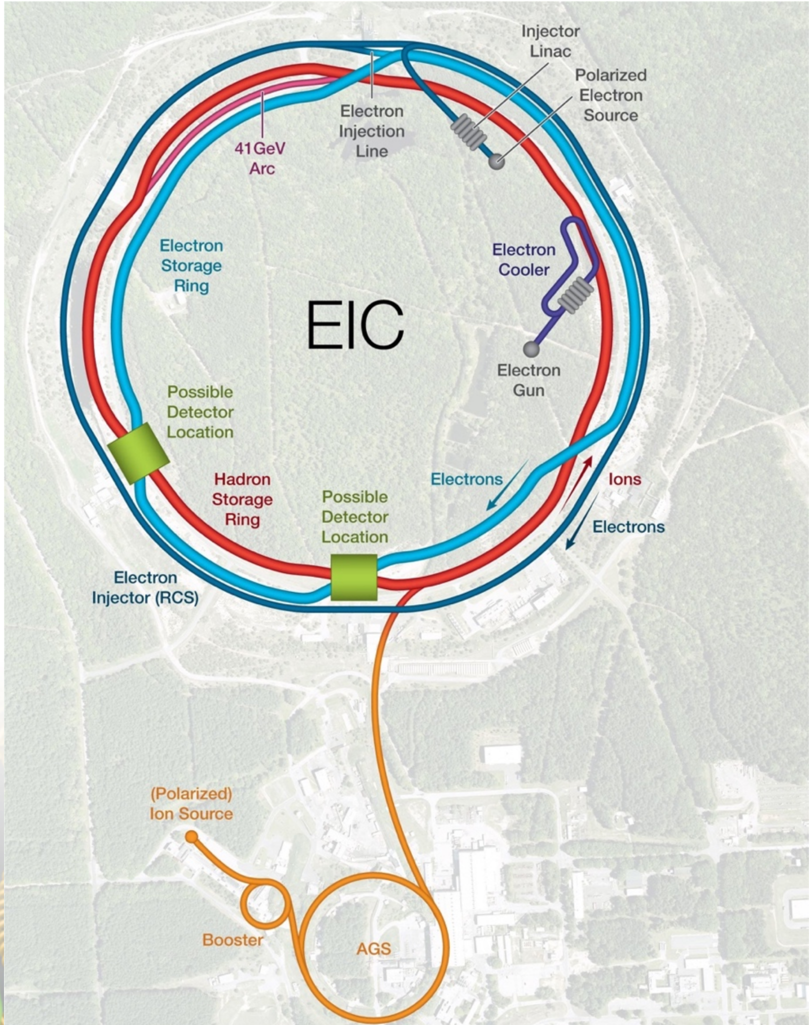
The Electron Ion Collider

Exploring the mysteries of the building blocks of matter

Brookhaven National Laboratory
and
Thomas Jefferson National Accelerator Facility

The Electron-Ion Collider (EIC) is a powerful new facility to be built in the United States at the U.S. Department of Energy's Brookhaven National Laboratory in partnership with Thomas Jefferson National Accelerator Facility. The EIC will study the substructure of protons, neutrons, and atomic nuclei with the most powerful electron microscope, combining 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. Its focus is to reveal how the most fundamental building blocks of visible matter interact to build up the structure and properties of everything we see in the universe today, from atomic nuclei to planets to people.



Brookhaven National Laboratory
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U.S. DEPARTMENT OF ENERGY
Office of Science

Protons and neutrons, the building blocks of nuclear matter, constitute about 99.9 percent of the mass of all visible matter in the universe. These building blocks are themselves made up of quarks that are bound by gluons that also bind themselves. Thus, the interactions and structures are inextricably mixed, in sharp contrast with more familiar atoms and molecular systems. Indeed, the observed properties of nucleons and nuclei, such as their mass and spin, emerge from a complex, dynamical system governed by quantum chromodynamics (QCD), the theory of strong interaction with quarks and gluons as the fundamental degrees of freedom. Consequently, the quark masses, generated via the Higgs mechanism, only account for a tiny fraction of the mass of a proton.

Key science questions that the EIC will address are:

- How do the properties of protons and neutrons such as mass and spin emerge from quarks and gluons and their underlying interactions?
- How are the quarks and gluons inside the protons, neutrons and atomic nuclei 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 color-neutral hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?
- How does a dense nuclear environment affect the dynamics of quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to gluonic matter or a gluonic phase with universal properties in all nuclei and even in nucleons?

To address these outstanding puzzles in modern nuclear physics, a broad international community of nuclear and accelerator scientists proposed the EIC. In 2018, a report by the National Academies of Sciences, Engineering, and Medicine commissioned by the US Department of Energy (DOE) positively endorsed the proposal: “In summary, the committee finds a compelling scientific case for such a facility. The science questions – How does the mass of the nucleon arise? How does the spin of the nucleon arise? What are the emergent properties of dense systems of gluons? – that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator-based science and society, from medicine through materials science to elementary particle physics.” In December 2019, the EIC was launched as an official project of the US government within the Department of Energy, Office of Nuclear Physics.

The way in which a nucleon or nucleus reveals itself in an experiment depends on the kinematic regime probed. A dynamic structure of quarks and gluons is revealed when probing nucleons and nuclei at higher energies, or with higher resolutions. Here, the nucleon transforms from a few-body system with its structure dominated by the three valence quarks to a regime where it is increasingly dominated by gluons generated through gluon radiation, as discovered at the former HERA electron—proton collider at DESY. Eventually, the gluon density becomes so large that the gluon radiation is offset by gluon recombination, leading to a saturated state of gluons if both are balance each other.

The properties of the EIC are well matched to reveal the quark-gluon structure of matter from the domain where a few valence quarks prevail to the domain where gluons dominate and the non-linear dynamics of the gluon’s self-interactions set in. The EIC will open up the unique opportunity to go far beyond the present one-dimensional picture of nuclei and nucleons, where the composite nucleon appears as a bunch of fast-moving (anti-)quarks and gluons whose transverse momenta or spatial images are not resolved. It will enable nuclear “femtography” by correlating the information of the quark and gluon longitudinal momentum component with its transverse momentum and spatial distribution inside the nucleon. Such femtographic images will provide, for the first time, insight into the QCD dynamics inside hadrons, such as the interplay between sea quarks and gluons, and how this QCD dynamics leads to the known mass and spin-spatial substructure of light hadrons – pions, kaons, protons and neutrons, and its impact in dense nuclear matter. The ultimate goal of the EIC is to reconstruct and constrain experimentally the so-called Wigner functions -- the quantities that encode the complete tomographic information and constitute a QCD genetic map of nucleons and nuclei.

The versatile EIC will for the first time be able to systematically explore and map out the dynamical system that is the ordinary QCD bound state, triggering a new area of study of the structure of visible matter at its most fundamental level. The advent of X-ray diffraction a century ago triggered tremendous progress in visualizing and understanding the atomic and molecular structure of matter. The introduction of large-scale terrestrial and space-based probes in the last two to three decades led to precision observational cosmology with multiple surprises. The EIC is foreseen to play a similar transformative role in our understanding of the rich variety of subatomic structures inside the proton.

The EIC – A machine pushing the frontiers of accelerator technology

The EIC accelerator complex is designed to provide high luminosity collisions (up to 10^{34} cm^{-2} s^{-1}) of above 70% polarized electron and ion beams over a wide center-of-mass (CM) energy range of 30-140 GeV. This complex is comprised of an existing hadron complex including a modified hadron storage ring (HSR), a new electron storage ring (ESR) with injectors, and a new high-luminosity interaction region (IR) including a 25 mrad crossing angle and beam crabbing. A new energy-recovery linac (ERL) is also required for hadron beam cooling, both to produce required hadron beam emittances and to counteract slow emittance growth from intra-beam scattering.

The HSR magnet and vacuum systems from the Relativistic Heavy Ion Collider (RHIC) will be reused, though the average beam current of 1 A will be up to 3 times higher than RHIC. This requires a vacuum system upgrade to lower resistive wall impedance and suppress electron cloud buildup. Copper-clad stainless-steel screens with amorphous Carbon (aC) films will be inserted into HSR vacuum chambers to suppress these effects. There is active collaboration with INFN to characterize the aC secondary electron yield for electron cloud suppression.

The ESR average beam current (up to 2.5 A) and bunch parameters (intensities up to 1.7x10^{11}) are similar to those envisioned for FCC-ee. There is active collaboration between EIC and CERN on diagnostics technologies for beams in this parameter range, including beam position monitoring and polarimetry, that should benefit the ESR diagnostic implementations and FCC-ee technical feasibility. After commissioning, the ESR may be useful for FCC-ee diagnostic testing, similar to tune feedback implementations at RHIC and LHC.

Hadron beam crabbing is required for both EIC and HL-LHC. A collaboration of EIC labs (BNL, Jefferson Lab) and CERN demonstrated and characterized hadron beam crabbing successfully in the SPS in 2018. Hadron crabbing still faces considerable challenges, such as very low crab cavity phase noise tolerances, crab bump closure tolerances, coupling compensation, and multipole considerations for beam dynamics. Collaboration with CERN colleagues and other worldwide experts is ongoing to solve these common problems for both EIC and HL-LHC.

Crab cavity fabrication and engineering are also challenging, as the crab cavity shapes are unprecedentedly complicated and require careful 3D assembly processes. EIC collaborations with CERN and ASTEC/Cockroft Institute in the UK are starting to develop international crab cavity and cryomodule production capabilities for future colliders including EIC.

EIC electron cooling requires a high-current (upwards of 100 mA) ERL with the average beam power approaching 10 MW. This is beyond the state-of-the-art, but comparable to and synergistic with European ERL activities on facilities such as bERLinPro (HZB) and PERLE (IJCLab). Jefferson Lab, responsible for the EIC ERL scope, also holds the record for demonstrated ERL beam power, and is an active collaborator on PERLE as a test bed for a possible LHeC electron-hadron collider at CERN. All high-power ERLs also require state-of-the-art developments for high-current superconducting RF (SRF) cavities and couplers, and understanding of beam dynamics limitations from SRF and magnet field quality.

The EIC design requires new NbTi superconducting magnets for the interaction region final focus and spectrometer bends, and electron beam spin rotator solenoids. Both traditional collared and direct wind magnets are envisioned, driven by space constraints and field requirements; the majority are cost-effective direct wind that should have excellent field quality. R&D is ongoing on longitudinally tapered two-in-one superconducting magnets to fulfill the aperture requirements of the IR. The spin rotator solenoids are particularly challenging due to their high fields (upwards of 10T), transverse space constraints, and shielding requirements that preclude passive shielding. Potential areas for European collaboration include superconducting cable production (CERN), and spin rotator solenoid design/production (CEA Saclay).

Collaboration with European colleagues on EIC accelerator topics is developing through a variety of mechanisms – wide scope international meetings, frequent bi-lateral discussions, and focused workshops on topics of mutual interests. The first accelerator partnership workshop, held in October of 2020, was hosted as a virtual event by the Cockcroft Institute of Accelerator Science and Technology, UK, and attracted more than 300 participants from more than 20 countries. This workshop, as well as the follow up accelerator partnership workshop hosted by TRIUMF, Canada in 2021, identified interests of many European partners in specific areas of EIC accelerator as described throughout this contribution. Frequent bi-lateral meetings with European partners also resulted in development of joint submissions to the Snowmass process [https://snowmass21.org], as well as in strong contribution of EIC experts into the European roadmap on accelerator science and technology, which include elements such as ERL that are key for the EIC and for planned European projects. Another result of widening collaboration activities of EIC with European partners is the series of working group meetings in Autumn 2022 focused on the areas of joint interest between FCC-ee and EIC, such as polarization, high current electron rings, impedances, feedback, and machine-detector Interfaces. Collaboration between the EIC accelerator team and European partners is mutually beneficial, and is expected to be deepened and widened further as noted through this section.

The EIC - State-of-the-art nuclear physics detector technologies

The need for detector R&D to address the scientific requirements for measurements at an EIC was realized early by the community and involved laboratories. In January 2011 BNL, in association with JLab and the DOE Office of Nuclear Physics, created a generic detector R&D program [https://wiki.bnl.gov/conferences/index.php/EIC_R%25D]. This program was open to the whole international EIC community and of the 75 participating institutions 50% were non-US. Many of the supported projects developed technologies that are now integral parts of the EIC detector, EPIC, design or are regarded as potential alternatives. The original generic detector R&D program ended in 2021 when the project driven R&D program [https://wiki.bnl.gov/conferences/index.php?title=General_Info] was started after EIC receiving CD-1. In Summer 2022 the DOE-supported generic R&D program [https://www.jlab.org/research/eic_rd_prgm] was reinstated and now focuses on potential upgrades to EPIC, the EIC detector part of the Project, as well as on technologies for a potential second EIC detector.

The generic R&D program is not the only source of support for R&D relevant for an EIC detector. Several National Laboratories (BNL, JLab, ANL, LBNL, LANL, and ORNL) supported EIC detector R&D through Laboratory Directed Research & Development Programs (LDRDs) and many university groups in and outside of the US, active in the many R&D projects received support from their respective departments and/or funding agencies. The EIC detector R&D also benefits from significant synergies with R&D for many HEP and NP experiments such as ALICE and LHCb at CERN, Panda and CBM at GSI and Belle-II at KEK.

Some examples of key detector technology R&D with synergy to European efforts are given here:

MAPS: The EIC Silicon Consortium, with strong collaboration from the UK, Italy and Czech Republic is partnering with the ALICE collaboration to develop the ITS3 sensor and to modify it, as necessary, for use at the EIC. This partnership will help to reduce the risk inherent in developing a detector solution in 65 nm technology. The plan is to use the ITS3 wafer-scale sensor for the vertex layers and to develop a smaller version for the silicon tracker barrel layers and disks. In parallel, R&D on the full detector infrastructure is ongoing to modify the vertex layers to fit the geometry of the beam pipe at the EIC and to develop stave and disk configurations of sensors – these are outside of the scope of ITS3. EIC detector R&D is further ongoing towards forming modules from sensors, and developing the EIC-specific infrastructure required to produce staves and disks, mechanical support structures, and cooling.

µRWell: Using µRWell detectors, originally developed at CERN, is compelling since they provide a reduced material budget, simpler construction, and lower cost when compared with other MPGD technologies. However, µRWell detectors have not yet been used in any major nuclear or high energy physics experiment. EIC-related R&D has started to build and test a large detector.

hpDIRC: The objective here is to validate the PID performance of a cost-optimized high-performance DIRC (hpDIRC) design with a vertical-slice prototype in a particle beam, and to develop compact readout electronics for the fast detection of single photons with high-density sensors. This development has strong synergies with the DIRC development at PANDA.

dRICH: The main immediate goal here is the preparation of the basic version of the dual RICH (gas and aerogel radiators) prototype with first test beams at CERN. These tests are organized in synergy with ALICE and will have, as complementary targets, the study of the single-photon response of SiPM coupled to the ALCOR readout electronics.

Environmental-Friendly Radiator Gases: A substantial challenge is related to the choice of radiator gas in the RICH detectors. In the baseline design the radiator gasses are fluorocarbons, gasses that exhibit extremely high Global Warming Power several thousand times that of CO_2. These gasses are increasingly prohibited all across the world. However, the RICH performance is preserved when fluorocarbons at atmospheric pressure are replaced with argon pressurized at a few bar. A solid pressurized vessel constructed with light materials would make this eco-friendly approach possible and benefit other RICH detector designs around the world.

Homogeneous Electromagnetic Calorimetry: In synergy with efforts at GSI/PANDA, development of high-quality PbWO4 crystals has been pursued. As a cost-effective solution for high-precision homogeneous electromagnetic calorimetry, scintillating glass is been developed as part of the EIC detector R&D that presently sees its last prototype test experiment with 40-cm long modules. There is a similar effort ongoing to develop uniform high-density glass with good production of both Cherenkov and scintillating light for very cost-effective hadronic calorimetry.

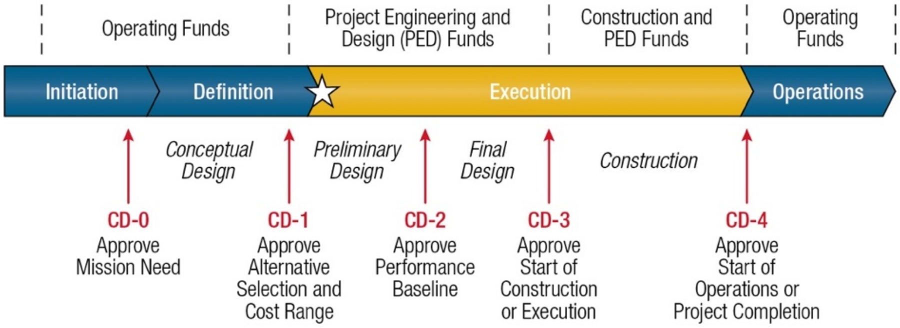
AC-LGAD: Extensive R&D is ongoing to reduce the active volume thickness and optimize implantation parameters to achieve a time resolution below 20 ps. One important effort specific to the ToF is to develop long strip AC-LGAD sensors to minimize the material budget. The needs for fast timing performance and finer granularity also pose significant challenges to the readout electronics, specifically to the ASIC readout chips. For example, the IJCLab (Orsay), Ècole Polytechnique/Omega and CEA (Saclay) groups are currently developing a new ASIC that meets the requirements set by the EIC’s Roman pot detector that also relies on the AC-LGAD technology.

Photosensors: The EIC requires highly pixelated photodetectors that are capable of operating in fields of up to 2T. This problem is most critical for RICH detectors and is not yet fully solved. The objective of ongoing R&D with strong collaboration from INFN Italy, is to mitigate technical, cost, and schedule risk related to readout sensors of Cherenkov detectors. R&D activities focus on the pixelization and improvement of the field resistance of LAPPDs and HRPPDs. Pixelized versions of LAPPDs are not sufficiently mature, with their field performance needing further improvement, but they can become an attractive option for all Particle Identification detectors. An attractive side-effect of these photosensors is that they can be used in parallel as ToF detectors by measuring the arrival time of photons produced in the sensor window by the charged particles.

The collaboration with European colleagues on EIC detector technology topics is strong and provides crucial mutually beneficial synergy. There is need for high-precision homogeneous electromagnetic calorimetry for Jefferson Lab experiments, for EIC and for GSI/PANDA. CRYTUR is the sole worldwide vendor for high-quality PbWO4 crystals, and a strong collaboration has emerged between CRYTUR, GSI/PANDA, Jefferson Lab and future EIC efforts to align the production of the needed high-quality PbWO4 crystals. The envisioned high-performance Detection of Internally Reflected Cherenkov (light), or hpDIRC, is developed taking advantage of and in strong synergy with efforts and expertise at GSI for the PANDA detector. The ongoing EIC detector R&D is beneficial to both. This is similarly true for detector R&D on Ring-Imaging Cherenkov (RICH) detectors, at CERN, at Jefferson Lab, and envisioned at the EIC. Obviously, efforts to reduce use of environmentally unfriendly radiator gases benefit all of us. Detector R&D towards cost-effective, magnetic field resistant, and radiation tolerant highly pixelated photo-sensors are also joint efforts between EIC-interested US laboratories and universities and their sister institutions in Europe, like INFN Trieste. Through EIC-related DOE funds, the possibility of making large-area and low-absorption aerogel tiles has also been pursued. The EIC Silicon Consortium is partnering with the ALICE collaboration to develop the MAPS/ITS3 sensor in 65 nm technology, of prospective use for the high-luminosity LHC experiments and EIC. Work on micro-pattern based gas detectors (MPGDs) takes advantage of synergy with GEM technology at CERN and MicroMegas at CEA-Saclay. Both in Europe and the U.S. there are numerous projects ongoing to take advantage of these developments for various applications. There is similar strong synergy on streaming readout and software development in a heterogeneous computing environment between BNL, Jefferson Lab, the EIC, and many European efforts. For example, the recent improvements to GEANT4 to take advantage of heterogeneous computing to vastly expedite simulations of light propagation and shower development was led through US efforts. The strong synergy between

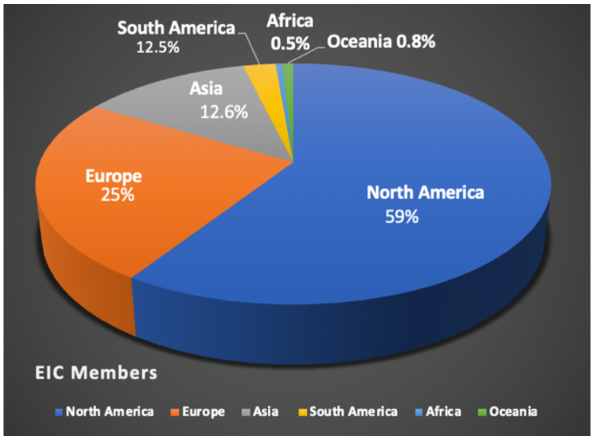
EIC and European efforts was also apparent in the joint EIC session at the November 2021 CERN/Experimental Physics R&D Day, with as main topics Silicon-based tracking, MPGD-based tracking, calorimetry, particle identification detectors, electronics, and computing and software.

The time to join is now!



The EIC Project is jointly managed by the U.S. Department of Energy's Brookhaven National Laboratory and Thomas Jefferson National Accelerator Facility. It has passed the first two of five DOE "critical decision" (CD) milestones and is in the R&D and design phase. Construction is expected to start around 2025, with operations beginning in the early 2030s, followed by 20+ years of scientific impact and continuing opportunities for innovation, improvement and future upgrades. The recent positive funding news from the US Inflation Reduction Act will enable the EIC Project to move without delays towards CD-3. The EIC represents a unique opportunity for the broad international scientific and accelerator communities to collaborate on realizing the EIC facility while advancing state-of-the-art accelerator and detector technologies at the only approved collider project worldwide. We invite you to be part of this groundbreaking research endeavor, and to contribute intellectually and through in-kind contributions. We fully anticipate that the benefits of such collaboration will be beneficial to other projects in US, Europe and Asia.

Vibrant international community



The EIC represents an opportunity for broad international communities of nuclear and accelerator physicists to collaborate on building this exciting new discovery machine. The project is attracting international partners who will contribute to accelerator and detector research and development (R&D), design, prototyping, and construction. This sharing of expertise will advance the state-of-the-art in accelerator and detector technologies, with possible spin-off applications in a wide range of other fields. The growing EIC Users Group—currently 1,300+ physicists from more than 267 laboratories and universities around the world, with an especially large contribution of the 335 scientists from Europe [1] — have been extremely active in developing the science case for the EIC, plans for the accelerator and detector(s), and submitting collaboration proposals for detectors at the EIC. While the project scope includes funding for one detector, this international community has presented a compelling case for a second detector to take full advantage of the EIC's planned capabilities. We invite you to join the EIC community of experimental nuclear physicists, accelerators scientists, and theorists working to develop partnerships and a path for realizing the full scientific potential of this unique machine.

[1] White-Paper: Electron-Ion Collider -- A U.S. machine for the European community to explore the mysteries of the building blocks of matter