

Title

Advancing Global Collaboration through the Electron-Ion Collider (EIC)

Abstract:

The Electron-Ion Collider (EIC) at Brookhaven National Laboratory represents a groundbreaking opportunity to explore the fundamental structure of matter by colliding polarized electron beams with polarized hadron beams. This facility is designed to address critical questions in Quantum Chromodynamics (QCD), particularly the role of gluons in binding quarks within nucleons and nuclei. With the potential to achieve luminosities up to $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, the EIC will rely on cutting-edge technologies such as hadron beam cooling, spin-transparent optics, crab cavities, and advanced superconducting magnets.

In addition to advancing scientific knowledge, the EIC project offers a unique opportunity for international collaboration, particularly for European institutions. By contributing to the EIC, European researchers will play a pivotal role in enhancing accelerator technology and advancing QCD research. Furthermore, this collaboration will foster innovation in accelerator technologies such as superconducting RF cavities and polarized beams dynamics, benefiting future accelerator projects worldwide.

The proposed EIC Accelerator initiative aims to provide a platform for collaboration and discussion, focusing on facilitating opportunities for US and European institutions to contribute to the EIC's construction and future upgrades. This initiative will also serve as a vital communication channel between the accelerator R&D community and EIC stakeholders, guiding the long-term development of the facility and exploring opportunities for future accelerator technologies. By taking a forward-thinking approach, the initiative will help ensure that the EIC remains at the forefront of accelerator innovation and contributes to the success of future particle colliders, serving as a testbed for new accelerator physics concepts and technologies.

Contact Persons:

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The Electron-Ion Collider (EIC), under development at Brookhaven National Laboratory in the United States, represents a significant advancement in our ability to explore the fundamental structure of matter. By enabling collisions between polarized electron beams and polarized protons or ions, the EIC will provide unprecedented insights into the role of gluons—the carriers of the strong force—in binding quarks within nucleons and nuclei. This facility is poised to address critical questions in Quantum Chromodynamics (QCD), thereby deepening our understanding of the strong interaction that governs atomic nuclei [1].

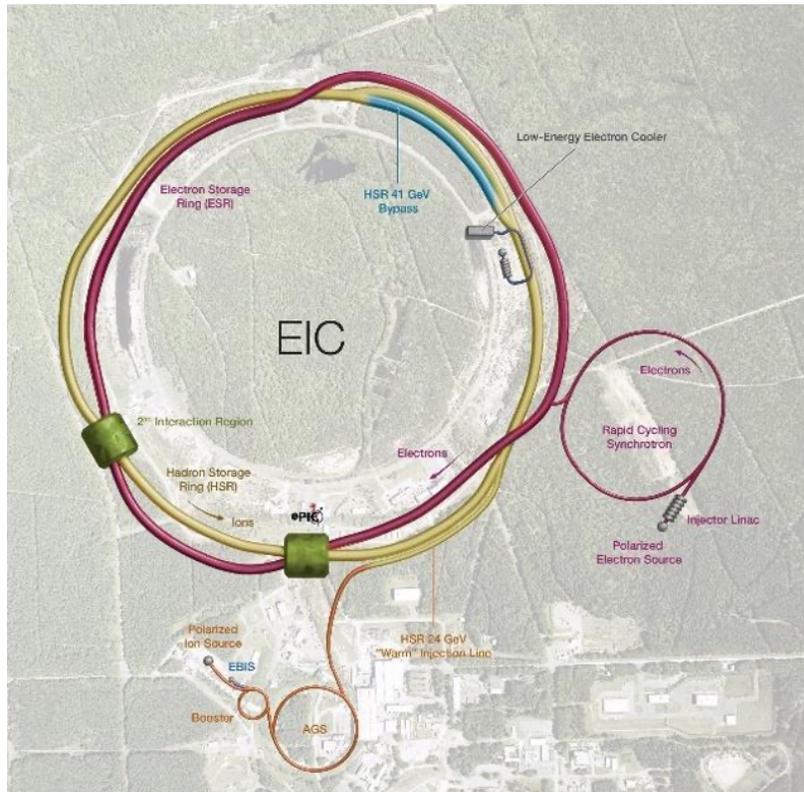


Figure 1: Schematics of the Electron-Ion Collider under construction at Brookhaven National Laboratory.

The European Strategy for Particle Physics has consistently emphasized the importance of international collaboration in advancing the field. The EIC offers a unique opportunity for European institutions to engage in a project that complements existing and planned facilities, such as those at CERN. European researchers have a longstanding tradition of contributing to global scientific endeavors, and their involvement in the EIC would enhance the scientific output and technological innovations stemming from this collider.

Opportunities for Collaboration:

1. **Scientific Research:** European physicists can play a pivotal role in the EIC's experimental program, bringing expertise in detector design, data analysis, and theoretical modeling. Collaborative efforts can lead to a more comprehensive understanding of QCD phenomena, benefiting the global particle physics community.

2. **Accelerator Technology:** The development of the EIC involves cutting-edge accelerator technologies, including advancements in superconducting radiofrequency (SRF) cavities and polarized beam sources. European laboratories, with their rich history in accelerator R&D, can contribute significantly to these technological developments, fostering innovation that will be beneficial for future accelerator projects worldwide [2].
3. **Educational Exchange:** The EIC project provides a platform for training the next generations of scientists and engineers. European universities and research institutions can participate in educational exchanges, joint workshops, and collaborative research programs, thereby enhancing the skills and expertise of young researchers in both Europe and the United States.

Scientific Research

A vibrant and dynamic user community is central to the success of the EIC (Electron-Ion Collider) and the broader physics research landscape. The establishment of such a community allows researchers from diverse backgrounds to engage in a collaborative exchange of ideas, methodologies, and results. This collaborative environment fosters the sharing of cutting-edge techniques, experimental data, and theoretical models, enriching the global understanding of complex phenomena in nuclear and particle physics. The Electron-Ion Collider User Group [3] is a vibrant growing community, consisting of more than 1500 physicists from over 300 laboratories and universities from 40 countries around the world. The ePIC collaboration [4], consisting of over 1000 collaborators from 178 institutions around the world, has been formed to design, build and commission the primary experiment at the EIC. The EIC Accelerator Collaboration [5] has been recently formed, to expand the collaboration opportunities into the area of accelerator science and technology.

With access to shared resources and expertise, scientists can compare results, refine methods, and develop new approaches to address longstanding questions in the field. This collaborative spirit ensures that innovative solutions are found by leveraging the collective knowledge of an increasingly interconnected scientific network.

Moreover, the potential for a second interaction region at the EIC offers exciting new possibilities for expanding the scope of research and addressing open physics questions. The additional interaction point opens up opportunities for conducting complementary experiments that can reach different aspects of physics at the EIC's energy scales. With this capability, the EIC is poised to host a much larger and more diverse user community.

In this context, the EIC not only acts as a cutting-edge facility but as a hub for global collaboration, enabling physicists from various disciplines and regions to come together, share insights, and drive forward the frontiers of knowledge in nuclear physics.

Accelerator Technology

The **EIC project** as sketched in Fig. 1 is designed with the following features:

- **Flat hadron bunches** with an **~10:1 emittance ratio**
- **Large crossing angle** at the interaction point of **25 mrad**

- **Beam-beam interaction limits** for both electron and proton beams (approximately **0.1 e for electrons / 0.01 p for protons**)

Collaboration in these areas will be crucial for leveraging the knowledge and experience gained from the LHC, while also helping to define and shape future colliders at CERN, whether they are FCC lepton or of hadronic flavors. For the lepton collider, these parameters align well with the assumptions at FCC-ee. The exploration of flat hadron beams will be an interesting addition to mixed-flavor colliders such as the LHeC, FCC-ep, and other future collider concepts.

Other important design considerations of the collider include:

- **Spin preservation** from source to collision for both protons and electrons
- An upgrade path for **hadron cooling** during collisions

These fundamental principles enable the achievement of a luminosity of $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ while ensuring high polarization at the collision points. Polarization studies are central to the precision measurement program at FCC-ee. Therefore, optics and polarization studies are key areas of collaboration, bringing the necessary expertise and knowledge to future projects such as the FCC-ee.

Hadron cooling will be crucial for the conceptual study of future hadron colliders, which are currently under discussion. Experts from various projects will be connected through advanced and complex beam dynamics concepts, where machine performance is pushed to its limits through strong beam-beam effects and possibly other collective behaviors that can hinder collider performance. These concepts are crucial for advancing the intensity and energy frontiers, as recently demonstrated by SuperKEKB, where collective beam instabilities are limiting collider performance. The need for international collaboration is key to addressing the unexplained mechanisms behind the fast losses observed, which have yet to be resolved.

In addition to the physics concepts that need to be addressed, there is a need to share knowledge between the lepton and hadron teams. This knowledge exchange is key to developing innovative technologies designed to overcome limitations and ensure robust and controlled collider performance.

The **EIC project** will push forward several key technologies that are critical for the operation of future colliders. These include:

- **Hadron beam cooling:** Cooling protons with very high densities in the presence of strong collective effects such as space charge or beam-beam interactions is a novel aspect that could be highly relevant for future hadron and muon colliders.
- **Spin-transparent optics:** Ensuring high polarization for both beams from source to collision. High polarization is essential for high-precision measurements of the center of mass in future lepton colliders; spin-transparent optics will be key to maintaining continuous measurements at the precision level required at FCC-ee.
- **Swap-out injection for electron bunches** (1 Hz) due to synchrotron radiation and quantum Sokolov-Ternov effect the e-bunch polarization quickly reduces in ESR. To keep average polarization high, at 18 GeV one would need to replace every bunch on

average every 2 minutes. So, this is achieved with swap-out injection of the entire bunch.

- **Crab cavities for beam alignment:** The use of crab cavities at large crossing angles (several mrad) remains a challenging and complex technology to handle, particularly due to the impact of cavity noise on the beams and the presence of collective impedance, which can degrade beam quality. To achieve high luminosity, it is necessary to relax long-range beam-beam encounters, and while crossing angles help, they can severely reduce luminosity, making it inefficient. Crab cavity technology should be developed to restore beam overlap while minimizing collective beam instabilities or incoherent growth, reducing RF noise, and ensuring that the cavities support the beams' dynamics transparently — a concept that still needs to be demonstrated in a short time frame at the HL-LHC for smaller angles and at the EIC for much larger ones in the mrad range
- **Interaction Region magnets:** large aperture, 2K superconducting magnets. The technology of magnets is the key to keep high energy particles on trajectories. Superconductivity is the key technology that allows such push. Studies and prototyping in this field also with new materials such as HTS or low temperature superconductors can overcome the present limitations in terms of maximum field and aperture allowed using low temperature superconductors.
- **Vacuum and material technology innovations** will play a key role in ensuring stability of large charge beams, in particular in the Hadron Storage Ring, where the surface of the existing RHIC vacuum chambers will need to be modified, with help of special inserts, to increase its conductivity and lower the Secondary Electron Yield to very low values, that may be also applicable to variety of future accelerators.
- The EIC (Electron-Ion Collider) offers a unique opportunity to serve as a testbed for **AI-driven technologies in accelerator control and operation**. As next-generation colliders become more complex, AI can play a crucial role in managing the increasing demands of real-time control and optimization. AI algorithms can autonomously adjust beam parameters, optimize collision conditions, and predict equipment maintenance needs, all while reducing human error. Machine learning can analyze vast amounts of data from detectors and systems to identify inefficiencies and ensure optimal performance, enhancing both the efficiency and safety of accelerator operations. In addition, AI can revolutionize data analysis, enabling faster processing and interpretation of collision data, leading to quicker scientific insights. By integrating AI into EIC operations, the collider can lay the groundwork for more autonomous, efficient accelerators in the future, positioning AI as a central component in advancing particle physics research.
- Last but not least, the option of a **second interaction region (IR)** at the EIC presents a unique opportunity to serve as a test facility for the development of future particle accelerators and experimental machines. This second IR could function as a versatile platform to test and prototype new accelerator concepts, detector technologies, and experimental techniques that will shape the next generation of high-energy physics research. One of the key benefits is to be open to proposals for a variety of experimental conditions and configurations. This allows researchers to perform real-world testing of novel components and systems in a controlled, yet dynamic, environment that mimics the high-energy conditions expected in some of the future accelerators under

discussion. For example, it could provide a testbed for new detector designs, beam collision technologies, or interaction schemes, enabling rapid iteration and optimization of concepts before they are deployed in more large-scale projects.

Educational Exchange

The EIC (Electron-Ion Collider) project not only drives scientific discovery but also offers a critical platform for training the next generations of scientists and engineers in the field of high-energy physics. As large-scale projects for the future of particle physics are expected to emerge after 2045, the EIC's ongoing operations will play a pivotal role in shaping the workforce needed to support these ambitious endeavors.

European universities and research institutions have the opportunity to collaborate through educational exchanges, joint workshops, and collaborative research programs. This will significantly enhance the skills and expertise of young researchers, fostering an international network of physicists and engineers from both Europe and the United States. The hands-on experience gained at the EIC will be invaluable in preparing students for the challenges of larger, future projects, ensuring they are well-versed in accelerator technologies, detector systems, and data analysis techniques that will be essential in the coming decades. Furthermore, having a running collider like the EIC in operation in the lead-up to these future projects provides a unique training ground. It will ensure that the experimental accelerator physics community remains strong and that students and early-career researchers are continually trained in real-world, high-energy physics environments. This is essential not only for the continuity of the field but also for the successful implementation of future colliders that will push the boundaries of knowledge even further. By fostering long-term collaborations and nurturing the development of new talent, the EIC will continue to be an indispensable resource in both maintaining cutting-edge accelerator science and preparing the scientific community for the next phase of high-energy physics.

Strategic Alignment

Engagement with the EIC aligns with the objectives outlined in the European Strategy for Particle Physics, which advocates for global coordination and the optimal use of resources. By contributing to the EIC, European institutions can ensure that their scientific goals are harmonized with international efforts, promoting a cohesive approach to addressing fundamental questions in particle physics [6]. Moreover, the EIC can serve as a potential test bench for technology in future European projects, similar to how RHIC or Tevatron were utilized in the past, playing a key role in shaping the technological choices for the LHC – Working Groups of the EIC Accelerator Collaboration will be instrumental in defining these synergistic tests.

Conclusion

The **Electron-Ion Collider (EIC)** presents a unique opportunity for European collaboration in a project that promises to deliver groundbreaking insights into the fundamental forces of nature. By participating in the EIC, European researchers and institutions will not only contribute to advancing our understanding of quantum chromodynamics (QCD) but also benefit from cutting-edge advancements in accelerator technology and the cultivation of a globally connected scientific

community. Such collaboration will strengthen the bonds between international research groups, fostering a spirit of shared discovery and innovation.

In alignment with this vision, our proposal aims to establish an EIC Accelerator initiative with the primary goal of advancing the development and success of the EIC project. This initiative will provide a discussion forum and serve as a platform for the working groups and topics related to the EIC accelerator. It will focus on creating opportunities for US institutions to actively contribute to the EIC construction project, as well as facilitating In-Kind contributions to both the project and its future upgrades.

Furthermore, the initiative will focus on identifying and developing future upgrades for the EIC facility, ensuring its continuous growth and evolution. It will also drive accelerator research and development by highlighting key areas for innovation and new opportunities. Additionally, the initiative will serve as a vital communication channel between the accelerator R&D community and EIC stakeholders, engaging with various long-range planning panels to ensure alignment with broader scientific objectives.

Beyond advancing EIC upgrades, the effort will play a crucial role in exploring longer-term perspectives, shaping the future of the EIC, and guiding decisions related to future accelerators. By adopting a forward-thinking, holistic approach, the initiative will contribute to steering emerging technologies. In this respect the EIC can serve as a testbed for the development of new physics concepts and technologies wherever possible, fostering a collaborative environment for innovation.

Through fostering meaningful contributions and continuous development, the EIC project and the collaboration initiative will be vital to the future success of the EIC project itself, as well as any future colliders that may follow. A complete list of the endorsements to this paper is available in [7].

References:

1. [EIC](#)
2. [European Strategy for Particle Physics - Accelerator R&D Roadmap, N. Mounet \(ed.\), CERN Yellow Reports: Monographs, CERN-2022-001 \(CERN, Geneva, 2022\)](#)
3. [EIC User Group](#)
4. [ePIC Collaboration](#)
5. [EIC Accelerator Collaboration](#)
6. [European Strategy for Particle Physics](#)
7. [List of Endorsements of this submission](#)