size MCP devices, known as HRPPD by Incom Inc.(1), under development in collaboration between academia and industry, are selected for the backward RICH.

The accelerator and detector effort are complemented by polarimetry requirements. Rapid, precise beam polarization measurements will be crucial for meeting the goals of the EIC physics program as the uncertainty in the polarization propagates directly into the uncertainty for relevant observables as asymmetries. The basic requirements for beam polarimetry are non-destructive with minimal impact on the beam lifetime, uncertainty at the 1% level, the capacity of measuring the beam polarization for each bunch in the ring with rapid, quasi-online analysis in order to provide timely feedback for accelerator setting up. The electron beam polarimetry will be based on the well-established Compton polarimeter techniques, where the polarized electrons scatter from 100% circularly polarized laser photons. This approach offers the advantage that both longitudinal and transversal polarizations are measured. Hadron polarimetry has been successfully performed on RHIC polarized proton beams for nearly two decades. Through continual development a relative systematic uncertainty $<1.5\%$ was achieved for the most recent RHIC polarized proton run. As the only hadron polarimeter system at a high

---

(1) Incom Inc., 294 Southbridge Rd, Charlton, MA, 01507, USA.

energy collider it is the natural starting point for hadron polarimetry at the EIC. Hadron polarization will be measured via a transverse single spin left right asymmetry in the pp interaction on targets by plastic material (H-C composition), where the experimental challenge is the control of the background events.

5. – Conclusions

The EIC project, shortly presented in this report, has unique scientific reach and at present is worldwide the only concrete facility option aiming at the ultimate understanding of QCD. Most likely, it will be the only novel collider in the next 20–30 years. The EIC project is approved and progressing according to schedule.

The ePIC Collaboration for the project detector effort has kicked-off. ePIC is preparing the TDR due in late 2024 according to the current project timelines. The ePIC detector is an enormous undertaking that will require participation and expertise from both the USA laboratory and academia communities, as well as the international contributions. At present, 60% of Institutions is from abroad, worldwide. In parallel, the new Collaboration has been formed and structured.

In summary, all the required prerequisites for the success of the EIC are there, concurring to guarantee the timely completion and the successful operation of this challenging facility for frontier QCD exploration.

* * *

The author expresses her gratitude to all the Colleagues engaged in realizing the EIC project, active within the project itself, the EIC User Group and contributing to the ePIC experiment. It is only thanks to this large and motivated community that EIC and ePIC are progressing. The author is largely indebted to them all for all she could learn from their knowledge, experience and expertise and for the great shared enthusiasm, a key ingredient for the success of a major project.

REFERENCES

[1] Accardi A. *et al.*, *Eur. Phys. J. A*, **52** (2016) 268.
[2] Baym G. *et al.*, *An Assessment of U.S.-Based Electron-Ion Collider Science*, `https://www.nap.edu/read/25171` (2018).
[3] ePIC Wiki Page, `https://wiki.bnl.gov/EPIC/index.php?title=Main_Page`.
[4] H1 and ZEUS Collaborations (Abramovicz H. *et al.*), *Eur. Phys. J. C*, **75** (2015) 580.
[5] Litvinenko V. N. and Derbenev Y. S., *Phys. Rev. Lett.*, **102** (2009) 114801.
[6] Abdul Khalek R. *et al.*, *Nucl. Phys. A*, **1026** (2022) 122447.
[7] The ALICE Collaboration (Aglieri Rinella G. *et al.*), *Nucl. Instrum. Methods A*, **845** (2017) 583.
[8] Alice ITS Project (Aglieri Rinella G. *et al.*), *Nucl. Instrum. Methods A*, **1028** (2022) 166280.