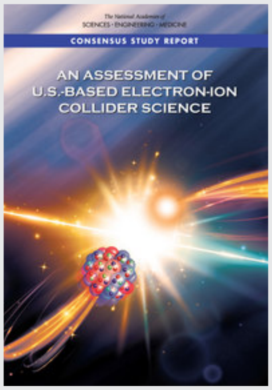


# An Assessment of U.S.-Based Electron-Ion Collider Science



## DETAILS

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## CONTRIBUTORS

Committee on U.S.-Based Electron-Ion Collider Science Assessment; Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

# AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE

Committee on U.S.-Based Electron-Ion Collider Science Assessment

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of

*The National Academies of*
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[1] Member, National Academy of Sciences.

# Preface

The National Academies of Sciences, Engineering, and Medicine convened the Committee on U.S.-Based Electron-Ion Collider Science Assessment to assess the merits and significance of the science that could be addressed by an electron-ion collider (EIC), and its importance to nuclear physics in particular and to the physical sciences in general.

The principal goals of the study were to evaluate the significance of the science that would be enabled by the construction of an EIC, its benefits to U.S. leadership in nuclear physics, and the benefits to other fields of science of a U.S.-based EIC. The science assessment included the special role of the structure of the nucleon in the broader context of nuclear science and the study of nuclei as the "heart" of matter. The complete statement of task is presented in Appendix A.

The committee was composed of experts from universities and national laboratories in the United States and Europe. The committee consisted mainly of nuclear physics experts but also included experts in other disciplines. Biographical information for the committee members is listed in Appendix B. The committee met four times in person during the 2017 calendar year. The first and fourth meetings took place in Washington, DC, on February 1-2 and November 27-28, respectively. The second meeting took place in Irvine, California, on April 17-18, and a third meeting took place in Woods Hole, Massachusetts, on September 11-12.

The committee invited and heard from scientists from the United States, Asia, and Europe in order to evaluate the international context of construction of an EIC as well as an evaluation of the most compelling science questions. The committee heard from the EIC users group regarding the white paper "The Next QCD Frontier" and a community report on the research and development thrusts to achieve the necessary conditions in addressing the most important science questions of an EIC. Presentations from the *Nuclear Physics Long Range Planning* report informed the committee of the broader context of an EIC in the community. Several presentations to the committee specifically addressed the challenges and necessary innovations in accelerator science needed for constructing an EIC capable of addressing the most important science questions. The federal agencies that support nuclear physics research also briefed the committee and gave their perspectives. The committee thanks all presenters and attendees who met and provided all the information necessary for its deliberations.

The co-chairs of the committee are most grateful to the committee members for their willingness to participate in this EIC science assessment, devoting many hours to meeting, discussing, preparing, and finally writing this report. The co-chairs also thank the National Academies' staff members for their guidance and their assistance.

Gordon Baym, *Co-Chair*
Ani Aprahamian, *Co-Chair*
Committee on U.S.-Based Electron-Ion Collider Science Assessment

# Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Halina Abramowicz, Tel Aviv University,
Jean-Paul Blaizot, CEA Saclay,
Larry Cardman, Thomas Jefferson National Accelerator Facility,
Donald Geesaman, Argonne National Laboratory,
Xiangdong Ji, Shanghai Jiao Tong University/Peking University,
David Kaplan, NAS,[1] University of Washington,
Chuck Shank, NAS/NAE,[2] Howard Hughes Medical Institute, and
Robert Tribble, Brookhaven National Laboratory.

Although the reviewers listed above provided many constructive comments

[1] Member, National Academy of Sciences.
[2] Member, National Academy of Engineering.

and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Arden L. Bement, NAE, Purdue University. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

# Contents

# Summary

The Committee on U.S.-Based Electron-Ion Collider Science Assessment was asked by the Department of Energy (DOE), in its statement of task, to assess the scientific justification for a U.S. domestic electron-ion collider (EIC) facility and to evaluate the importance and urgency of the science that an EIC would address to both nuclear science and the physical sciences more broadly. The committee's task also included assessing the role of an EIC in the global context, including its relationship to other facilities within the United States and around the world. Lastly, the committee was asked to assess the broader impacts of an EIC, including on U.S. science leadership. The full statement of task is included in Appendix A.

In summary, the committee finds a compelling scientific case for such a facility. The science questions 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 also benefit other fields of accelerator-based science and society, from medicine through materials science to elementary particle physics.

Understanding of protons and neutrons, or "nucleons"—the building blocks of atomic nuclei—has advanced dramatically, both theoretically and experimentally, in the past half century. It is known that nucleons are made of fractionally charged "valence" quarks, as well as dynamically produced quark-antiquark pairs, all bound together by gluons, the carrier of the strong force. A central goal of modern nuclear physics is to understand the structure of the proton and neutron directly from the dynamics of their quarks and gluons governed by the theory of their interac-

tions, quantum chromodynamics (QCD), and how nuclear interactions between protons and neutrons emerge from these dynamics. With deeper understanding of the quark-gluon structure of matter, scientists are poised to reach a deeper picture of these building blocks, and atomic nuclei themselves, as collective many-body systems with new emergent behavior. Viewing nucleons and nuclei as complex interacting many-body systems gives rise to profound questions about the nature of ordinary matter.

Three central scientific issues that would be addressed by an EIC are as follows. The first is to understand in detail the mechanisms by which the mass of nucleons, and thus the mass of all the visible matter in the universe, is generated. The problem is that while gluons have no mass, and quarks are nearly massless, the nucleons that contain them are heavy; the total mass of a nucleon is some 100 times greater than the mass of the valence quarks it contains. The second is to understand the origin of the internal angular momentum or spin of nucleons, a fundamental property that underlies many practical applications, including magnetic resonance imaging (MRI). How the angular momentum, both intrinsic as well as orbital, of the internal quarks and gluons gives rise to the known nucleon spin is not understood. And third, the nature of gluons in matter—that is, their arrangements or states, and the details of how they hold matter together—is not well known. Gluons in matter are somewhat like dark matter in the universe—unseen but playing a crucial role. An EIC would potentially reveal new states resulting from the close packing of many gluons within nucleons and nuclei. These issues are fundamental to an understanding of the matter in the universe.

To pursue these questions requires peering into nucleons and nuclei with very-high-energy electrons, which would necessitate using the most powerful (in terms of its unique combination of resolving power and intensity) electron microscope ever to be built. The high energy is required to achieve the needed resolution, and the only practical way of reaching the needed energies is to collide counter-rotating beams of electrons with protons or atomic nuclei (ions). To carry out the scientific investigations, such a machine must be capable of colliding a beam of "polarized" electrons (all spinning in the same direction) of energies from 4 GeV up to possibly 20 GeV with a beam of polarized ions of energies from 30 GeV up to some 300 GeV at high "luminosity"—the measure of the rate at which collisions occur. In addition to achieving larger energy collisions of electrons and nucleons than would be attainable with a fixed target accelerator, a collider allows the center of mass of the target and projectile system to be tuned to be approximately at rest in the laboratory, allowing ready analysis of scattering events.

The immediate science that an EIC would enable is manyfold. It would permit "tomography" of nucleons and nuclei, in which one builds together many high-resolution, lower-dimensional slices, like in an MRI, to arrive at a composite multidimensional picture of their quark and gluon components. It would also be a laboratory for studying QCD—the theory of quarks and gluons producing the strong forces holding matter together—with unprecedented depth, opening the study of the collective behavior of quarks and especially gluons. The situation is analogous to going from a knowledge of the Coulomb force between electric charges to seeing the complex phenomena that the force can produce, from superconductivity to weather. Understanding the collective physics of gluons offers the opportunity for the most surprises, including new phases of matter and deep insights about quantum field theory. Furthermore, the increased understanding of nucleons, nuclei, and QCD itself that an EIC would bring would have direct impact in particle physics, basic energy sciences, plasma physics, and astrophysics, as well as revealing connections to the study of materials and other fields of science.

The committee also finds that an EIC would be much more capable and much more challenging to build than earlier electron or polarized proton machines. The accelerator challenges are twofold: a high degree of polarization for both beams and high luminosity. It would be the most sophisticated and challenging accelerator currently proposed for construction in the United States and would significantly advance accelerator science and technology here and around the world. The committee's study resulted in a set of nine findings, which are summarized here.

Hearing from experts on the science that an EIC would be able to carry out, the committee finds that

**Finding 1:** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- 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?

Consideration of the accelerator requirements to answer these questions leads to the second finding.

**Finding 2:** These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

As a result of the comprehensive survey the committee made of existing and planned accelerator facilities in both nuclear and particle physics around the world, it finds that

**Finding 3:** An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.

An EIC would be the only high-energy collider planned for construction in the United States. Its high design luminosity and highly polarized beams would push the frontiers of accelerator science and technology. For these reasons, the committee finds that

> **Finding 4:** An EIC would maintain U.S. leadership in the accelerator science and technology of colliders and help to maintain scientific leadership more broadly.

The committee looked carefully at the requirements for building an EIC, and at the proposed design concepts for an EIC that uses existing infrastructure, accelerator expertise, and experience at both Brookhaven National Laboratory (BNL) and the Thomas Jefferson National Accelerator Facility (often referred to as the Jefferson Laboratory, or JLab), and finds that

> **Finding 5:** Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

Given the design challenges that remain, neither existing design can fully deliver on the three driving science questions. The DOE research and development (R&D) investment has been and will continue to be crucial to retiring design risk in a timely fashion, and thus the committee finds that

> **Finding 6:** The current accelerator R&D program supported by DOE is crucial to addressing outstanding design challenges.

The scientific challenges that would unfold with EIC require a robust theory program, not simply to design and interpret experiments, but also to develop the broad implications in an understanding of the quantum world, both through analytic theory as well as through lattice QCD simulations on large-scale computers. Thus, the committee finds that

> **Finding 7:** To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD and, furthermore, to glean the fundamental insights into QCD that an EIC can reveal.

The conclusion that the scientific advances made possible by an EIC would be profound culminates many years of study of the issues by the U.S. nuclear community. Accelerator R&D for an EIC was recommended in the Nuclear Science Advisory Committee's 2007 Long Range Plan,[1] which continues to be supported by

[1] *The Frontiers of Nuclear Science*, 2007 DOE/NSF Long Range Plan for U.S. Nuclear Science.

the DOE. More recently, the 2015 Long Range Plan for Nuclear Science[2] provided a clear and authoritative discussion of the scientific scope of the field and a ranked list of priorities for the field. Thus, the committee finds that

> **Finding 8:** The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high-luminosity polarized EIC as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

Beyond its impact on nuclear science, an EIC will help to maintain international leadership in the accelerator science and technology of colliders. The accelerator-collider expertise in the United States now resides within the Office of Nuclear Physics at DOE. Future accelerator facilities with high energy or high luminosity will benefit significantly from the expertise developed for an EIC, and so the committee finds that

> **Finding 9:** The broader impacts of building an EIC in the United States are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

An EIC would have impact on other research areas, including particle physics, astrophysics, and theoretical and computational modeling, as well as rich intellectual connections to atomic and condensed matter physics. Enabled by an EIC, nuclear science would continue to attract outstanding graduate students, more than half of whom will go on to science, technology, engineering, and mathematics jobs in industry and DOE National Nuclear Security Administration and Office of Science laboratories.

The committee concludes that the science questions regarding the building blocks of matter are compelling and that an EIC is essential to answering these questions. Furthermore, the answers to these fundamental questions about the nature of the atoms will also have implications for particle physics and astrophysics and possibly other fields. Because an EIC will require significant advances and innovations in accelerator technologies, the impact of constructing an EIC will affect all accelerator-based sciences.

An EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading and will ensure global U.S. leadership in nuclear science, as well as in accelerator science and the technology of colliders.

[2] *Reaching for the Horizon*, 2015 DOE/NSF Long Range Plan for U.S. Nuclear Science.

# 1

# Introduction

A central goal of modern nuclear physics is to understand the structure of the proton and neutron directly from the dynamics of their quarks and gluons, governed by the theory of their interactions, quantum chromodynamics (QCD), and how nuclear interactions between protons and neutrons emerge from these dynamics.

## ELECTRON-ION COLLIDER

In the 1960s, scientists at the Department of Energy (DOE) Stanford Linear Accelerator Center (SLAC) discovered that protons and neutrons, the building blocks of nuclei, are themselves made of smaller constituents—"quarks." This remarkable structure was revealed by scattering electrons on protons and other nuclei, and indeed the SLAC 2-mile-long electron accelerator became the world's most powerful "electron microscope," peering inside neutrons and protons (see Box 1.1). To this day, electrons, as point-like particles apparently without internal structure, remain a clean and powerful probe of matter at the most basic level.

Understanding of nucleons—that is, protons and neutrons—and the larger family of hadrons—strongly interacting particles made of quarks and antiquarks—has advanced dramatically since the first SLAC experiments. Fractionally charged[1] quarks and antiquarks are held together in hadrons by the "color" force, whose

[1] That is, fractions such as 1/3 and –2/3 of the charge of the electron.

**BOX 1.1**
**Why Electron Scattering?**

Because electrons do not manifest any internal structure, they can be used as a precise probe of the more complicated nucleons and nuclei. Electron-scattering study of the structure of nuclei began with post-World War II experiments in Illinois and was continued in the 1950s by Robert Hofstadter at Stanford University, who used electrons to peer *inside* the nucleon itself. A scattered electron creates a *virtual* photon to see inside the nucleon; the photon energy (technically the square root of $Q^2$, its total momentum squared) determines its resolving power (see Figure 1.1.1). Hofstadter's groundbreaking experiments, recognized with the 1961 Nobel Prize, demonstrated that nucleons are not elementary; rather, the charge distribution of the proton has a size of order $10^{-13}$ cm.

Following Hofstadter's discovery, electron accelerators were built to continue these studies at laboratories around the world, including at Saclay in France, the Massachusetts Institute of Technology (MIT) Bates Lab in the United States, the National Institute for Subatomic Physics in the Netherlands, and at Bonn and Mainz in Germany. These accelerators revealed more details about the structure of the nucleon and the behavior of nucleons within the nucleus, and their development led to improved accelerator technology as well.

To reveal the substructure of nucleons, higher resolution would be needed, which requires using electron beams of significantly higher energy. In 1967, the newly built 2-mile long electron accelerator at the SLAC enabled a new kind of electron-scattering experiment, known as "deep-inelastic scattering" (DIS), in which the energy is large enough to destroy the proton target. While the destroyed proton became a complicated final state containing many particles, theorists Richard Feynman and James Bjorken showed that such processes could be explained simply in terms of fractionally charged constituents—then called "partons"—each of which carry a portion of the target proton's momentum.

*continued*

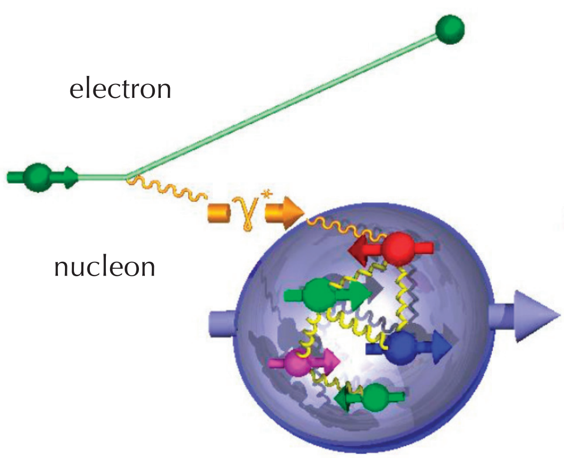


**FIGURE 1.1.1** A virtual photon, γ*, created by a scattered electron, probes the inner workings of the nucleon. SOURCE: U. Elschenbroich (HERMES).

**BOX 1.1 Continued**

The whole picture came together when partons were identified as fractionally charged quarks. The interactions of the quarks, mediated by gluons, each of which carry a "color" (literally a type of internal charge analogous to electric charge) are described by the theory of QCD. One central feature of QCD is "confinement," which is the locking together of quarks in hadrons. Unlike the electromagnetic force, the color force increases in strength as the distance between quarks or quarks and gluons increases, thus explaining why quarks and gluons do not exist as free particles, and why studying them inside nucleons and nuclei with electrons has been and will continue to be so valuable to advancing science's understanding. Nobel Prizes were awarded to Jerome Friedman, Henry Kendall, and Richard Taylor in 1990 for the SLAC experiments, and to David Gross, David Politzer, and Frank Wilczek—also from U.S. institutions—in 2004 for their insights into how the color force works. Bjorken shared the 2015 Wolf Prize and the 2015 EPS-HEPP Prize for his contributions.

Electron scattering experiments have continued at JLab, in the United States, from 1995 to the present, and at HERA in Hamburg, Germany, from 1991 to 2007. JLab, building on earlier work at SLAC, has pioneered new accelerator technology, including sources and acceleration of polarized electron beams, superconducting accelerators, higher-intensity beams, and more sophisticated detectors and analyses. HERA pioneered high-energy collisions of longitudinally polarized electron and positron beams with unpolarized proton beams. The HERA Measurement of Spin (HERMES) fixed-target experiment pioneered the measurement of pure lepton-hadron scattering, without any complication from extraneous material or end-windows. HERA experiments revealed the great abundance of gluons within neutrons and protons, which has led to the new questions that the proposed EIC will be able to address.

carrier is the massless "gluon." Quarks and gluons carry a color charge.[2] The fundamental "strong force," which is also responsible for binding nucleons together in nuclei, is very different from the electromagnetic force holding atoms and molecules together, and is described theoretically by QCD, a remarkable but mathematically complicated generalization of ordinary electricity and magnetism. Discovering how the structure of nucleons arises from the dynamics of their quark and gluon constituents, and how interactions between protons and neutrons in nuclei arise from these dynamics, is a major goal of modern nuclear physics.

With deeper understanding of the building blocks of nucleons and their interactions, nuclear physicists are developing a view of nucleons and nuclei as collective many-body systems, not simply clouds of independent particles. In these systems, dynamical interactions among the components lead to new emergent phenomena—as has been seen over the years in condensed-matter systems—for example, weak attractive interactions among electrons leading to superconductivity. Viewing nucleons

[2] "Color" refers to a generalization of electrical charge. As one forms an electrically neutral atom with equal numbers of positive and negative electric charges, one finds that it takes three different colors to produce a "color-neutral" nucleon.

and nuclei as complex, interacting, many-body systems gives rise to profound questions about the nature of ordinary matter. Three central issues are at the fore.

Gluons have no mass and quarks are nearly massless, but nucleons and nuclei are heavy, making up most of the visible mass of the universe. *How do nucleons acquire mass?* At a qualitative level, it is known that gluons and quark-antiquark pairs (called "sea quarks") that exist inside nucleons are crucial to their properties. However, the precise arrangement, or states, of gluons and sea quarks inside the nucleon is not known, and the mechanism by which mass is generated remains only partially understood.

A second fundamental property of the nucleon is that it has internal angular momentum, or spin. *How does the spin arise from its elementary quark and gluon constituents?* The quarks within the nucleon are known to contribute only a fraction of the total spin.

Colored quarks and gluons form color-neutral bound states and, in particular, protons and neutrons. A remarkable feature of the strong force, crucial to an understanding of the world around us, is that neutrons and protons arrange themselves into composite objects, or nuclei. Nuclei are bound by residual color forces, mediated by gluons and sea quarks. *What are the emergent properties of dense systems of gluons? What are their quantum states? How are they distributed in both position and momentum, and how are they correlated among themselves and with the quarks and antiquarks present?*

To pursue the science needed to answer these questions will require peering into nucleons and nuclei with high energy electrons, as was done in the seminal SLAC experiments that first revealed the existence of the inner structure of the nucleon. One needs high energy in order to achieve the needed resolution, which in turn requires colliding a beam of electrons with a counter-moving beam of protons or nuclei in an electron-ion collider (EIC). To address the science questions above, such a machine must be capable of colliding a beam of "polarized"[3] electrons of energies from 4 GeV up to possibly 20 GeV with a beam of polarized ions (complex nuclei) of energies from 30 GeV up to some 300 GeV at high "luminosity"—the measure of the rate at which collisions occur—approaching $10^{34}$ $cm^{-2}$ $s^{-1}$. The high-energy electrons create both virtual[4] photons and virtual quark-antiquark pairs in the collisions, and these virtual particles will precisely probe the target nucleons and ions, shedding light on their internal workings. The ability of the EIC to accelerate large ions as well as protons will also advance understanding of how nucleons are bound together by the color force to form nuclei. In addition to needing a collider to allow much larger energy collisions of electrons and nucleons than would be attainable with a fixed target accelerator, the center of mass of the

[3] Polarized particles have their angular momenta aligned in chosen directions, rather than being disordered.

[4] The term "virtual" indicates that the created particles have only a momentary fleeting existence.

target and projectile system in a collider can be tuned to be approximately at rest in the laboratory,[5] greatly simplifying analysis of scattering events, whereas in a fixed-target machine, the center of mass travels practically along the beam direction. Figure 2.4 in Chapter 2 illustrates how the physics reach of an EIC depends on the collider center-of-mass energy and luminosity.

The concept of an EIC—which the 2015 Nuclear Science Advisory Committee (NSAC) Nuclear Physics Long Range Plan[6] identified as the highest-priority project for new construction in nuclear physics—builds upon a long heritage of electron scattering machines. In the postwar period, this heritage begins with the Illinois Betatron, the Hansen Experimental Physics Laboratory (HEPL) machine at Stanford University, then the SLAC 2-mile accelerator, and continuing with the more recent Hadron-Electron Ring Accelerator (HERA) electron-proton collider, which operated from 1991 to 2007 at the Deutsches Elektronen-Synchrotron (DESY) Lab in Hamburg, Germany, and the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLab) in Virginia, which has operated since 1995 (see Box 1.1). An EIC also builds on the polarized proton beam facility at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), which has been in operation since 2002. However, an EIC would be much more capable and much more challenging to build than these earlier machines. The accelerator challenges are twofold: a high degree of polarization for both beams and high luminosity (almost three orders of magnitude beyond HERA). It would be the most sophisticated and challenging accelerator currently proposed for construction in the United States and would significantly advance accelerator science and technology here and around the world.

## CONTEXT

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.[7]
>
> —Richard P. Feynman, 1964

[5] In an EIC the effective center-of-mass energy depends on the momentum of the struck parton and varies from collision to collision. What matters for the design of detectors is that the reaction products are kinematically separated.

[6] *Reaching for the Horizon*, 2015 DOE/NSF Long Range Plan for U.S. Nuclear Science.

[7] Richard P. Feynman, The Feynman Lectures on Physics, Volume 1, Section 1-2, Addison-Wesley, Reading, MA, 1964.

Feynman's enthusiasm about the importance of atoms may seem extravagant. However, the more one thinks about it, the more one is likely to agree. Pursuing the atomic hypothesis has led to the discovery of chemistry, thermodynamics, quantum mechanics, molecular biology, and so much more. Without an understanding of atoms, the technology that has created the lifestyle and world humans enjoy today would not be possible.

However, two big puzzles remain in understanding atoms as the building blocks of the physical world. The first is the full extent of the periodic table of chemical elements and how many isotopes each element has. The second is how two of the three building blocks of atoms—neutrons and protons—are themselves put together from quarks and then how they combine to form the nuclei of atoms. (The third atomic building block, the electron, is to the best of scientists' knowledge fundamental.) Both of these questions in nuclear physics are ripe to be answered now.

The story of atoms begins with Democritus, who put forward the idea of fundamental, indivisible elements of matter circa 400 BCE. The modern term "atom" derives from *atomos*, the Greek word for indivisible. Humans have come a long way from Empedocles's first attempt at identifying the basic building blocks—earth, fire, water, and air—and the alchemists, who saw an "application" of atomic theory, the transforming of lead into gold. Little could they realize that the applications of atomic theory would be far more transformational and rewarding.

Modern atomic theory dates back to John Dalton, who in the early 19th century laid out the basic rules of chemistry. Armed with atomic theory and a list of the chemical elements that would grow to 92 and beyond, chemists began to transform human existence by identifying and creating the myriad of substances that comprise the physical world. Today, molecular biologists and biophysicists continue the march into the living world, which is constructed from the very same chemical elements.

By the end of the 19th century, atomic theory was well developed and producing practical results. But a burning question remained: Are atoms real or just useful mathematical constructs, and what rules do they obey? Einstein's study of Brownian motion—the random, thermal motions of atoms, molecules, and even larger clumps of matter—provided the first concrete confirmation that atoms actually exist and gave a reasonably accurate estimate of their masses: a single gram is comprised of some $6 \times 10^{23}$ atoms.

At the beginning of the 20th century, the understanding of the atom deepened further with experiments revealing that atoms comprise a tiny nucleus (size of order $10^{-13}$ cm) containing neutrons and protons surrounded by a much larger cloud of electrons (size of order $10^{-8}$ cm). Atoms themselves are made of three smaller building blocks. Around the same time, the discovery of quantum mechanics, the rules that govern the microscopic world, opened the door to understanding how atoms behave and can be manipulated.

The science of materials is based on how electrons interact when atoms combine to form molecules, all governed by the rules of quantum mechanics. Building upon this knowledge, chemists and physicists have been refining the abilities to understand materials and to create new ones. A new, related field arose, known as condensed matter (initially called solid-state) physics, and is concerned with the various phases of matter that exist, from conductors and insulators to crystalline states of matter to even more exotic phases of matter including superconductors and other macroscopic quantum states of matter. The ability to design and build materials almost atom by atom has opened yet another chapter in the saga began by Democritus: nanoscience and nano-engineering.

The discovery after World War II of hundreds of subatomic particles spawned a new investigation: elementary particle physics. As these studies revealed, neutrons and protons are not fundamental, but rather made of smaller quarks. Quarks may or may not be Democritus's *atomos*. The quest for the ultimate indivisible pieces and the rules that govern them continues, with the most recent discovery being the Higgs boson. Today, the stakes are even higher, with ideas about how the fundamental particles and forces are related to the structure and origin of space-time, as well as to the birth and early evolution of the universe.

In the material world, two big questions remain about the atoms that are its building blocks. First, what is the full range of nuclei—and hence kinds of atoms—that can exist? Finding the range of nuclei that can exist far from stability is a primary aim of the Facility for Rare Isotope Beams (FRIB) being constructed at Michigan State University. The second question involves the nature of the two building blocks of the nucleus. The neutron is made of two "valence"-down quarks (charge 1/3 that of the electron) and one valence-up quark (charge −2/3 that of the electron), while the proton is made of two valence-up quarks and one valence-down quark. Simple enough. But there is a puzzle: the mass of the proton is about 100 times that of two up and one down quark; similarly, the mass of the neutron is about 80 times that of two down and one up.[8] Furthermore, the three quarks within nucleons do not, as is mentioned below, account for their spins. What then accounts for the mass and spin of the neutron and of the proton?

The other components are gluons and the sea quarks—of all six types: up, down, strange, charmed, bottom, and top (see Box 1.2). However, a fundamental understanding of how gluons and sea quarks are distributed, both in space and

[8] The mass of a nucleus is slightly less—from about 0.1 percent typically to nearly 1 percent—than the sum of its component neutrons and protons. That mass defect or binding energy is the mass equivalent energy that is released when the nucleus is assembled; it is the origin of nuclear energy. Likewise, the mass of an atom is very, very slightly less—parts in a billion or smaller—than the sum of its component nucleus and electrons. This is the chemical binding energy that can be released in chemical reactions. The problem with the neutron and proton is just the opposite. Its mass is far greater than that of its constituents.

in momentum, within neutrons and protons, and how they determine the basic properties of neutrons and protons remains unanswered. Furthermore, how gluons and the color force then bind these nucleons into nuclei remains a mystery, as is the issue of whether or not there are more exotic states of matter made of gluons.

The primary aim of an EIC (see Box 1.3) is to understand how up and down quarks, sea quarks, and gluons create the building blocks of the nuclei of atoms, neutrons, and protons. Furthermore, although the question of the full extent of the periodic table of elements appears to be a separate one, knowledge gained from an EIC is likely to shed light on that big question as well, through a better understanding of how neutrons and protons in nuclei are held together by the color force.

Twenty-five hundred years after Democritus and the human quest for *atomos*, the indivisible constituents of matter, physicists are closing in on a fundamental understanding of the chemical elements that comprise the materials of the physical world. That understanding has already had enormous direct benefits in the design and manufacture of all kinds of materials, with many more benefits on the horizon. Along the way, this scientific adventure has spun off the fields of thermodynamics, quantum mechanics, molecular biology, nanoscience, and particle physics, all of which have had their own benefits to humankind and an understanding of the universe in which we live. Feynman's extravagant claim may well have been an understatement.

## SCIENCE OPPORTUNITIES

An EIC is needed to address the picture of nucleons and nuclei as complex interacting many-body systems, and in particular to address three immediate and profound questions about neutrons and protons and how they are assembled to form the nuclei of atoms:

- *How does the mass of the nucleon arise?* In other words, how do the constituents of the nucleon, the valence quarks, the sea quarks, and the gluons, and importantly their interactions, lead to a mass some 100 times larger than the sum of the three constituent quarks alone? Physicists are used to the mass of a bound system—a nucleus made of neutrons and protons, an atom made of a nucleus and electrons or even two black holes bound together by gravity—having a mass less than the sum of its parts. The difference is the binding energy of the system. In a nucleon, the opposite is true: half of the mass exists in the gluons that hold it together. How do gluons provide this mass? (See Figure 2.1 in Chapter 2.)
- *How does the spin of the nucleon arise?* Spin, or internal angular momentum, is one of the basic properties of a neutron or proton, central both to understanding atoms and their practical applications such as magnetic

**BOX 1.2**
**Molecules and Atoms and Nuclei and Nucleons**

Democritus would be surprised at how his *atomos* hypothesis has evolved. The chemical elements—92 or so naturally occurring atoms, from hydrogen to uranium—are each made of a positively charged nucleus surrounded by a cloud of negatively charged electrons that balance the charge of the nucleus to form a neutral atom. The electrons are bound to the nucleus by the electromagnetic force, transmitted by its force carrier, the photon. While atoms are neutral, they distort each other's electron clouds and become bound into molecules when brought close enough together—for example, two hydrogen atoms combine with one oxygen atom to create a water molecule. The force that holds atoms in molecules is just a weaker effect of the electromagnetic force, known as the van der Waals force, which arises because of the distorted electron clouds. High-resolution images of molecules show that the atoms within retain their identities; molecules are not giant atoms, but rather are made of well-defined atoms.

Like molecules, nuclei are made of smaller entities—nucleons—that come in two types, neutrons and protons. And like atoms, nucleons are made of smaller particles—quarks. A neutron is made of two down-type quarks and one up-type quark, and a proton is made of two up and one down. (There are six types of quarks, and hundreds of particles made of quark triplets and quark-antiquark pairs. Only the proton and neutron occur stably in nuclei; the other "elementary" particles—the pi mesons, lambdas, and on and on—are very short lived and cannot form stable, more exotic "nuclei.") The strong color force, transmitted by its force carrier the gluon, holds neutrons and protons together in color-neutral objects. Just as the van der Waals force holds neutral atoms together in molecules, a residual aspect of the color force holds colorless neutrons and protons together in the nucleus. And within the nucleus, neutrons and protons appear generally to retain their individual identities just as atoms do within a molecule (see Figure 1.2.1).

This is where the analogy between molecules and nuclei ends, where things become even more interesting, and where grand mysteries remain. The color force is much stronger than the electromagnetic force, and constituent quarks cannot simply be pulled out of nucleons (neutrons and protons can be knocked out of a nucleus, as was discovered about 100 years ago). Furthermore, there are eight gluons compared to one photon, and unlike the uncharged photon, the gluon is colored like the quarks and feels the strong color force. Moreover, the color force between quarks increases with separation. Understanding this next layer more fully is one of the principal goals of an EIC.

Among the many mysteries remaining are these: What is the largest nucleus that can exist, thereby determining the full extent of the periodic table? How many isotopes of each element exist—that is, nuclei with the same number of protons and chemical properties but different numbers of neutrons? How do gluons and the other (sea) quarks within a nucleon determine its mass and spin? How exactly are nucleons held together in a nucleus, and if enough nucleons are crammed together—say, in a very heavy nucleus or in a neutron star—to what extent do the individual nucleons lose their identities and instead take on the form of a giant, formless collection of quarks and gluons?

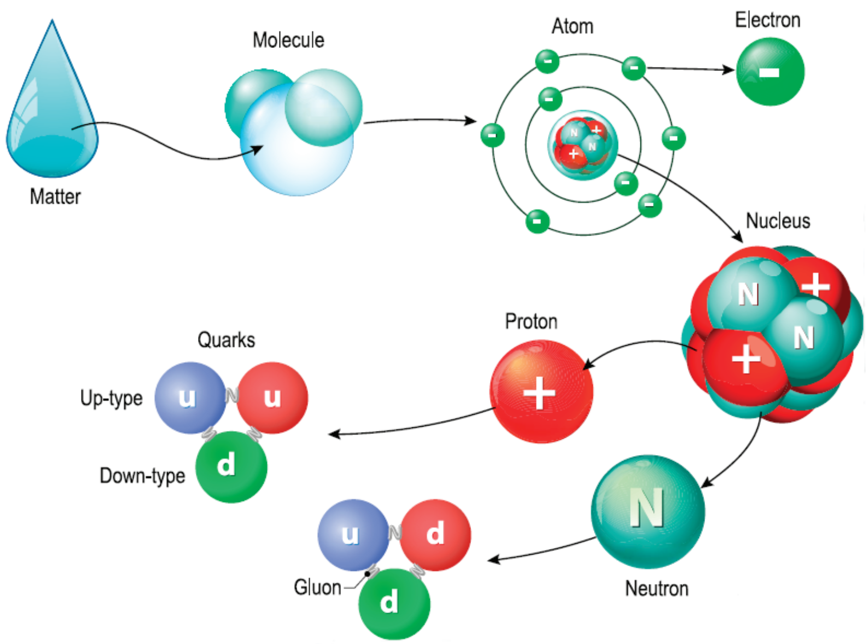


**FIGURE 1.2.1** The deconstruction of matter into molecules, comprised of atoms; atoms into their electrons and nuclei, comprised of neutrons and protons; and neutrons and protons into quarks. Two forces—the strong color force and the electromagnetic force—are responsible for holding the fundamental pieces—quarks and electrons—together. The color force binds quarks into neutrons and protons, and neutrons and protons into nuclei. The electromagnetic force binds electrons and nuclei into atoms, and atoms into molecules. SOURCE: Shutterstock.

**BOX 1.3**
**Basic Physics of an Electron-Ion Collider**

The EIC builds on the accomplishments of accelerators like the Stanford Linear Accelerator Center (SLAC), Hadron-Electron Ring Accelerator (HERA), and JLab, described in Box 1.1. These machines focused on a process called DIS in which an electron interacts with a nucleon but the target fragments are not detected. Information about the structure of the nucleon is obtained by measuring the likelihood of this process as a function of two variables, the resolution $Q^2$ and a second variable that was simply called $x$ by Feynman and Bjorken.

The quantity $Q^2$ is the square of the momentum of the exchanged photon, and it determines the spatial resolution with which the quark distribution in the proton is measured. At high resolution, corresponding to large $Q^2$, the photon can resolve new phenomena, such as the possibility that a quark radiates or absorbs a gluon or that gluons produce quark-antiquark pairs. The quantity $x$ (Bjorken's $x$) is a measure of the energy of the exchanged photon, where large energy corresponds to small $x$ (throughout this report, the committee generally refers to Bjorken's $x$ as simply "$x$.") The physical meaning of $x$ is most transparent in the picture in which the photon interacts with a single quark in the target, and $x$ determines the fraction of the total momentum of the colliding nucleon carried by that constituent. DIS experiments have established a basic picture of the nucleon in which, at low resolution, the nucleon is composed of three valence quarks, each with $x$ approximately 1/3. With increasing resolution, additional sea quarks and gluons become visible, and these extra constituents dominate the small $x$ regime.

Sea quarks and gluons are crucial for understanding the total mass and spin of the proton, and an EIC would be able to study the mechanism for generating mass and spin by precisely measuring the spatial and momentum distributions of these constituents. This program is referred to as "nucleon tomography." Just as a magnetic resonance imaging (MRI) technician can study the branching of the vascular and pulmonary systems by zooming through a series of two-dimensional (2D) images of the human body, an EIC would provide a series of 2D images of parton (i.e., quark and gluon) distributions. These pictures will allow us to take a three-dimensional (3D) journey through nucleons and nuclei, beginning at large $x$, where few partons are visible, and then studying the branching of valence partons into sea quarks and gluons at lower $x$. An EIC would determine both the position of the partons in the transverse plane (transverse to the direction of the momentum transferred by the electron), and, in a separate set of images, their transverse motion.[1] Proton tomography is enabled by a new set of experimental observables that involve identifying the momentum and spin of final state particles in DIS, and new theoretical tools that relate these observables to tomographic images.

A crucial aspect of the EIC program is the ability to study gluons, not only quarks. How, one may ask, can a colorless virtual photon probe colored gluons? The key is to observe reactions that are dominated by a two-step process in which the virtual photon splits into a quark-antiquark pair that interacts with the color field of the target nucleon (see Figure 2.2 in Chapter 2). The pair forms a color dipole controlled by its size $r_T$, which can be used to map the Lorentz-contracted gluons in the colliding nucleon or nucleus. This method is particularly powerful in the low $x$ regime, where the number of gluons is very large. Quantum mechanics has taught us that classical electric and magnetic fields of a highly charged ion can be understood as a large collection of photons. Reversing this idea, the highly occupied gluon state of a large nucleus at low $x$ can be viewed as a classical color field (see Figure 2.10 in Chapter 2).

[1] Figures 2.5 and 2.7 in Chapter 2 are an indication of what these images might be like.

resonance imaging (MRI). While nucleons are made of three quarks, each with spin ½ (technically ħ/2, where ħ is Planck's constant), the spins of these quarks constitute only a small fraction of the nucleon's spin, the rest seemingly carried by the gluon spins, the sea quarks, and the orbital motion of the quarks and gluons. (See Figures 1.1 and 2.6.)

- *What are the emergent properties of dense systems of gluons?* The color force mediated by gluons is fundamentally different from the electromagnetic force that binds atoms and molecules. In particular, the force between quarks strengthens as the objects get farther apart, and quarks are permanently confined in neutrons and protons. Two questions concerning the gluons arise when nucleons are combined into nuclei: How is the gluon field modified in a nucleus to accommodate the binding of nucleons? And does a novel regime of nuclear physics emerge in the high-energy limit, a regime in which the complicated structure of the nucleus is radically simplified, leading to a state in which the whole nucleus becomes a dense gluon system?

These three questions are simple to state and yet are of paramount importance in completing an understanding of the building blocks of the physical world—atoms. The answers to all three questions involve a better understanding of the gluons within nucleons and nuclei, and nucleons and nuclei as collective many-

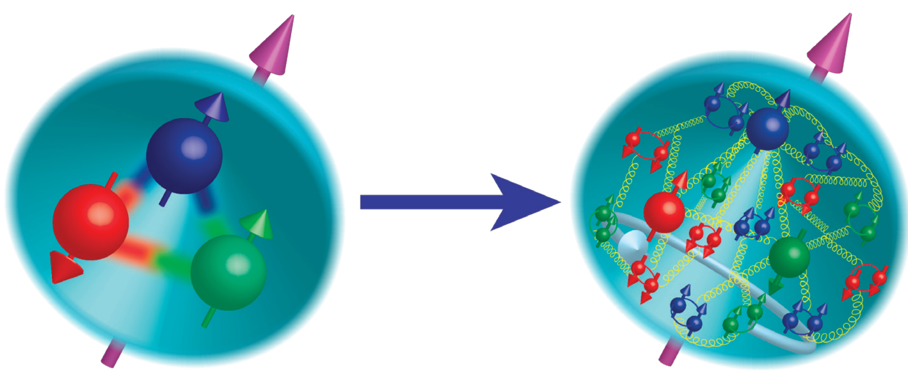

**FIGURE 1.1** The evolving understanding of the structure of the proton. The 1980s picture, on the left, is that the proton was composed of three valence quarks, with total spin ½. The current point of view, shown on the right, is that the proton contains quarks, as well as dynamically generated sea quark-antiquark pairs and gluons; the total spin is composed of that of the elementary spins (colored arrows) and orbital motion, as indicated by the light blue arrow. SOURCE: Z.-E. Meziani.

body systems more generally. The following sections discuss in more detail how an EIC would better enable the exploration of the gluon content of nucleons and nuclei and answer these questions. Box 1.3 summarizes the key physics ideas mentioned here.

### How Does the Mass of the Nucleon Arise?

In broad-brush terms, the answer to this question is that most of the mass of a nucleon is accounted for by the gluons, the sea quarks, and the kinetic energy of the valence quarks within it, but the details are poorly understood. There is evidence that the largest fraction of the mass is contributed by gluons (see Figure 2.1), but the gluon is not electrically charged, and the energy stored in the gluon field is a form of invisible energy. The role of the gluon field energy has been inferred indirectly, but never directly measured.

An EIC will address this gap in the understanding of fundamental aspects of the nucleon in several ways. First, an EIC will map the gluon distribution in the proton, both in space and in momentum, with unprecedented precision, using the new technique of parton tomography described in Chapter 2. Traditional DIS measurements provide information on only the fraction of the longitudinal momentum carried by the various components of the nucleon—that is, the momentum component in the direction of the momentum transferred by the electron to the target. Tomography measurements allow two additional properties of the constituents to be measured: transverse distance $x_T$ (perpendicular to the direction of the transferred momentum) and transverse momentum $k_T$. Studying the interplay of quark and gluon distributions in the proton would allow us to see gluons at work. Tomography provides a series of images of the proton in the transverse plane, labeled by the longitudinal momentum fraction of the parton. Scanning through these pictures, starting from the valence quark regime, will enable the determination of where and how gluons and sea quarks appear and whether the gluon distribution has a compact core, smaller than the electric charge radius of the proton, or whether the gluon distribution is extended. A variant of tomography would study transverse motion rather than transverse position. These images can be used to analyze the coupling between spin and orbital angular momentum.

An EIC would not only determine the distribution of gluons but also measure the distribution of gluonic energy density and pressure in the proton. These measurements would directly inform our understanding of the origin of mass and constrain models of the gluon field inside the nucleon—for example, models based on flux tubes or solitonic solutions.

Two key features of an EIC enable measurements of gluons. The first is large kinematic coverage, which provides multiple independent avenues for accessing gluons, as explained in Chapter 2. The second is large luminosity, which is important for identifying specific final states in DIS. It is this information that can be used to obtain tomographic images.

### How Does the Spin of the Nucleon Arise?

The spin of a nucleon is an important property; through the electric charges of quarks, spin allows protons and neutrons to behave as tiny magnets. The magnetic axis is aligned with the spin axis, and external radio frequency fields can drive resonant spin transitions. This is the basis of MRI imaging and many other applications. It is remarkable that scientists do not know in detail the origin of the proton (or neutron) spin.

The proton has spin ½, and in a simple quark picture the total spin arises from three valence quarks of spin ½ that combine to form a total spin ½. While this naïve picture qualitatively describes the observed magnetic moment of the proton, it fails quantitatively. In particular, experiments at SLAC, the European Organization for Nuclear Research (CERN), and HERA have shown that the sum of all quark spins in the nucleon accounts for only about one-third of the total spin of the proton. The remainder of the proton spin must reside in orbital angular momentum or gluon spin (gluons have spin 1, twice that of the quarks; see Figure 1.1).

An EIC can comprehensively explore these contributions. The orbital angular momentum of quarks and gluons can be extracted using the transverse position information contained in the tomographic measurements, discussed at length in Chapter 2. Measurements of the gluon-spin contribution to the spin of the proton are based on the idea that the gluon can transfer its polarization to a quark-antiquark pair, which can be probed using polarized electrons.

### What Are the Emergent Properties of Dense Systems of Gluons?

Nuclear physics exhibits one remarkable limit where simplicity emerges. Despite the extraordinary complexity of QCD—the strength and presence of interactions among all quarks and gluons—at ordinary densities and low temperature, nuclei can be accurately modeled as collections of colorless composite particles—nucleons—interacting through long-range forces understood as arising from the exchange of mesons. An EIC would seek to explore a second regime where great simplicity may emerge, despite the inherent complexity of QCD: In this regime, quarks are predicted to behave as a nearly static source of a gluon field that reaches a limiting density, producing "dense gluonic matter." At an EIC, this regime would manifest itself in terms of DIS reactions on nuclei that cannot be understood in terms of approximately independent nucleons. Box 1.2 describes the similarities between how the electromagnetic force binds neutral atoms into molecules and how the color force binds colorless nucleons into nuclei. Because the color force is so profoundly different than the electromagnetic force, there are also big differences and deep mysteries to be understood, including how quark distributions are modified in nuclei, how the gluons are distributed, and how gluons bind nucleons into nuclei.

Physicists understand well why atoms retain their individual identities in molecules, but not why nucleons retain their identities within nuclei. In fact, nuclear matter can have simpler states where nucleons do not retain their individual identities, as in the quark matter seen in ultrarelativistic heavy ion collisions, and inferred in massive neutron stars.

In addition, nucleons and nuclei differ from atoms and molecules because they contain so many gluons, a fact discovered at the HERA facility, whose implications are still not well understood.

This abundance of gluons provides the opportunity to address fundamental questions about nucleons and nuclei. As HERA found, the number of gluons grows significantly in the small $x$, high-energy limit. This means that gluons must overlap in the plane transverse to the electron-ion collision. The most interesting case is when this limit can be achieved at high resolution (high $Q^2$), so that the number of gluons that can be packed into the transverse area of a proton or nucleus is large. An EIC of sufficiently large energy would be able to reach this limit. Under such conditions, a quantum state of "cold dense gluonic matter"[9] is posited to exist. Such a state is possibly analogous to Bose-Einstein condensates of clouds of cold atoms created in atomic physics laboratories.

An EIC would be able to reach unprecedented gluon densities by using the concentrated gluon fields of large nuclei. Relativistic length contraction implies that the number of gluons per transverse area is proportional to the radius of the nucleus, which is itself proportional to the one-third power of the nuclear mass number A. Although an EIC would operate at lower energies than HERA (which collided beams of electrons and protons), an EIC would achieve higher gluon densities because it can accelerate ions with high atomic weight.

A good part of high-energy scattering can be understood in terms of "diffraction" of the projectile by the target. Diffraction is well known in optics, where light waves bend around the edge of an obstruction, producing an interference pattern on a screen placed behind the object. One of the remarkable predictions is that at a high-energy EIC, such events would constitute a significant fraction of the total number of events, and a classical diffraction pattern would be observed—periodic oscillations of the scattering rate as a function of the scattering angle (see Figure 2.9). Analyzing diffractive events would provide a wealth of information about dense gluon matter, the strength of the color field, fluctuations in the color

[9] "Cold" in the sense that the matter has no thermal motion, only quantum zero-point energy.

field of the proton and of nuclei, and the interaction of color dipoles with the gluon field of the target.

## ACCELERATOR TECHNOLOGY

Building an EIC capable of fully exploring the physics described above is by no means an easy task. The machine must collide electrons with protons and other atomic nuclei (ions) over a range of energies. There must be enough collisions for the experiment to gather adequate data to elucidate or settle the known physics questions, and other questions that may emerge, in a reasonable time. A collider's ability to squeeze many particles of two beams into a tiny volume where they collide defines its luminosity. The luminosity ultimately required of an EIC is comparable to those of the highest performing colliders built to date, such as the Large Hadron Collider (LHC) at CERN and the B-meson factories at SLAC and High Energy Accelerator Research Organization (KEK).

Furthermore, given the crucial role of spin, both beams must be polarized. That is to say, the spins of the individual particles in each beam must be made to line up with each other, overcoming their natural tendency to point "every which way" at random.

To achieve these goals, a host of techniques in accelerator physics and technology must be brought to bear. Only a few are mentioned here. State-of-the-art superconducting radio frequency (SRF) cavities will accelerate high-intensity beams efficiently. Further specialized radio frequency (RF) cavities will rotate the beams as they collide to optimize their overlap. Elaborate interaction region designs must squeeze two very different beams simultaneously into the tiny collision volume using advanced superconducting magnet designs. The hadron beams must be compressed in volume by sophisticated new "beam cooling" techniques that involve subtle interaction with yet other electron beams. Polarized beams require polarized particle sources, special magnets, and a further level of mastery of beam physics to preserve the polarization through the acceleration process to the collisions. Polarized colliding stored beams have been achieved before only at HERA (polarized $e^+/e^-$ on unpolarized protons) and at RHIC (both proton beams polarized).

These and numerous other accelerator physics and technology challenges are discussed in more detail in Chapters 4 and 5. Not only would development of an EIC advance accelerator science and technology in nuclear science, it would benefit other fields of accelerator-based science and society. The accelerator physics and technology advances required for an EIC will, importantly, have the potential to extend the capabilities of many particle accelerators built for other purposes, from medicine through materials science to elementary particle physics.

Fortunately, an EIC does not have to be built from scratch—significant parts of the accelerators, their injector complexes, and other infrastructure already exist at two locations in the United States. BNL already has the hadron rings of RHIC, which could be converted to an EIC by the addition of a suitable electron accelerator and storage ring and further upgrades. JLab, conversely, has an electron accelerator but would need to add the hadron injectors and storage ring and an electron storage ring. This has resulted in two somewhat different designs for an EIC, both of which push the limits of present technology. While neither the technical assessment nor the choice between these designs was a task of the present report, the committee found it appropriate to summarize them to illustrate how such benefits might accrue from the construction of an EIC.

Experience at all the world's major accelerator laboratories has demonstrated the value of building not only on existing hardware (going back over 60 years in long-established labs like BNL and CERN), but on the less visible collective expertise of the beam physicists, engineers (magnets, RF, vacuum, controls, civil, etc.), and operators among the laboratory staff. Construction of an EIC would sustain and develop this precious national asset and help the United States to maintain a leading role in international accelerator-based science.

Chapter 2 lays out in detail the basic science that could be achieved at an EIC. Chapter 3 describes the role of an EIC within the context of U.S. and international nuclear physics. Chapter 4 presents the accelerator challenges of building an EIC, and Chapter 5 compares a future U.S. EIC to current and future facilities both in the United States and internationally. Chapter 6 summarizes the impact of an EIC on other fields of physics, and Chapter 7 summarizes the conclusions and findings of this report.

# 2

# The Scientific Case for an Electron-Ion Collider

This chapter reviews in detail the fundamental scientific issues that would be addressed by an electron-ion collider (EIC).

## THE ORIGIN OF MASS

The majority of the visible mass of the universe resides in the two types of nucleons—protons and neutrons. Nucleons are made of massless gluons and almost massless quarks. In the Standard Model of particle physics, the masses of quarks, just like the mass of the electron, arise through their coupling to the Higgs field. Excitations of this field, Higgs particles, have recently been observed at the Large Hadron Collider (LHC). This observation has confirmed the basic Higgs mechanism. However, while the Higgs mechanism can explain all of the mass of the electron, it accounts for only a small part of the mass of the nucleon—namely, that associated with the masses of quarks.

The remainder of the mass of the nucleon is encoded in a slight rearrangement of Einstein's relation $E = mc^2$. In relativistic theories, mass is given by $m = E/c^2$, and the energy of the quark and gluon fields contributes to the mass of the nucleon. Quantum fields are richer than classical fields, because the vacuum of the theory is not empty, but filled with quantum fluctuations of particles and antiparticles. These fluctuations contribute to the energy of empty space. The nucleon is a state

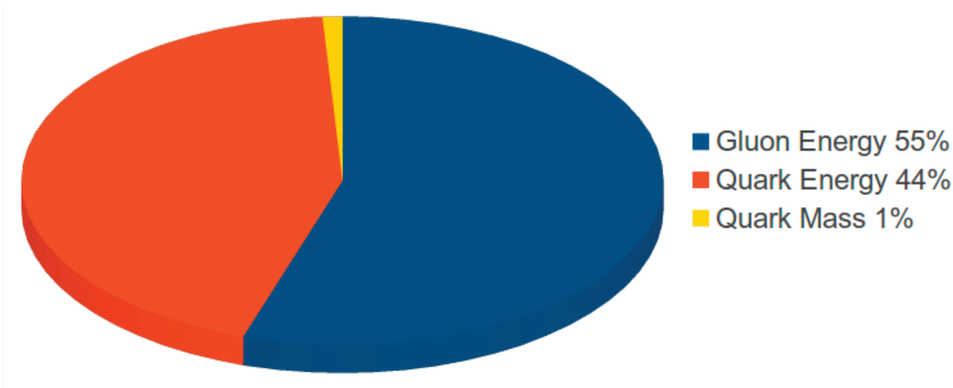


**FIGURE 2.1** Contributions to the total mass of the nucleon from valence quark masses as well as gluon and quark energy. SOURCE: T. Schaefer.

defined by its quantum numbers: baryon number,[1] electric charge, and spin, and its mass is determined by the difference in the energy between a quantum state containing a single nucleon and the energy of the vacuum.

The minimum configuration of quarks that can provide the quantum numbers of the nucleon is called the "valence quark content." In the proton, the valence content is two up quarks and one down quark. Because quarks and gluons are light, and because the coupling between valence quarks and gluons is strong, valence quarks are surrounded by a large number of sea quarks (quark-antiquark pairs) and gluons. An inventory[2] of the mass of the nucleon is shown in Figure 2.1. The contribution of the valence up and down quark masses is less than 1 percent. The remainder of the mass is associated with the energy of the highly relativistic quark and gluon fields. One can observe that the largest contribution to the mass of the proton originates from the gluon field energy. In this sense, the source of visible mass in the universe is not the Higgs field, but the gluon field.

Conducting a thought experiment allows an exploration of the mass of the proton by ionizing it, removing sea quarks and gluons from the valence quark core, and carefully monitoring the binding energies in the process. As explained in

[1] "Baryon number" is a conserved quantity that ensures that the proton cannot decay into a positron and a photon. In the Standard Model of particle physics, each quark carries baryon number 1/3.

[2] This inventory is based on data from deep-inelastic scattering (DIS). In particular, using relativistic invariance, one can relate the momentum fraction carried by quarks and gluons to the total quark and gluon energy. See X. Ji, 1995, A QCD analysis of the mass structure of the nucleon, *Phys. Rev. Lett.* 74:1071.

Chapter 1, confinement implies that this experiment cannot be realized. Instead, the EIC will explore the contents of the proton using a well-understood probe, the photon. In high-energy collisions of virtual photons and nucleons, the quark and gluon fields in the nucleon manifest themselves as quark and gluon "partons" (see Box 1.1 in Chapter 1). By selecting the energy and resolution of the virtual photon, an EIC can address different regions of Bjorken $x$ (explained in Box 1.3 in Chapter 1) going from the regime of moderate $x$ dominated by valence quarks to the small $x$ regime controlled by sea quarks and gluons. These types of experiments have been carried out before, but the EIC will add several new dimensions by studying the distribution of partons in the plane transverse to the motion of the nucleon, and by determining their transverse motion (see Box 2.1). These measurements will provide tomographic images of nucleons and nuclei. These images can be used to study several profound questions about the structure of the nucleon and the nucleus. First, as a function of Bjorken $x$, what is the relative spatial size of the valence quark, sea quark, and gluon distributions? Second, what is the spatial structure of the different contributions, shown in Figure 2.1, to the energy density and pressure forces in the nucleon? Lastly, what is the spatial distribution of gluons in a large nucleus?

### Imaging Quarks and Gluons

Tomographic images of both quarks and gluons in the nucleon are enabled by advances in quantum chromodynamics (QCD) theory since the mid-1990s combined with the unique capabilities of an EIC. First, the advances in theory that facilitate measurements of the transverse position of partons are described.

The two prototype reactions that have been analyzed are called deeply virtual Compton scattering and deeply virtual meson production (see Figure 2.2). The following text will refer to these processes as real photon and meson production in electron scattering. In real photon production, the incoming electron produces a high-energy virtual photon that interacts with the target nucleon or nucleus just as it does in deep-inelastic scattering (DIS). However, instead of destroying the target, the nucleon is left intact, and a real photon is produced. In real meson production, the final state consists of the target nucleon as well as a quark-antiquark bound state, such as a vector meson. The virtual photon is characterized by its resolution and energy, as in DIS, but there is an additional kinematic observable, the momentum transfer between the initial and final state proton. The crucial advance in QCD theory is the observation that the dependence of the cross section on the momentum transfer contains information about the transverse position of the struck parton.

Real photon production directly determines the transverse position of quarks. Information on the gluon distribution can be obtained from real meson produc-

**BOX 2.1**
**Visualizing the Subatomic World**

New instruments for visualizing the world around us—telescopes that image the macro-cosmos, and microscopes that explore the micro-cosmos—have played an important role in advancing our understanding of the physical world. Images of the arrangements of atoms in crystalline solids, obtained using X-ray diffraction, played a crucial role in establishing the atomic theory of solids. Images of the momentum distribution of electrons in metals, derived from photoemission spectroscopy, provide the foundation of modern theories of metallic states. Images of the spatial and momentum distribution of protons in nuclei, extracted from electron scattering experiments at facilities like the Bates Research and Engineering Center, the Saclay Linear Accelerator, and the Thomas Jefferson National Accelerator Facility, established the microscopic picture of the nucleus in terms of protons and neutrons.

An EIC would provide a new level of resolution in mapping the subatomic world by determining the position and momentum of quarks and gluons inside protons and nuclei. Current information about the structure of the nucleon comes from two sources. Elastic electron scattering experiments have determined the distribution of electric charge and magnetic moment in the nucleon. There are small but significant disagreements, at the level of about 3 percent, between these results and determinations of the size of the proton using atomic spectroscopy, currently under investigation. Similar information about the distribution of weak charge, the coupling to neutrinos and heavy vector bosons, is obtained via neutrino scattering.

The second source of information is DIS, as described in Boxes 1.1 and 1.3 in Chapter 1. In these experiments a virtual photon with a known energy and resolution scatters off a nucleon or nucleus. In the collider geometry, the nucleon or nucleus carries a large momentum. The measured cross sections determine the probability that a quark carries a fraction $x$ of the total momentum of the target. As the resolution is increased, the virtual photon resolves quantum fluctuations on shorter length scales. At low (squared momentum transfer) $Q^2$, the nucleon is dominated by a small number of valence quarks with $x \sim 1/3$. At higher $Q^2$, additional sea quarks appear, and momentum conservation implies that partons must be shifted toward smaller values of $x$. Quark-antiquark pairs are produced by gluons, and the rate at which the quark distribution changes with $Q^2$ provides an indirect measurement of the gluon distribution.

An EIC would significantly extend our knowledge of the distribution of quarks and gluons in nucleons and nuclei. Using additional data gained by detecting the final state of the target, it will provide information about the transverse position of partons (see Figure 2.1.1). These measurements will enable parton tomography, a series of two-dimensional (2D) images of the proton stacked along the Bjorken $x$ direction. Starting at large $x$, in the domain of valence quarks, and proceeding toward lower $x$, the regime of sea quarks and gluons, these images will reveal where quarks and gluons are located in the transverse plane. If the target is unpolarized, or if the spin is aligned with the direction of motion, then the distribution is rotationally symmetric in the

tion. The interpretation of this process is most direct when the focus is on the production of a heavy-quark bound state like the $J/\psi$, a charm-anticharm state, or the Upsilon ($\Upsilon$), a bottom-antibottom pair. In this case, the dominant process is shown in the right panel of Figure 2.2, where the virtual photon produces a quark-pair that interacts with the target via two-gluon exchange. Gluonic density

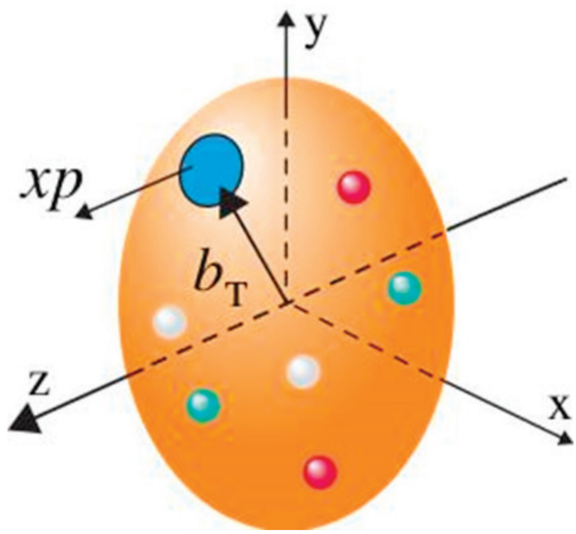


**FIGURE 2.1.1** Schematic depiction of a nucleon containing a parton with longitudinal momentum *xp* and transverse position $b_T = (b_x, b_y)$. The *z*-direction is the beam direction. The transverse momentum (not shown) of the parton is $k_T = (k_x, k_y)$.
SOURCE: A. Accardi et al., 2016, Electron-ion collider: The next QCD frontier, *Eur. Phys. J. A* 52:268.

transverse plane. In this case, parton tomography provides a series of radial distributions, as shown in Figure 2.5.

Using a related class of observables, an EIC would also measure the transverse motion of partons. This information is important for a variety of reasons. The uncertainty principle relates the typical transverse momentum of a parton to the spatial extent of the quark or gluon field that produced it, thus providing clues that will help to identify the nature of fluctuations of the color field in the nucleon. The full richness of transverse momentum information is explored when transverse polarization (when the spin direction is orthogonal to the direction of motion) is added. In this case, orbital motion leads to correlations between spin and transverse momentum $k_T$, and tomographic images of the $k_T$ distribution are fully 2+1 dimensional, as seen in Figure 2.7.

profiles are also obtained independently through varying the probe resolution $Q^2$ in real photon production. The combination of real photon and meson production therefore provides an important cross-check on transverse gluon profiles. Exploratory studies of real photon production were carried out at the ZEUS and then H1 experiments at the Hadron-Electron Ring Accelerator (HERA), at Thomas

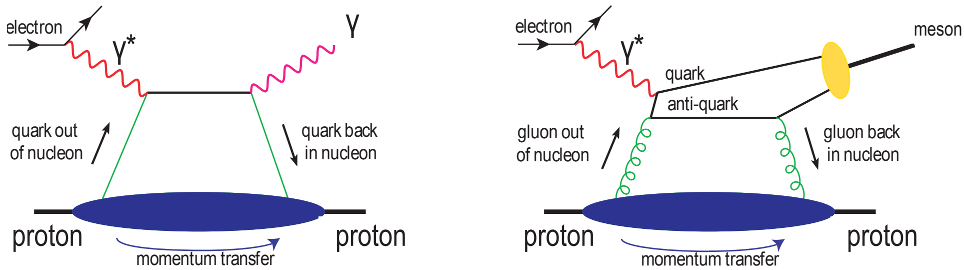


**FIGURE 2.2** Real photon production (*left*) and real meson production (*right*). The virtual photon $\gamma^*$ is emitted by the incoming electron. The final state photon and meson are real particles that can be observed in the detector. For the two-gluon process to dominate real meson production, the produced state should be heavy, like the $J/\psi$ (a charm-anticharm quark bound state) or the Upsilon (Υ) particle (a bottom-antibottom quark bound state). In both processes, the nucleon remains intact but is deflected by a nonzero angle. SOURCE: Z.-E. Meziani.

Jefferson National Accelerator Laboratory (JLab) with a 6 GeV electron beam on a fixed proton target, at the HERA Measurement of Spin (HERMES) experiment at Deutsches Elektronen-Synchrotron (DESY), and at the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) experiment at the European Organization for Nuclear Research (CERN). These experiments suffered from limited statistics or kinematic reach. In the near future, JLab, with its 12 GeV-energy high-luminosity upgrade, will provide high-precision images of the valence quark region.

An EIC would dramatically improve on these measurements, via detailed images of gluonic profiles and would also offer a path to determine the orbital contribution of sea quarks and gluons to the nucleon spin. The counter-propagating electron and hadron beams configuration of an EIC is the most efficient means to achieve high energy and high resolution for a given energy of the electron or hadron beam. The collider geometry also has significant advantages in terms of the detector geometry (see Figure 2.3). In a fixed target experiment, all reaction products end up in a narrow region of the detector along the beam line, making it difficult to clearly separate and measure the deflected electron and the target nucleon or its decay products. In a colliding beam detector, the reaction products are clearly separated in the laboratory, enabling precise measurements of the kinematic variables on which tomographic images are based. Furthermore, carefully designed forward detection of the recoiling particles, the proton in the case of Figure 2.2, can select the desired exclusive reaction.

The scientific program of an EIC will be enabled by a unique combination of three crucial variables—energy, luminosity, and polarization—combined with the

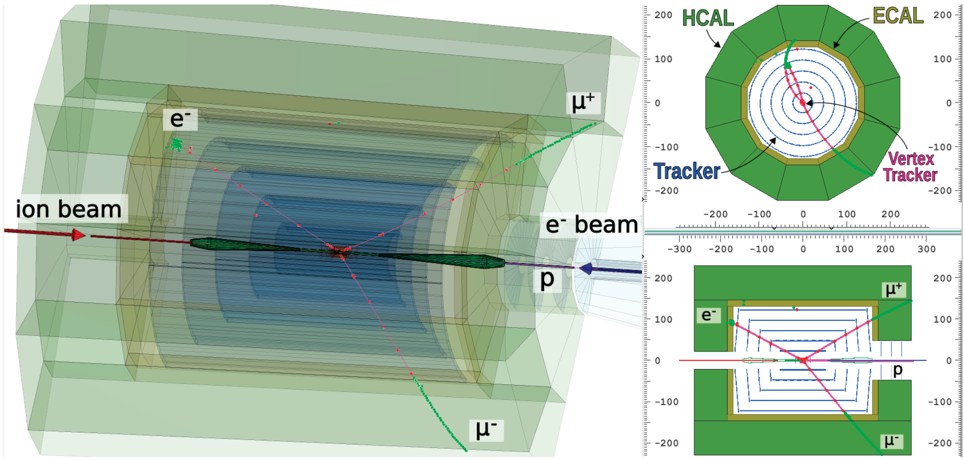


**FIGURE 2.3** Simulated event display for real meson production in a design for an electron-ion colliding beam detector. The direction of the beams is indicated in the perspective (*left*) and side views (*lower right*). The upper-right panel shows a view along the beam direction. In this event, the colliding proton stays intact, and a heavy J/ψ meson is produced. The J/ψ decays into a pair of muons, which are detected together with the scattered electron. The scattered proton labeled p is close to the beam direction and detected in a separate detector farther from the interaction point. Events of this type are the basis of gluon tomography, as shown in Figure 2.5, and provide information on the gluon orbital angular momentum contribution to the nucleon spin. Similar events where an Upsilon ($b\bar{b}$) meson is produced on a proton close to "threshold," never before measured, will also help determine the gluon contributions to the mass of the nucleon. SOURCE: Argonne National Laboratory.

ability to collide electrons with both nucleons and nuclei. Polarization, or alignment of spins, is needed to access the carriers of spin and angular momentum in the proton. The energy-luminosity regimes required to fully explore the central pillars of an EIC science program, determining the origins of the mass and spin-flavor composition of the proton, imaging the spatial and momentum distribution of their partons (quarks and gluons), and studying dense gluon matter, are indicated in Figure 2.4.

High energy is needed to produce high-resolution images of the partons in nucleons and nuclei that carry a small fraction *x* of the momentum of the target. This regime is dominated by gluons and sea quarks. High energy also provides large kinematic coverage, which is crucial in extracting gluon distributions. Lastly, high energy provides access to the regime of very high gluon density, a new frontier in QCD.

Luminosity determines the rate at which collisions occur. High luminosity is needed because parton imaging is based on the detection of very specific final states,

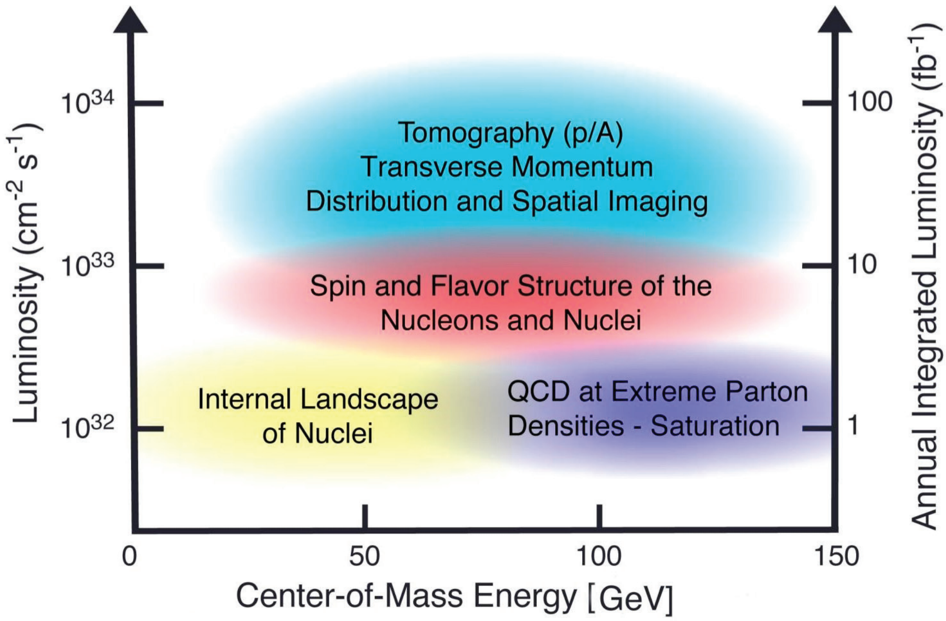


**FIGURE 2.4** The energy-luminosity landscape that encapsulates the physics program of an EIC. The horizontal axis shows the center-of-mass energy of the collider when operated in electron-proton mode. The two vertical axes show the instantaneous and annual integrated (electron-nucleon) luminosity; the latter is in units of inverse femtobarns and assumes a running time of $10^7$ seconds per year. SOURCE: Presentation of EIC Science by A. Deshpande on behalf of the EIC Users Group.

such as an intact nucleon combined with a final state photon or vector meson, that occur in only a small fraction of all reactions. Parton imaging also requires an accurate determination of not only total interaction rates, but of the dependence of these rates on the deflection angles of all scattered particles, for which large luminosity is also needed. Figure 2.4 indicates both the instantaneous luminosity as well as the annual integrated luminosity (for running time of $10^7$ seconds per year, a 30 percent duty factor) that can be achieved. It is the latter that ultimately controls the experimental uncertainty. Figure 2.5 shows the accuracy of the transverse gluon profiles that can be obtained from J/ψ production using an integrated luminosity of 10 $fb^{-1}$. Note the precision that can be achieved at large transverse radii $b_T$, which is important for understanding the way in which confinement of quarks and gluons is reflected in the transverse spatial profile of parton distributions.

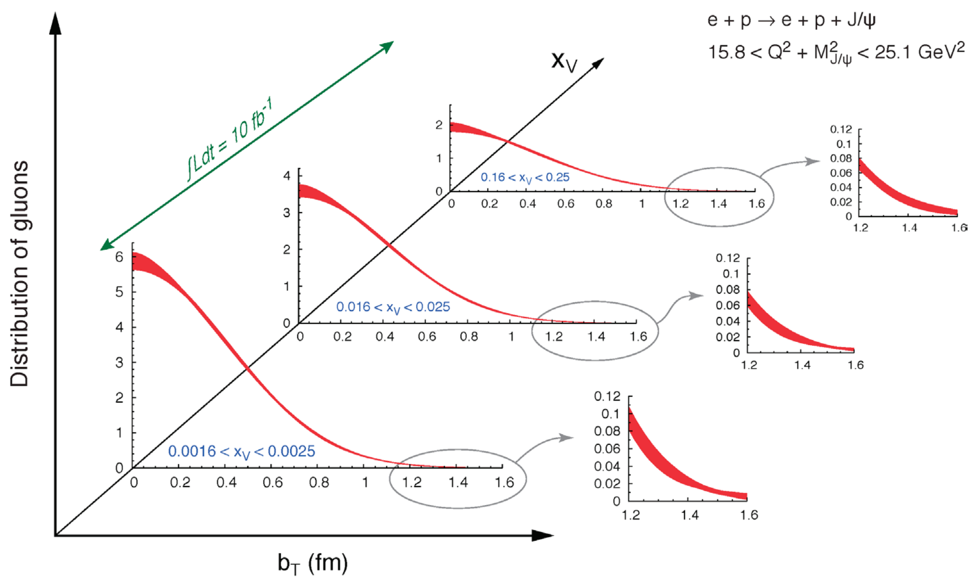


**FIGURE 2.5** Gluon density distribution at several values of Bjorken *x*. An estimate of the precision that can be achieved using real meson production at an EIC is shown, based on an integrated luminosity of 10 $fb^{-1}$. The small insets illustrate the accuracy that can be achieved for large radii, relevant to the confinement problem. SOURCE: *Reaching for the Horizon,* 2015 DOE/NSF Long Range Plan for U.S. Nuclear Science.

### 3D Imaging in Momentum

An important complement to the program of imaging the transverse position of partons is the determination of transverse motion. Combined with the dependence on longitudinal motion encoded in Bjorken *x*, transverse momentum distributions (TMDs) provide a three-dimensional (3D) picture of the nucleon in momentum space. Due to the uncertainty principle, the transverse momentum of partons is related to the characteristic size of the quantum mechanical fluctuation from which it originated. Transverse momentum imaging therefore constrains the possible evolution of color fluctuations with Bjorken *x*, going from the valence sector at large *x* to the sea quark and gluon regime at small *x*. In the small *x* regime, the results provide important information about the limit of high gluon density, discussed in the last section of this chapter. In a polarized proton, one also expects that the orbital motion of partons is correlated with the spin direction, leading to correlations among spin, transverse motion, and transverse position.

The transverse dynamics of partons can be accessed using a process called semi-inclusive deep-inelastic scattering (SIDIS). As in DIS, the target nucleon is destroyed, but at least one of the outgoing hadrons is detected. These reactions are referred to as coincidence experiments, because the outgoing hadron (typically a meson) is detected in coincidence with the scattered electron. Information about the transverse motion of partons is encoded in the transverse momentum of the produced hadron. Coincidence scattering is most powerful when combined with polarization, which is discussed in the following section.

## THE ORIGIN OF SPIN

Spin is a fundamental property of elementary particles. Matter particles, like electrons and quarks, have a spin or an intrinsic angular momentum equal to $\hbar/2$, where $\hbar$ is Planck's fundamental constant. (For simplicity, the $\hbar$ is not written further, leaving it tacitly understood, and the nucleon is referred to, for example, as having spin ½.) Force carriers, like photons and gluons, have spin 1. Composite particles acquire angular momentum from a combination of the fundamental spins and orbital angular momentum of their constituents. Nucleons are bound states of quarks and gluons with total spin ½; the total angular momentum of a nucleon is the sum of the spin and orbital angular momenta of the quarks and gluons they contain. Similarly, the total angular momentum of nuclei is the sum of the spin and orbital motion of nucleons, and in atoms it is the combination of nuclear angular momentum with the spin and orbital motion of electrons.

Charged particles, or neutral particles made of charged constituents, have magnetic moments that in the absence of external electromagnetic fields are aligned with the direction of spin. The fact that protons and neutrons behave as magnets is of great technological importance. For example, the magnetic moment of the proton is the basis of magnetic resonance imaging (MRI). In a magnetic field, protons with spin aligned or anti-aligned with the field have different energy, and this energy difference can be probed using radio frequency (RF) fields.

### Gluon Spin and Orbital Angular Momentum

The textbook picture of the spin of the proton is that of three spinning valence quark tops. The total spin ½ is obtained because two of the valence quarks are aligned, and the third one is anti-aligned with the spin of the proton. This simple picture qualitatively accounts for the magnetic moments of the proton and the neutron. It explains, for example, why the neutron, despite its vanishing electric charge, has a nonzero magnetic moment. However, the valence quark picture fails to account for more detailed studies of the spin structure of the nucleon. Beginning in the late 1970s experiments at Stanford Linear Accelerator Center (SLAC), CERN, DESY, and JLab studied DIS using polarized protons. These experiments determine the net polarization of quarks along the direction of the spin of proton.

In units of the total spin ½ of the proton, the valence quark picture predicts that this polarization should be 100 percent. In fact, it was found that the quark polarization is only about 30 percent. The remainder of the spin must reside in orbital angular momenta of quarks and gluons or gluon polarization.

This observation has motivated a broad program aimed at measuring other contributions to the total spin of the proton. Exploratory measurements of the quark orbital angular momentum in the valence quark regime are an important part of the physics program at the 12 GeV upgrade of JLab. Polarized proton-proton collisions at the Relativistic Heavy Ion Collider (RHIC) have provided the first evidence for a nonvanishing gluon spin polarization in the proton. A central goal of the EIC program is to provide a determination of the gluon spin contribution and its orbital angular momentum. The uncertainties in the gluon spin contribution will be dramatically reduced (see Figure 2.6). These measurements would be based on the resolution dependence of polarized DIS. This dependence arises from quark and gluon partons radiating additional partons. When a polarized gluon radiates a quark-antiquark pair, the spin orientation of the gluon is transferred to

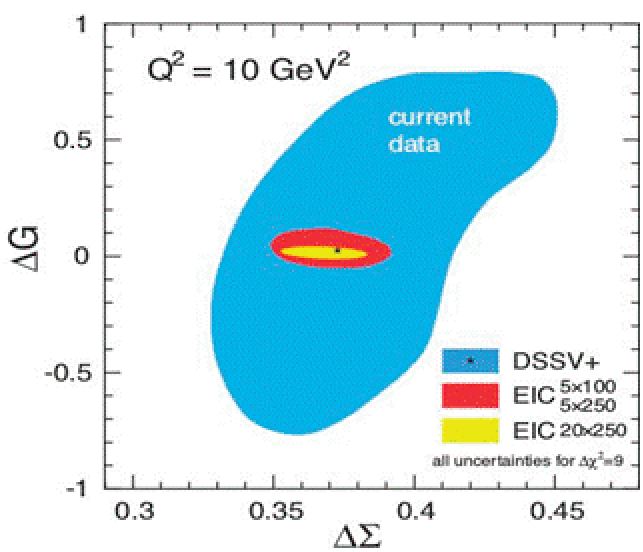


**FIGURE 2.6** An EIC would be able to resolve the quark (ΔΣ) and gluon (ΔG) spin contributions to the nucleon (both quantities given here in units of ħ/2). Existing data constrain the quark contribution to be about 1/3, but leave the gluon spin contribution essentially unconstrained. The missing total angular momentum after summing ΔΣ and ΔG is provided by orbital motion. SOURCE: E. Aschenauer, R. Sassot, and M. Stratmann, 2012, Helicity parton distributions at a future electron-ion collider: A quantitative appraisal, *Phys. Rev.* D86:054020.

the quark and the antiquark. This effect can be measured using polarized electron scattering with a polarized proton beam.

The orbital angular momentum of gluons can be probed via the exclusive measurements described in Figure 2.2. Precise knowledge of the spin of gluons combined with sum rules of the generalized parton distributions (GPDs) determined in these measurements offer the possibility of isolating the contribution to the nucleon spin of the orbital angular momentum of gluons.

## Transverse Motion in Polarized Nucleons

The dynamics of spin-orbit correlations in QCD can be studied using the transverse momentum distribution of partons in a transversely polarized proton, one with its spin direction orthogonal to its direction of motion. Consider a nucleon as shown in Figure 2.1.1 with its spin instead in the $y$-direction. If part of the spin is carried by orbital motion, then this will be reflected at the parton level by a correlation between momentum in the $x$-direction, and position in the $z$-direction. In coincidence experiments this relationship can manifest itself as a correlation between the transverse spin of the nucleon and the direction of motion of the observed hadron. This type of observable is referred to as a "spin asymmetry" in a coincidence experiment.

For spin-orbit correlations to manifest themselves as spin asymmetries, a second ingredient is required. As explained in Box 2.2, this second prerequisite is that the struck parton acquires a quantum-mechanical phase from traveling through the color field of the nucleon. As a consequence, spin asymmetries probe the dynamics of QCD in novel ways. Pioneering studies of spin asymmetries in coincidence experiments were carried out in fixed-target experiments at HERMES, COMPASS, and the JLab 6 GeV facility. Figure 2.7 shows transverse momentum profiles extracted from a global fit to existing data, the distribution of unpolarized u and d sea quarks in a polarized proton. A very important result was observed: Whereas d quarks in the proton show strong spin-orbit correlations, the corresponding effects in the u quark sector are weak. It was also observed that spin-orbit effects are large in the valence regime, but disappear in the low $x$ regime.

An EIC would improve on these experiments in several ways. It would significantly extend the kinematic coverage of spin asymmetries in terms of Bjorken $x$, transverse momentum, and resolution. This extended range will allow detailed tests of QCD in terms of spin-orbit effects and color phases (see Box 2.2). An EIC would for the first time measure spin asymmetries in the gluon sector. Currently, nothing is known about spin-orbit correlations of gluons.

**BOX 2.2**
**Transverse Motion and Quantum Phases in Quantum Chromodynamics**

The essence of quantum theory is that physical phenomena are described by probability amplitudes, analogous to the height of a water wave, rather than probabilities, and this feature leads to quantum interference effects. An important class of such effects arise from Aharonov-Bohm phases, which a charged particle acquires when traversing an electromagnetic vector potential.[1] An interesting aspect of Aharonov-Bohm phases is that the vector potential can be nonzero even where the electric and magnetic fields vanish, remarkably leading to observed interference effects between charged particles that propagate through field-free regions around a magnetic solenoid.

Interference does not play a role in inclusive DIS. However, an Aharonov-Bohm type effect appears when transverse motion is studied. Consider a nucleon with its spin pointing in the $y$-direction, transverse to the direction of motion (the $z$-direction). If partons carry angular momentum, then there is a correlation between motion in the $x$-direction and position in the $z$-direction.

This implies that partons with different $k_x$ originate from different positions in the proton and acquire different quantum phases from interacting with the gluonic vector potential. This is the origin of the $k_x$ imbalance observed in Figure 2.7. Experimentally, this imbalance manifests itself as a correlation between transverse spin polarization and the direction of motion of final state hadrons. Empirically, these types of spin asymmetries are known to be large. The crucial observation is that this correlation is absent without the presence of an Aharonov-Bohm phase. An EIC would test the idea that the origin of these effects is related to the gluon field of the proton and, for the first time, directly detect a quantum phase generated by the color force. For example, EIC measurements of transverse momentum dependent parton distribution functions will directly probe observables sensitive to the color phases generated by the proton's constituents.

There is an interesting cross-check for this interpretation based on comparing spin asymmetries in DIS with analogous asymmetries in the Drell-Yan process, which involves quark-antiquark annihilation in proton-proton scattering. As originally explained by Feynman in the context of positrons and electrons,[2] the Aharonov-Bohm phase of an antiquark is the same as that of a quark going backward in time. This implies that the spin asymmetries in the Drell-Yan process are expected to be opposite in sign to those an EIC will observe.

[1] The vector potential is the magnetic analog of the electrostatic potential. Just like electric field energy arises from the interaction of charges with the electrostatic potential, magnetic field energy is due to the interaction of electric currents (which have a direction, hence vectorial) with a vector potential.

[2] R.P. Feynman, The theory of positrons, *Phys. Rev.* 76:749, 1949.

## GLUONS IN NUCLEI

An EIC would be able to study the gluons that bind quarks and antiquarks into nucleons and nuclei with unprecedented precision. A central goal of such studies is to explore the limit of low Bjorken $x$, where the number of gluons in the target

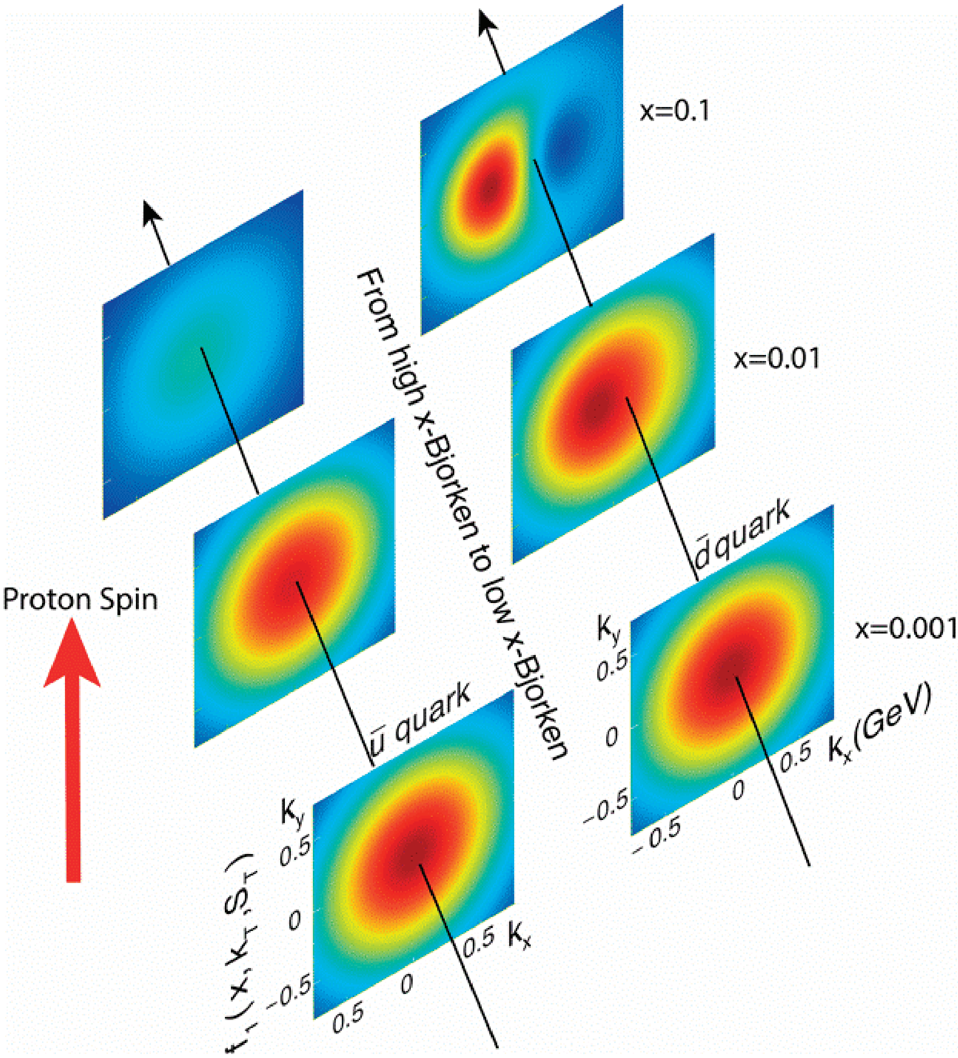


**FIGURE 2.7** Transverse momentum profile of anti-up ($\bar{u}u$) and anti-down ($\bar{d}d$) quarks in a proton. The figure shows three slices, ranging from the valence quark region at large Bjorken *x* to the sea quark regime at low *x*. The color range is from zero (dark blue) to largest positive values (deep red). The transverse momentum is given in units of GeV. The visible distortion of the $\bar{d}$ anti-down quark profile at large *x* is a signature of the correlation of a large quark orbital angular momentum with the spin of the proton. The spin direction of the proton is indicated by the red arrow. Extrapolations to the smallest *x*, using a simple analytic function, are given for illustration. SOURCE: Z.-E. Meziani and A. Prokudin.

is very large. Here, the description of the nucleus in terms of colored degrees of freedom is expected to simplify dramatically, and discovery of a new type of state composed of dense gluon matter is also expected. An EIC would also be able to explore modifications of the quark distributions in nuclei, as explained in more detail in Box 2.3.

There are several strategies for turning beams of electrons into calibrated probes of nuclear gluons. The first of these methods, based on measurements of the evolution of the quark distribution as a function of resolution, was previously used at other electron machines. As the resolving power of the virtual photon is increased, it becomes sensitive to quark-antiquark fluctuations at shorter distances. In protons and nuclei, these pair fluctuations are produced by gluons, so that a measurement of the change of the quark distribution with scale probes the gluon distribution. Figure 2.8 shows a summary of parton distributions obtained at HERA. It can be observed that the number of gluons grows significantly in the low $x$, high-energy regime; low $x$ matter is gluonic matter.

This method has a number of limitations. It assumes that the interactions between quarks and gluons are sufficiently weak that one can compute the rate at which quark-antiquark pairs are radiated by gluons. This assumption is questionable in the regime of small $x$, where the gluon density is large, as well as in the regime of low $Q^2$, where the interaction is strong. An EIC would employ a new and independent method, based on measuring the cross section of *longitudinally* polarized photons. This cross section vanishes in the simple quark-parton model, but it is not zero if gluon constituents or gluonic interactions are taken into account. A measurement of the longitudinal DIS cross section on the nucleon requires varying the energy of the electron and hadron beams, and there has been only one previous attempt, also from HERA, to measure this cross section. An EIC would perform systematic measurements of the longitudinal photon cross section in both nucleons and nuclei. These measurements would not only constrain the distribution of gluons, but also test theories of the interaction of virtual photons with dense gluon matter, in particular the dipole picture discussed below. An EIC would significantly extend measurements of nuclear parton distribution functions in the low $x$ regime.

Measurements of nuclear structure functions address a very fundamental question about the properties of nuclei in QCD: To what extent is a nucleus just a collection of individual nucleons? Existing determinations of the parton distribution in the valence quark regime show a depletion with respect to the expectation for a noninteracting system of nucleons, an observation believed to reflect the effects of nuclear binding (the European Muon Collaboration [EMC] effect). Nuclear gluon distributions are very poorly constrained at present. Future experiments at an EIC would measure these functions and study how the gluon field of an individual nucleon is modified by its interaction with other nucleons in the nucleus.

The most striking conclusion one might draw from the measurements of the

**BOX 2.3**
**Using Nuclei to Study Quantum Chromodynamics**

Confinement implies that colored quarks and gluons are bound into color neutral protons and neutrons. One of the central questions in nuclear physics is how the residual color force between color neutral nucleons leads to the formation of nuclei, which are nuclear bound states. This question can be addressed by studying the modification of the parton distribution of free nucleons when they are embedded in a nucleus. Measurements of the Bjorken $x$ distribution of partons in a nucleus were pioneered by the European Muon Collaboration (EMC) at the European Organization for Nuclear Research (CERN). The EMC results revealed a clear difference between the longitudinal quark distributions in heavy nuclei compared to those in deuterium, but a detailed understanding of these modifications in terms of quantum chromodynamics (QCD) has yet to emerge. Multidimensional imaging of quarks and gluons in a nucleus will provide key new information that will enable progress in this area.

The EIC will be the first facility in the world to access with high resolution the 3D sea quark and gluon structure of a fast-moving nucleus. While the basic processes used in tomography of the nucleus are similar to those in the nucleon, an additional challenge is the detection of the intact scattered nucleus. The final state particles produced in these processes, including the scattered nucleus, have small momenta in the target rest frame, which makes their detection difficult. A collider provides a significant advantage over a fixed target machine since the slow particles in the target rest frame move along the beam direction and can be detected with a well-designed forward system. With such capability, an EIC would allow imaging of nuclei by measuring both quark and gluon density profiles.

The nucleus is also a laboratory for understanding the dynamics of confinement, the process by which a high-energy parton created by the interaction of a virtual photon with the nucleus is color neutralized and evolves into a hadron. A high-energy parton radiates soft gluons and quark-antiquark pairs. Collectively, this swarm of particles is known as a "jet." The process by which partons in the jet form hadrons is known as "hadronization." Hadronization has been studied at the Stanford Linear Accelerator Center (SLAC; in the mid-1970s in End Station A), at CERN (in the 1980s with EMC), as well as at the Hadron-Electron Ring Accelerator (HERA; starting in the 1990s). Jets and hadronization have also been studied at electron-positron as well as proton-proton colliders, and the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider

gluon distribution shown in Figure 2.8 is that the number of gluon grows, apparently without bound, in the low $x$ limit. Clearly, at some point, however, the density becomes so large that gluons lose their individual identity and are strongly overlapping. Where this happens, as a function of Bjorken $x$, depends on the resolution, because gluons have a spatial extent determined by the resolution $Q^2$. One can therefore ask, for a given value of Bjorken $x$: *Below what resolution scale is the number density so large that gluons are no longer independent?* This scale is called the "saturation scale," $Q_s$.

An important new regime in which nuclear physics becomes simple but the full richness of QCD is retained arises if the saturation scale is large. In this limit,

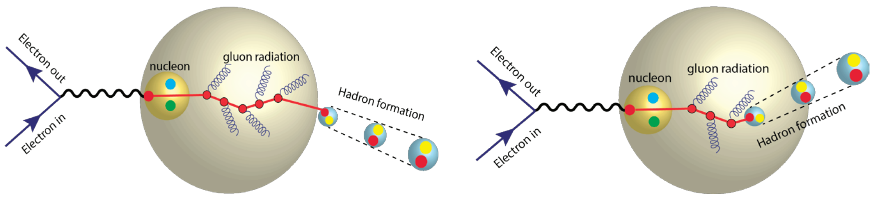


**FIGURE 2.3.1** Schematic illustration of the interaction of a parton (red line) moving through nuclear matter: the hadron is formed either outside the nucleus (*left*) or inside (*right*). SOURCE: *Reaching for the Horizon*, 2015 DOE/NSF Long Range Plan for U.S. Nuclear Science.

(LHC) have pioneered studies of jet energy loss in a hot quark gluon plasma. An EIC would be uniquely positioned to study the evolution of jets in a cold nuclear medium.

In studying the propagation of energetic quarks, the nucleus becomes a QCD laboratory, providing femtometer-scale detectors and a medium with known properties, such as size and density. Hadronization in cold nuclear matter is only qualitatively understood; questions remaining about its space-time dynamics include its dependence on the quark mass and flavor and the mechanisms by which quarks and gluons lose their energy and become hadrons.

Electron-nucleus collisions in which a meson is detected are an excellent tool for studying hadronization. With electrons as the probe, one can select the energy of the virtual photon, thus controlling the momentum transfer to the quark, and obtain clean measurements of medium-induced energy loss by choosing high-photon energies, which lead to hadronization outside of the nucleus (see Figure 2.3.1, left). Similar techniques can be used to delineate the interplay between quark propagation and hadron formation mechanisms (see Figure 2.3.1, right). Studying hadronization for light and heavy quarks in cold nuclear matter can unravel some of the remaining mysteries surrounding energy loss in a quark-gluon plasma. For example, experiments at RHIC and the LHC showed that light and heavy quarks lose energy at a similar rate, despite the fact that if the QCD interactions were weak, heavy quarks would be less likely to lose energy via medium-induced radiation of gluons.

asymptotic freedom predicts that the interaction strength is weak, but the large gluon density implies that the gluon self-interaction, which is a central feature of QCD, is crucial. This regime is referred to as "dense saturated gluon matter."[3] If $Q_s$

[3] This state is frequently described as a color glass condensate, where "glass" refers to slowing of the time evolution in a fast-moving nucleus by Lorentz time dilation, and "condensate" indicates that the phase space density of gluons is very high. The existence and the properties of this state are a direct consequence of the field equations of QCD. In the limit of large occupation number, these equations are approximately classical. Classical QCD has no intrinsic scale, and the color glass condensate leads to simple scaling relations for cross sections and particle production rates. It also provides initial conditions for the production of a quark-gluon plasma in heavy ion collisions. In collisions of two

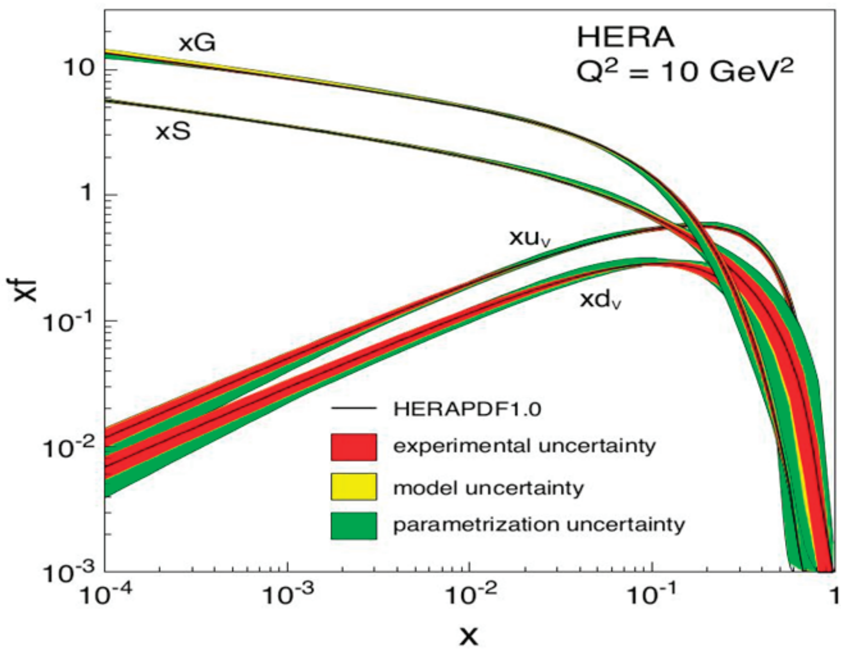


**FIGURE 2.8** A global fit to parton distribution functions of the proton based on DIS data obtained at the Hadron-Electron Ring Accelerator (HERA). Distribution of gluons, G, sea quarks, S, and valence up and down quarks, $u_V$ and $d_V$, are shown as a function of Bjorken *x*. SOURCE: Adapted from H. Abramowicz et al., 2015, Combination of measurements of inclusive deep-inelastic $e^{\pm}p$ scattering cross sections and QCD analysis of HERA data, *Eur. Phys. J.* C75:580.

is much bigger than typical hadronic energy scales, then the properties of saturated gluon matter depend only on $Q_s$ and not on details of the nucleon or nucleus that is being probed.

Producing dense, saturated gluon matter requires high energy and small *x*. Estimates of the saturation scale at HERA, which collided protons and electrons at a center-of-mass energy of 318 GeV, give a value around 1 GeV, which is not much larger than typical hadronic energy scales. The EIC will operate at lower energy, but it will provide a new lever arm, the ability to accelerate nuclei, enabling it to explore the saturation regime. At high energy, the nucleus is Lorentz contracted along the

ions, the kinetic energy of the gluons is thermalized, and the dense gluon component evolves into a hot gluon plasma. Gluons in the plasma radiate quark-antiquark pairs, and the equilibrium state becomes a hot quark-gluon plasma that cools and decays into hadrons. The hot quark-gluon plasma is currently being studied at RHIC and LHC, but the dense gluonic system that provides the initial state can be studied only at an EIC.

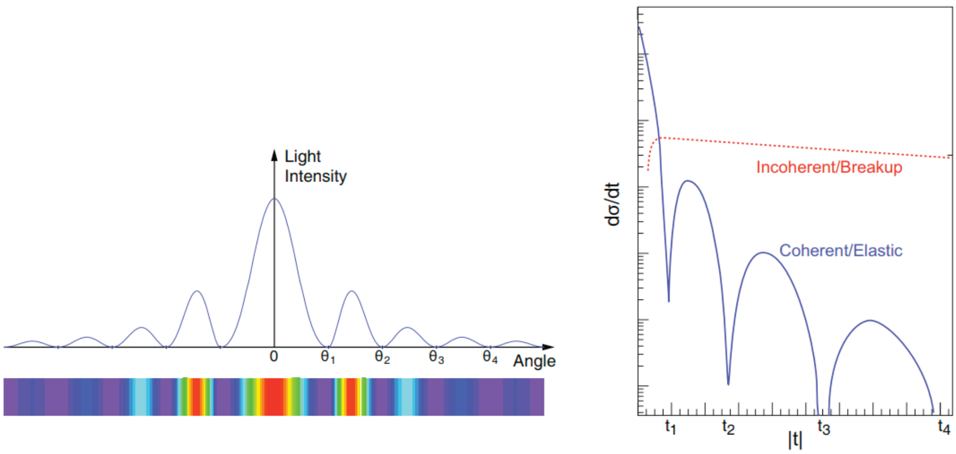


**FIGURE 2.9** *Left:* Diffraction pattern in optics, showing the light intensity landing on a screen behind a circular obstacle. *Right:* The expected differential cross section for coherent and incoherent diffractive production of J/ψ particles on nuclei. The variable *t* is related to the momentum carried by the scattered proton, which provides a measure of the scattering angle. The incoherent/breakup curve is explained in the text. SOURCE: *Reaching for the Horizon,* 2015 DOE/NSF Long Range Plan for U.S. Nuclear Science.

direction of motion, and the effective gluon density increases as the nuclear radius, proportional to the cube root of the mass number A of the nucleus. Empirical studies of the growth of the gluon distribution provide an estimate of the effective gain in center-of-mass energy afforded by the ability to accelerate heavy nuclei.[4] These studies indicate that saturation effects at an EIC are equivalent to those at an electron-proton collider operating at an energy $A^{1/2}$, or about 15 times higher.[5]

An important aspect of saturation effects in DIS at an EIC is the role of "diffractive scattering." Diffraction is a well-known effect in optics. When light waves encounter an obstacle with a sharp boundary, they are bent around the object and produce an interference pattern on a screen located behind the obstacle (see the left panel of Figure 2.9). For a given wavelength of the light, the distance between the minima is determined by the size of the object. Diffraction is also observed

[4] See, for example, E. Aschenauer et al., The electron-ion collider: Assessing the energy dependence of key measurements, arXiv:1708.01527.

[5] There is some uncertainty in the value of the saturation scale, and there is no definitive theoretical prediction for how large $Q_s$ has to be for the full simplicity of the saturation picture to manifest itself. However, much of the experimental program, measuring nuclear effects in the gluon distribution function, studying diffractive scattering in the regime of high gluon density, and mapping the gluon distribution in the transverse plane, does not depend on any particular picture of QCD in the regime of high gluon density.

in the scattering of highly energetic particles on nuclear targets in the limit that the interaction is strong and the projectile is strongly absorbed by the target. If the target is a completely absorbing black disk, then the total cross section is twice the geometric cross section of the target; half of the cross section is due to diffractive scattering.

The high-energy limit of nuclear DIS can be viewed as a process in which the virtual photon produces a quark-antiquark pair with a color dipole moment that interacts with the nuclear target (see Figure 2.10). In the low *x* regime, the target is dense gluonic matter and the probability for absorbing the quark-antiquark dipole will be large, and may approach unity. This implies that a significant part of the total cross section is diffractive scattering. Experimentally, one observes reactions in which the target nucleus remains intact, called "coherent diffraction," or reactions in which the target is excited, but there is a large separation in the detector between the decay products of the struck quark and the remnants of the nucleus. The latter events are called "incoherent diffraction."

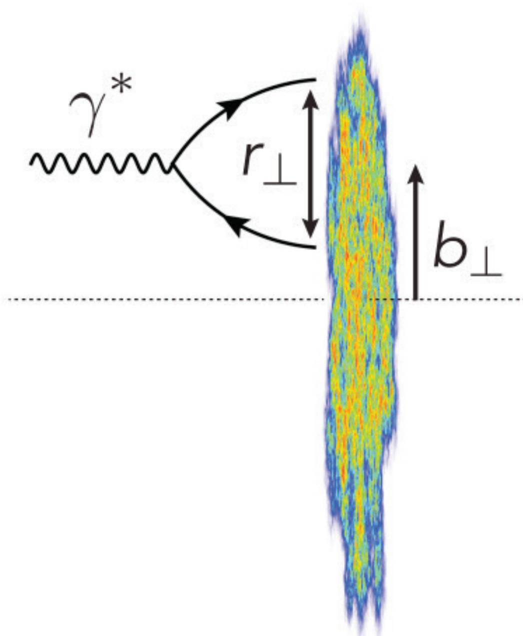


**FIGURE 2.10** Schematic view of the interaction of a virtual photon with the color field of a large nucleus (shown in green-blue). The photon produces a quark-antiquark pair, which is a color dipole of size $r_\perp$. The dipole interacts with the Lorentz-contracted gluon field of the nucleus at an impact parameter $b_\perp$. The figure also indicates that the color field is fluctuating, and that the boundary of the nucleus is not sharp. SOURCE: E. Aschenauer et al., 2017, The electron-ion collider: Assessing the energy dependence of key measurements, arXiv:1708.01527.

Diffraction in QCD is a more complicated process than diffraction in optics. If the resolution of the photon is larger than the saturation scale, then the dipole probe of the gluon field is small, and the absorption cross section is small. This means that the target is black at low resolution and gray at high resolution. Also, the nucleus does not have a sharp boundary; it is black in the center and gray near the boundary. Lastly, the nucleus is a quantum system, and the gluon density fluctuates. The nucleus has black spots that fluctuate from event to event.

These complications provide important opportunities. The fact that the blackness of the target depends on resolution implies that the saturation scale can be measured using the dependence of the diffractive cross section on the resolution scale and the nuclear mass number. The observation that the nucleus has a diffuse boundary means that the transverse location of gluons in the nucleus can be mapped. Lastly, the fact that the blackness of the target fluctuates can be used to extract shape fluctuations of the nucleon and correlations between nucleons in the target.

The picture of DIS based on the dipole picture—that the virtual photon turns into a quark-antiquark color dipole—predicts the energy and nuclear mass dependence of diffractive DIS. The diffractive cross section rises steeply with energy at low energy, but becomes an approximately constant fraction of the total cross section in the regime that an EIC would explore. A substantial increase in the rate of diffraction is achieved by going to nuclear targets. At a given energy, nuclear targets contain more gluons and are closer to the black disk limit. The blackness of the target decreases as the resolution is increased, but diffraction is expected to persist at high $Q^2$. This is a reflection of the large saturation scale: gluons are tightly packed, and the target appears black even if the resolution is high. An EIC will enable detailed studies of the dependence on nuclear mass number, the resolution of the virtual photon, and the mass of the diffracted object. These results will test the universality of the dipole model—the assumption that a single dipole cross section can account for many different observables. They will determine the gluon density and therefore the saturation scale in the target and study the onset of gluon self-interaction effects that come into play as the dipole cross section approaches the black disk limit.

The right panel of Figure 2.9 shows a prediction of the diffraction pattern that is expected to emerge in the coherent production of $J/\psi$ mesons. One clearly observes the minima and maxima that are characteristic of diffraction. One also sees that the pattern is expected to disappear if the target nucleus is excited, as shown in the incoherent/breakup curve. The interference patterns are governed by quantum mechanics, and the quantum mechanical rules for combining amplitudes imply that the difference between coherent and incoherent diffraction can be related to fluctuations of the gluon density.

The power of this result is illustrated in Figure 2.11, which shows a model of

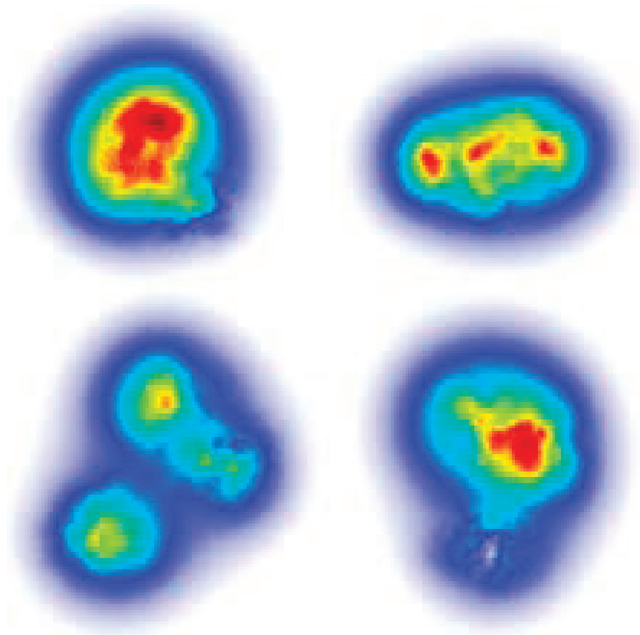

**FIGURE 2.11** Shape fluctuations of the proton. Four possible configurations of the gluon field in the proton are shown, where red denotes regions of strong field and blue denotes regions of weak field. The magnitude of the fluctuations between these samples is constrained by the observed coherent and incoherent diffractive J/ψ production cross sections. SOURCE: H. Mäntysaari and B. Schenke, 2016, Evidence of strong proton shape fluctuations from incoherent diffraction, *Phys. Rev. Lett.* 117:052301.

gluon fluctuations in the proton. It was generated using existing data on J/ψ production on the proton. One can observe dramatic fluctuations in the shape of a single proton and that these fluctuations are quite different from what one would expect for a simple bound state of three constituent quarks. This is a far cry from early models of the proton. At low resolution, one expects to see correlations of nucleons in nuclei, and at fine resolution, one will determine fluctuations in the number of valence partons and fluctuations in the color field surrounding these partons. An EIC would be able to explore the power spectrum of fluctuations in nuclei and nucleons in detail and revolutionize the understanding of the emergence of matter from quantum fields of colored quarks and gluons.

# 3

# Role of an EIC Within the Context of Nuclear Physics in the United States and Internationally

## INTRODUCTION

The National Research Council 2010 decadal survey of nuclear physics[1] describes this very broad field as follows:

> Nuclear physics today is a diverse field, encompassing research that spans dimensions from a tiny fraction of the nucleon volume to the enormous scales of astrophysical objects. Its research objectives include the desire not only to better understand the nature of the forces and masses that interact at the nuclear level, but also to describe the primordial matter that existed at the Big Bang, where those nuclear forces dominated interactions, as well as the nature of neutrinos and the liquid state of quarks and gluons that can now be produced in the most advanced colliding-beam accelerators.
>
> The impact of nuclear physics extends well beyond furthering a body of scientific knowledge. Tools developed by nuclear physicists often have application to other sciences: medicine, computational science, and material research, among others. Its discoveries impact astrophysics, particle physics and cosmology. Finally, many of today's major societal problems—energy, climate, national security, and nonproliferation—are addressed with tools, instruments, and techniques obtained from nuclear physics.

This chapter places an electron-ion collider (EIC) in the context of nuclear science, within the United States in particular, and describes the role of an EIC in maintaining U.S. leadership within the global nuclear science community.

[1] National Research Council, 2012, *Nuclear Physics: Exploring the Heart of Matter* (NP2010), The National Academies Press, Washington, D.C.

## U.S. NUCLEAR SCIENCE CONTEXT FOR AN ELECTRON-ION COLLIDER

A central goal of modern nuclear physics is to understand the structure of the proton and the neutron directly from the dynamics of quarks and gluons governed by quantum chromodynamics (QCD) and how nuclear interactions between protons and neutrons emerge from these dynamics. Remarkable advances have been made to date. For example, the interaction of protons and neutrons can be described with an effective field theory using the symmetries of QCD in conjunction with input from experimental measurements. Combined with modern many-body methods, the effective field theory treatment of nuclear forces is the basis of ab initio structure calculations of atomic nuclei. Low-energy properties of protons and neutrons, such as their masses and the strength of their weak interactions, can now be extracted directly from QCD using numerical simulations of lattice QCD (LQCD) theory, discussed in Chapter 6. Advances in accelerator science and technology have made it possible to illuminate the proton and neutron with beams of high-energy electrons. When probed at high energies, the proton and neutron reveal a substructure of quarks, antiquarks, and numerous gluons. High-energy collisions of heavy nuclei have made it possible experimentally to explore the transformation from hadronic matter to quark and gluon matter at densities several times the normal nuclear density or temperatures in excess of 2 trillion degrees Kelvin. Such a quark-gluon plasma is thought to have been the dominant form of matter in the universe shortly after the Big Bang. QCD studies of proton and neutron structure as well as quark-gluon plasma constitute essential pillars of fundamental nuclear physics in the United States, alongside studies of the extremes of nuclear structure, neutrino physics, and fundamental symmetries in nature.

As described in greater detail in Chapter 5, the quark-gluon structure of nucleons and nuclei is being studied using electron scattering at the Thomas Jefferson National Accelerator Facility (JLab), and using polarized proton collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) in the United States. At JLab, the recent upgrade has increased the electron beam energy to 12 GeV. A major focus of the program is to image the valence quark distributions in protons and nuclei. This effort engages many of the questions described in Chapter 2, but with a focus on the valence quark sector of the target nucleon or nucleus. The energy upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) accelerator at JLab enables a program that includes measurements of real photon and meson production as well as semi-inclusive deep inelastic scattering (SIDIS). These experiments will lead to studies of generalized parton distributions, tomographic images of the quark distribution in the proton, and transverse momentum distributions. Spin-polarized electron scattering on polarized protons is an important element of the JLab experimental program, complementing polarized proton-proton scattering experiments at RHIC; the latter have provided evidence for positive gluon polarization in the proton.

A different regime of nuclear physics is explored in heavy ion collisions at RHIC in the United States and the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). These machines probe the properties of the hot quark-gluon plasma, similar to that which existed shortly after the Big Bang until the universe cooled to the point that neutrons and protons were formed. Experiments at RHIC and LHC have revealed that contrary to expectations, the quark-gluon plasma behaves as a nearly perfect fluid—that is, with extremely low viscosity. Understanding the properties and characteristics of the hot, dense QCD matter formed in high-energy heavy ion collisions is currently a major goal of nuclear physics.

An EIC would provide an important bridge between the existing JLab and RHIC programs, and it would connect with the LHC heavy ion program as well. It would deepen the understanding of the QCD structure of nucleons and nuclei by focusing on the crucial role of gluons in generating the mass and spin of the proton, it would determine the distribution of gluons in nuclei with unprecedented accuracy, and it would study the highly occupied state of gluons that is expected to be the initial state for the formation of a quark-gluon plasma. A dedicated theory program, involving both continuum and lattice QCD, would be required to predict and interpret the results. Combined, theory and experiment would lead to first-rate insights into how the observed world emerges from the basic laws of QCD.

In addition, the 12 GeV JLab program will investigate the spectroscopy of exotic hadrons—QCD bound states that cannot be interpreted as simple three-quark or quark-antiquark states. QCD allows for new kinds of exotic hadrons, the first of which has recently been discovered at the LHC. “Glueballs” are states that have thus far not been observed and are, to a good approximation, composed of only gluons. If they exist, these states could probe the unique nature of the gluon as a force carrier that can interact with itself. Another example, the so-called hybrid mesons are hypothesized quark-antiquark states that have nontrivial gluonic components—that is, gluon admixtures that modify the quantum numbers of the quark-antiquark pair. Study of such configurations of gluons could foreshadow interesting states of gluons that may be possible to study at an EIC.

Nuclear physics also includes high-priority programs in neutrino physics and fundamental symmetries. Neutrinos are messengers from hot and dense environments like the solar interior, type II supernova explosions, and cooling neutron stars. In a supernova explosion, most of the energy is carried in neutrinos, and neutrino scattering is an integral part of the dynamics of a supernova explosion. Neutrinos also provide an important window into fundamental symmetries and possible extensions of the Standard Model of particle physics. One central question is whether the neutrino is its own antiparticle, which would imply that neutrinos would violate lepton number conservation. Evidence for lepton number violation is being sought in neutrinoless double beta decay experiments, and nuclear physicists are actively working toward a ton-scale detector of such processes. Electron accelerators have also made important contributions to the study of fundamental symmetries. JLab studies parity-violating electron scattering, and a series of past and planned experiments, Q-WEAK, Measurement of Lepton Lepton Elastic Reactions, and Solenoidal Large Intensity Device, study the evolution of the fundamental electroweak coupling, and search for physics beyond the Standard Model. An EIC would naturally extend this program, studying fundamental symmetries at higher energies.

Complementary to research efforts in QCD, neutrinos, and fundamental symmetries, understanding the extremes of nuclear structure is currently a major focus of study worldwide, and world-leading new capabilities will be made available at the Facility for Rare Isotope Beams (FRIB) at Michigan State University. This facility will explore nuclei at the limits of stability in terms of the number of protons and neutrons that can be added to the known isotopes. Very neutron rich nuclei are important for the formation of heavy elements in the universe and inform an understanding of the matter that is expected to exist in the outer layers of neutron stars. In the interior of neutron stars, gravity compresses nuclear matter to densities beyond those that occur in nuclei. In this regime, one expects a change in degrees of freedom with increasing density from nucleonic to deconfined quark matter in the interior, with possible Bose condensates of mesons playing a role.

## U.S. LEADERSHIP IN NUCLEAR SCIENCE

Nuclear physics in the United States is a substantial field of physical science. The Division of Nuclear Physics of the American Physical Society (APS) has a membership in excess of 2,500, which accounts for over 5 percent of the total APS membership across all physical sciences. In the United States, about 90 universities produce about 115 Ph.D.s per year[2] (see Chapter 6 for the societal impact of U.S. nuclear physics Ph.D. production) in the four experimental research focus areas of hadronic physics, heavy ion physics, nuclear structure and astrophysics, and fundamental symmetries and neutrinos. With CEBAF at JLab and RHIC at BNL offering unique, world-class facilities in hadronic physics and heavy ion physics, nuclear physics in the United States over the past several decades has provided strong scientific leadership internationally. FRIB, under construction at Michigan State University, will enhance U.S. leadership in nuclear structure physics for the

[2] *Implementing the 2007 Long Range Plan*, Report to NSAC by the Subcommittee, R. Tribble, chair, January 31, 2013.

next several decades. An EIC is vital as a next-generation facility beyond CEBAF and RHIC to maintain U.S. leadership in QCD.

U.S. strength in nuclear physics lies not only in its experimental programs enabled by world-class facilities but also in the caliber of its nuclear theory research. For example, the theoretical prediction of the necessary conditions to observe the quark-gluon plasma was essential to its discovery at RHIC. The gluon momentum and polarization distributions in the proton cannot be extracted from lepton scattering data without the QCD theoretical framework. Nuclear theory has played an essential role in developing and defining the EIC science program, described in Chapter 2. For example, the concepts of the color glass condensate and generalized parton distributions were respectively invented and co-invented by U.S. nuclear theorists. These now have become part of the universal language to describe high-energy lepton scattering from hadrons and are essential to defining the most important experiments at an EIC.

The U.S. QCD community, from both experimental and theoretical perspectives, has carefully considered the scientific opportunities that would be made possible with new facilities in a series of meetings and discussions that have extended over almost two decades.[3,4,5,6,7,8,9] This culminated in the Nuclear Science Advisory Committee (NSAC) 2015 Long Range Plan for U.S. Nuclear Science,[10] where a high-luminosity, polarized EIC was recommended as the top priority for new construction after the completion of FRIB. An EIC is universally accepted as the essential next-generation facility to explore the high-energy structure of nuclei, to image for the first time the gluons and sea quarks in hadronic matter and to complete the understanding of nuclear matter in terms of the fundamental quarks and gluons of QCD. The realization of an EIC would unify the U.S. QCD community, which at present is two distinct research communities studying hadronic physics and heavy ion physics. The U.S. QCD community amounts to about half of the field of nuclear physics in the United States. About 80 percent of U.S. uni-

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[3] *EPIC '99 Workshop*, April 8-11, 1999, IUCF, Bloomington, Ind.

[4] *Physics with an Electron Polarized Light-Ion Collider*, MIT, September 14-15, 2000, AIP Conference Proceedings No. 588, Ed. R. Milner.

[5] *Opportunities in Nuclear Science*, 2002 DOE/NSF Long Range Plan for U.S. Nuclear Science.

[6] A. Deshpande, R. Milner, R. Venugopalan, and W. Vogelsang, 2005, *Ann. Rev. Nucl. and Part. Sc.* 55:165.

[7] *The Frontiers of Nuclear Science*, 2007 DOE/NSF Long Range Plan for U.S. Nuclear Science.

[8] D. Boer, M. Diehl, R. Milner, R. Venugopalan, and W. Vogelsang, 2011, *Gluons and the Quark Sea at High Energies: Distributions, Polarizations, Tomography*, Report on the Joint BNL/INT/JLab Program on the Science Case for an Electron-Ion Collider, September 13 to November 19, 2010, Institute of Nuclear Theory, University of Washington, Seattle.

[9] A. Accardi et al., 2016, Electron-ion collider: The next QCD frontier, *Eur. Phys. J. A* 52:238.

[10] *Reaching for the Horizon*, 2015 DOE/NSF Long Range Plan for U.S. Nuclear Science.

**BOX 3.1**
**The Electron-Ion Collider User Group**

The EIC User Group was officially formed in 2016 to coordinate the activities of the scientific community interested in the realization of a U.S.-based EIC. As of December 2017, it comprises more than 700 Ph.D. scientists from 168 institutions in 29 countries on 6 continents. Thirty-nine percent of the members are from institutions outside the United States, reflecting very strong interest among the international community. The EIC User Group performs the following functions:

- Continues to enhance and refine the science case beyond that contained in the EIC white paper written for the 2015 U.S. Nuclear Physics Long Range Plan;[1]
- Provides a forum for discussion and promotes collaboration across the accelerator, experimental, and theoretical communities to enhance progress toward realization of an EIC;
- Represents the interests of EIC users in discussions with the laboratories and the funding agencies;
- Represents the EIC users in discussion of scientific trade-offs that may be imposed by budget realities; and
- Organizes outreach to physicists, scientists, policy makers, and the general public about an EIC facility and its physics program.

A steering committee, with members elected by institutional representatives and one member each appointed by the Thomas Jefferson National Accelerator Facility (JLab) and Brookhaven National Laboratory, coordinates the efforts of the EIC User Group. The steering committee also serves as an initial point of contact for new groups and individuals with interest in participating in an EIC or for anyone seeking further information about an EIC and its physics program. The steering committee is furthermore responsible for the organization of working groups of EIC User Group members with similar interests in the areas of physics, detector research and development (R&D), accelerator R&D, and outreach.

[1] *Reaching for the Horizon*, 2015 DOE/NSF Long Range Plan for U.S. Nuclear Science.

versities in nuclear physics produce Ph.D.s in these areas.[11] The realization of an EIC is absolutely crucial to maintaining the health of the field of nuclear physics in the United States.

A 2004 report[12] on a study of education in nuclear science recommended that "the nuclear science community work to increase the number of new Ph.D.'s in nuclear science by approximately 20 percent over the next five to ten years." In

[11] *Assessment of Workforce Development Needs in the Office of Nuclear Physics Research Disciplines*, Report to NSAC from the Subcommittee on Workforce Development, J. Cizewski (Chair), July 18, 2014.

[12] *Education in Nuclear Science*, Report to NSAC from the Subcommittee on Education, J. Cerny (Chair), November 2004.

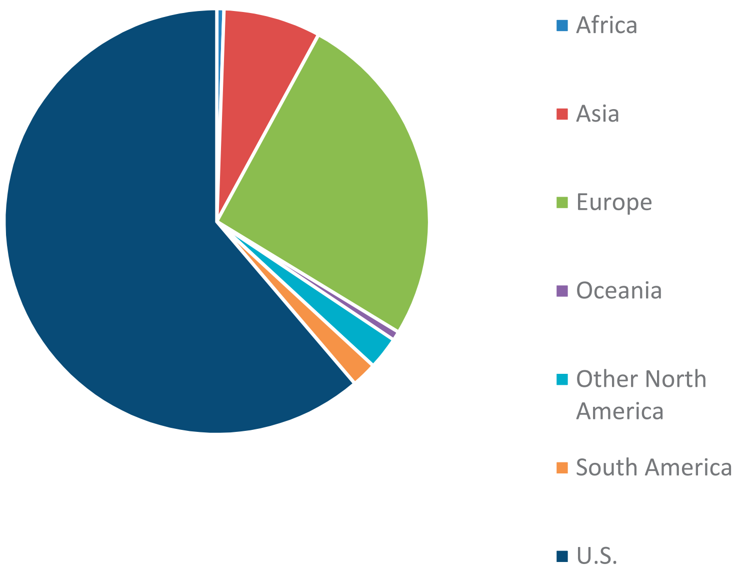


**FIGURE 3.1.1** Geographical distribution of the EIC User Group membership. SOURCE: Christine Aidala.

part, this recommendation was motivated by the national security need for technical expertise in the areas of stockpile stewardship and nonproliferation. However, the annual number of new Ph.D.s in nuclear physics in the United States has been approximately constant in time since then. The most recent assessment,[13] in 2014, reports that there is a substantial increase in the percentage of Nuclear Physics Early Career Awards to individuals who received their Ph.D.s outside the United States. In addition, an increasingly large fraction of nuclear science faculty members

[13] *Assessment of Workforce Development Needs in the Office of Nuclear Physics Research Disciplines*, Report to NSAC from the Subcommittee on Workforce Development, J. Cizewski (Chair), July 18, 2014.

has received Ph.D.s from non-U.S. institutions. Furthermore, the 2014 assessment specifically identifies workforce challenges in the areas of accelerator science and high-performance computing. See Chapter 6 for further discussion of the nuclear physics workforce.

U.S. nuclear physics user facilities are strong attractors to the global nuclear science community because of their unique and powerful capabilities. A significant fraction of the international QCD community is currently performing research in the United States at JLab and RHIC, with 36 percent of JLab users and 42 percent of RHIC users from institutions outside the United States. Chapter 5 describes international facilities where QCD research is performed, including the heavy ion program at the LHC at CERN, the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) hadronic physics experiment also at CERN, as well as the future Facility for Antiproton and Ion Research (FAIR) in Europe and the Nuclotron-Based Ion Collider Facility (NICA) in Russia. FAIR and NICA will study hadronic collisions at lower energies than the range currently available at RHIC or planned for an EIC. Although EIC concepts at the High Intensity Heavy-Ion Accelerator Facility (HIAF) in China and at CERN in Europe have been discussed, there are currently no plans to build a machine outside the United States. The existing infrastructure at CERN, and elsewhere, could not be easily adapted for the construction of a polarized EIC, and resources are committed to other projects and facilities with different physics goals. These aspects will be discussed in detail in Chapter 5.

There is in fact already well-defined international interest in a U.S.-based EIC. Following the 2015 long-range planning exercise, the EIC Users Group was formed. Currently, 39 percent of the EIC User Group members are from institutions outside the United States, with total User Group membership presently consisting of more than 700 Ph.D. scientists (see Box 3.1). Multiple international groups are already participating in the EIC Generic Detector R&D program. Furthermore, in Europe, the Nuclear Physics European Collaboration Committee (NuPECC) of the European Science Foundation recently published its 2017 Long Range Plan,[14] which expresses explicit interest in a U.S.-based EIC: "NuPECC highly recognizes the science of the EIC project, presently under study, representing an opportunity for a major step forward in the field of hadron physics."

[14] European Science Foundation, 2017 *Perspectives in Nuclear Physics*, NuPeCC 2017 Long Range Plan, http://www.nupecc.org/lrp2016/Documents/lrp2017.pdf.

# 4

# Accelerator Science, Technology, and Detectors Needed for a U.S.-Based Electron-Ion Collider

## INTRODUCTION

In order to definitively answer the compelling scientific questions elaborated in Chapter 2, including the origin of the mass and spin of the nucleon and probing the role of gluons in nuclei, a new accelerator facility is required, an electron-ion collider (EIC) with unprecedented capabilities beyond previous electron scattering programs. An EIC must enable the following:

- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times higher than the earlier electron-proton collider Hadron-Electron Ring Accelerator (HERA) at Deutsches Elektronen-Synchrotron (DESY), to allow unprecedented three-dimensional (3D) imaging of the gluon and sea quark distributions in nucleons and nuclei.
- Spin-polarized (~70 percent at a minimum) electron and proton/light-ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin. Polarized colliding beams have been achieved before only at HERA (with electrons and positrons only) and Relativistic Heavy Ion Collider (RHIC; with protons only).

- One or more interaction regions, which integrate the detectors into the collider and preserve the extensive kinematic coverage for measurements.

In addition, modern particle detector systems will be essential for an EIC. Generic research and design efforts are under way on novel ideas, including compact calorimetry and various tracking and particle identification detectors.

The EIC accelerator requirements are by and large beyond the limits of current technology and their realization requires significant research and development (R&D). Indeed, an important element of the scientific justification for a U.S. electron-ion facility is that it drives advances in accelerator science and technology, which in turn will benefit other fields of accelerator-based science and society.

The three primary areas that require significant accelerator science and technology R&D are energy, luminosity, and polarization. The extensive energy variability and elaborate interaction region of an EIC require advanced superconducting magnet designs beyond state of the art. To attain the highest luminosities demanded by the science, cooling of the hadron beam is essential. Novel beam cooling techniques are under development. Energy recovery linacs (ERLs), a special type of recirculating linac, presently offer the *only* credible concept for electron cooling of high-energy, colliding beams. To optimize the overlap of the colliding beams at the interaction point, specialized superconducting radio-frequency (SRF) cavities rotate the beams as they collide. Polarized beams require polarized particle sources beyond the state of the art, special magnets, and a further level of mastery of beam physics to preserve the polarization through the acceleration process to the collisions.

Two conceptual designs for an EIC facility have evolved in the United States, each of which proposes using infrastructure already available to the U.S. nuclear science community. One, eRHIC, is based on the RHIC ion complex at Brookhaven National Laboratory (BNL); and the other, Jefferson Laboratory Electron Ion Collider (JLEIC), uses the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLab) as a full-energy electron injector. In order to motivate the accelerator science, technology, and detector R&D required for the realization of a U.S.-based EIC, the sections below provide a description of the two conceptual designs of an EIC.

## DESCRIPTION OF BNL AND JLAB ACCELERATOR CONCEPTS

### The eRHIC Conceptual Design

The proposal for an EIC to be built at BNL already has a long history during which several variants of the design have been explored in depth. All have been based on reutilization of the existing RHIC facility as the hadron accelerator, thereby leveraging a substantial past investment. RHIC is one of only two hadron colliders in the world and is now the only collider of any kind operating in the United States. Since its start-up in 1999, it has proved to be a remarkably flexible collider of heavy and light ions as well as polarized protons (discussed further in Chapter 5).

The present eRHIC proposal would add a high-intensity 5-18 GeV electron storage ring in the RHIC tunnel to collide electrons with the protons (up to 275 GeV—compared with the 255 GeV currently used in experiment) and ions (up to 100 GeV per nucleon) in one of the two existing RHIC rings, as shown in Figure 4.1. This design considerably reduces the technical risk that was associated with the previous linac-ring concept (see Box 4.1). The luminosity achievable in this way is sufficient to pursue an important set of EIC physics goals (see Figure 4.2). However, the full luminosity goals of eRHIC require the implementation of a radically new hadron cooling technology, discussed further below.

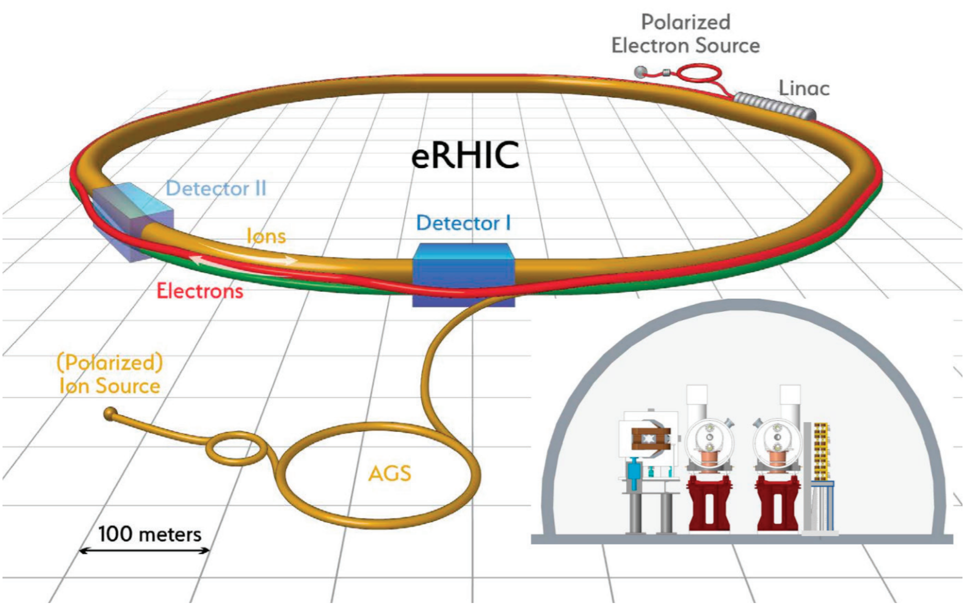


**FIGURE 4.1** Schematic layout of eRHIC, showing the existing hadron injector complex (ion source, alternating gradient synchrotron [AGS], etc.) and Relativistic Heavy Ion Collider (RHIC) tunnel containing two superconducting hadron rings. The addition of a polarized electron source, full-energy injector linac and high-energy electron ring in the same RHIC tunnel opens up the possibility of polarized electron-hadron collisions. SOURCE: C. Montag et al., 2017, "Overview of the eRHIC Ring-Ring Design," IPAC.

**BOX 4.1**
**The Linac-Ring Alternative**

An alternative linac-ring design for eRHIC (see Figure 4.1.1) utilizes a new facility based on an energy recovery linac (ERL) with fixed-field alternating gradient accelerator arcs to be built inside the Relativistic Heavy Ion Collider (RHIC) tunnel. This would accelerate electron beams and collide them with RHIC's existing high-energy polarized proton and nuclear beams. A fixed-field alternating gradient is a circular *accelerator* concept that can be characterized by time-independent magnetic fields ("fixed-field") and the use of *strong focusing* ("alternating gradient"). The CBETA[1] project will serve as prototype of the fixed-field alternating gradient-ERL concept. The design incorporates several highly innovative concepts and could achieve higher performance at lower cost. However, it requires a polarized electron gun with flux far beyond (by a factor about 50) the present state of the art. Research and development progress toward this goal is not fast enough for it to be the basis of a proposal. In addition, in order to reach the required luminosity, the ERL must be capable of accelerating an unprecedented average beam current of about 500 mA, which presents a number of other challenges, including the superconducting radio frequency systems and interaction region design.[2]

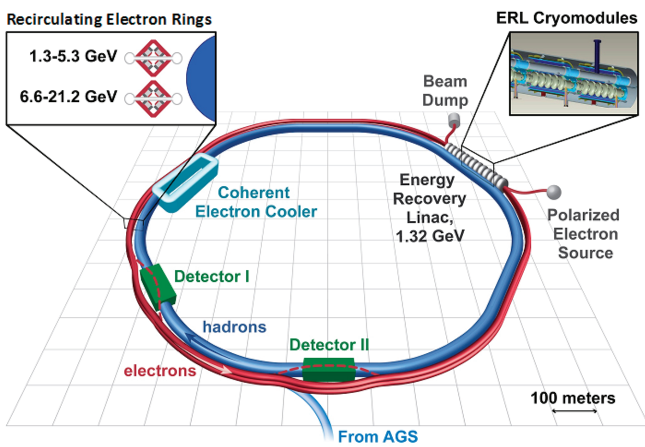


**FIGURE 4.1.1** Schematic of the linac-ring concept of eRHIC at Brookhaven National Laboratory, which would require construction of an electron beam facility (red) to collide with the Relativistic Heavy Ion Collider blue beam at up to three interaction points. NOTE: AGS, alternating gradient synchrotron. SOURCE: Brookhaven National Laboratory.

1 CBETA—Cornell University Brookhaven National Laboratory Electron Energy Recovery Test Accelerator, in *Proceedings of IPAC 2017*, Copenhagen, Denmark, TUOCB3, http://accelconf.web.cern.ch/AccelConf/ipac2017/papers/tuocb3.pdf. See also Chapter 6.

2 Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics, February 13, 2017.

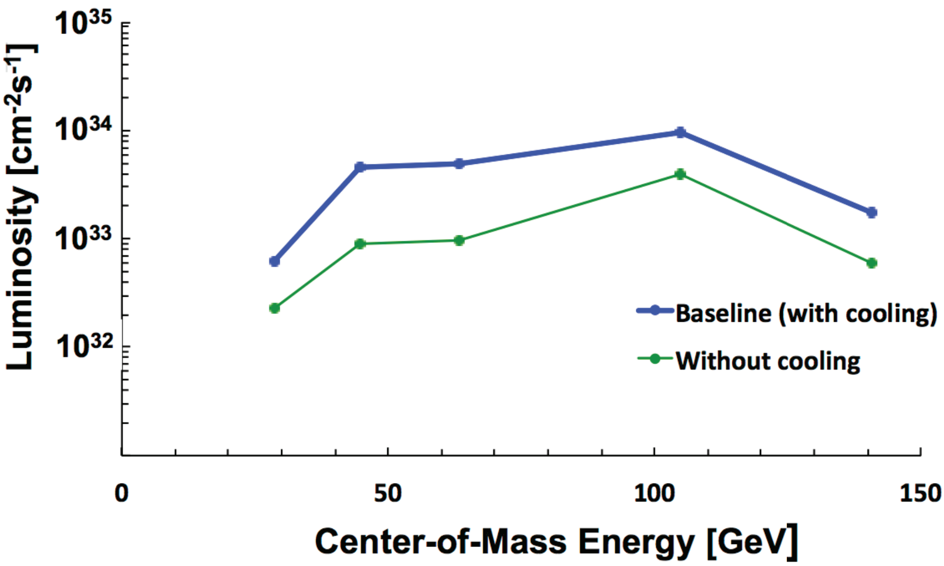


**FIGURE 4.2** eRHIC luminosity versus center-of-mass energy for the baseline case with hadron cooling and without hadron cooling. The strength of the hadron cooling in the baseline is chosen just to reach $10^{34}$ $cm^{-2}s^{-1}$ maximum luminosity. SOURCE: V. Ptitsyn, 2017, "Progress in eRHIC Design," EIC Collaboration Meeting, Brookhaven National Laboratory, October.

*Energy*

Electrons and ions or protons are collided at the effective electron-nucleon center-of-mass energy $\sqrt{s_{eN}} = 2\sqrt{E_e E_N}$, where $E_e$ is the electron energy and $E_N$ is the energy of a proton beam or the energy per nucleon of an ion beam. With electron energies of 5-18 GeV, protons of 41-275 GeV, and ions of up to 100 GeV per nucleon, a wide range of $\sqrt{s_{eN}}$, from 30-140 GeV (for ep) and up to 100 GeV (eA) is accessible. The Electron Beam Ionization Source (EBIS) and injector complex of RHIC can supply a broad range of heavy and light species.

*Luminosity*

High luminosity is achieved by colliding many high-intensity bunches of particles. It is further increased by reducing the beam sizes as much as possible at the collision point by focusing the beams very strongly. This is limited by the "emittance," or intrinsic phase space volume (in real space and momentum space) occupied by the particle distribution. The electron beam emittance is essentially determined by synchrotron radiation in the bending and focusing magnets of the

**TABLE 4.1** Main Parameters of eRHIC for Collisions of Protons, at Their Maximum Energy of 275 GeV, with 10 GeV Electrons

| Parameter | Units | No Hadron Cooling | | Strong Hadron Cooling | |
|---|---|---|---|---|---|
| Particle | | Protons | Electrons | Protons | Electrons |
| Center-of-mass energy | Gev | 105 | | 105 | |
| Beam energy | Gev | 275 | 10 | 275 | 10 |
| Collision frequency | MHz | 56.3 | | 112.6 | |
| Particles/bunch | $10^{10}$ | 10.5 | 30 | 6 | 15.1 |
| Beam current | A | 0.87 | 2.5 | 0.99 | 2.5 |
| Bunch length, RMS | cm | 7 | 1.9 | 5 | 1.9 |
| Emittance norm (x,y) | μm | 4.1/2.50 | 391/87.1 | 2.7/0.36 | 391/19.0 |
| Luminosity / IP | $10^{34}$ cm$^{-2}$s$^{-1}$ | 0.44 | | 1.02 | |

NOTE: Two sets of parameters are given, indicating the maximum luminosity performance achievable with and without strong hadron beam cooling. RMS, root mean square.
SOURCE: F. Willeke, "eRHIC Overview," Design Choice Validation Review, April 5-6, 2017.

electron ring. The hadron beam emittance is determined in the injection system but can be influenced by a cooling system.

The electron ring is designed to store beam currents up to 2.5A in 1,320 bunches per ring, a performance similar to B-factories. With the hadron emittance and density provided by the injectors, the eRHIC design should achieve a peak e-p luminosity of $4.4 \times 10^{33}$ cm$^{-2}$s$^{-1}$. Strong hadron beam cooling would boost this by a factor of approximately 2.5 to achieve the peak luminosity of $1.02 \times 10^{34}$ cm$^{-2}$s$^{-1}$ for which the eRHIC facility is designed. Beam parameters for these two conditions are given in Table 4.1.

Besides the collisions with other ion species, the collider is flexible enough to provide a range of different operational conditions. For example, the study of Deeply Virtual Compton Scattering (Chapter 2) requires limiting the proton momentum and proton beam divergence, or angular spread, to less than 1 percent of the beam momentum. Because strongly focused beams have high divergence, this leads to alternative "high acceptance" parameter sets with reduced luminosity that would allow the detection of protons with low transverse momenta.[1,2]

[1] C. Montag et al., 2017, Overview of the eRHIC ring-ring design, in *Proceedings of IPAC 2017*, Copenhagen, Denmark, WEPIK049, http://accelconf.web.cern.ch/AccelConf/ipac2017/papers/wepik049.pdf.

[2] R.B. Palmer and C. Montag, 2017, Parameters for eRHIC, in *Proceedings of IPAC 2017*, Copenhagen, Denmark WEPIK049, http://accelconf.web.cern.ch/AccelConf/ipac2017/papers/wepik050.pdf.

*Electron Ring*

The new electron ring to be installed in the RHIC tunnel would be composed of focusing and defocusing quadrupole magnet cells, except in the two experimental straight sections. While their focusing structure is quite conventional, their bending magnets are not; these "superbends" are designed as a sequence of three magnets with a strong central pole. While each magnet bends in the same direction at high energy, the central pole is reversed at lower energies, introducing a scalloped form of the orbit. The purpose of this is to increase the energy lost by synchrotron radiation to a value defined by a trade-off between the operational cost and the beneficial effect of increasing the radiative damping of the particle oscillations. The radiation damping makes electron bunches more immune to disruption by the beam-beam interaction when they collide with the hadrons. This boosts the luminosity that can be achieved at lower energies.

*Hadron Ring*

The hadron ring consists essentially of the main superconducting magnets of one of the two existing RHIC rings. However, it must be modified to cope with a much larger number of particle bunches (a factor 10 more than the present 120 in RHIC).

New injection kickers with a 30 ns rise time and a new injection transfer line arrangement will be needed. The high beam current would induce an unacceptable heat load on the stainless steel beam pipe. To counter this, BNL is developing technologies for in situ coating the pipe with copper, and then amorphous carbon, to reduce the secondary electron yield.

*Interaction Region*

The design of an interaction region that must focus, collide, and separate beams of quite different momenta is necessarily complex. Figure 4.3 gives an impression of the solution adopted for eRHIC. The bunches of the two beams are collided at an angle of 22 mrad (about 1.25 degrees), which would result in reduced overlap and luminosity. This is avoided by rotating both beams to achieve full overlap using "crab cavities" in the interaction region. These are a special design of SRF cavities, which deflect, rather than accelerate, the beam.

The cold masses of the focusing quadrupoles for the two beams are arranged in an interleaved pattern. Special designs are required to shield the electron beam from the stray field of the hadron quadrupoles. There are numerous other features and constraints on the design of the interaction region that are not discussed here.

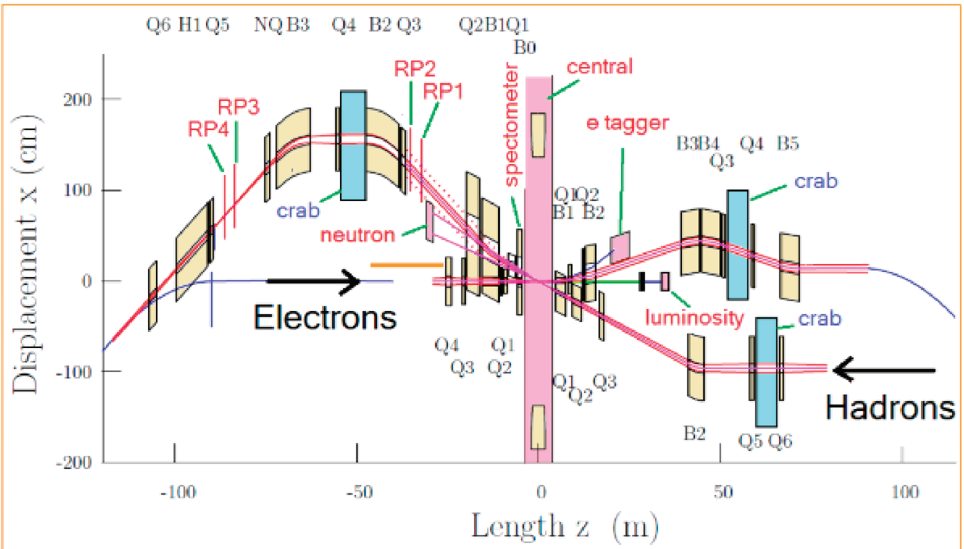


**FIGURE 4.3** Schematic layout of the eRHIC interaction region in the horizontal plane, showing the orbits and interleaved electron and hadron focusing quadrupoles (Q1 through Q6), the crab cavities, and luminosity-related instrumentation. Note the very different scales in the longitudinal and horizontal directions. SOURCE: C. Montag et al., 2017, "Overview of the eRHIC Ring-Ring Design," IPAC.

*Radio Frequency Systems*

At a maximum energy of 18 GeV, the eRHIC electron ring would require 41 MV of peak circumferential voltage to compensate synchrotron radiation losses and ensure adequate beam lifetime. Considerations of cost, space, and mitigation of the unwanted higher order mode power have led to the selection of a 563 MHz 2-cell cavity for the electron ring radio frequency (RF) system. Thirty-six cells are required to compensate for the losses at peak energy. The overall power provided to the electron beams is limited administratively to 10 MW.

In the hadron ring, the present 197 MHz RF system will be replaced by a higher frequency system to shorten the hadron bunch length to a scale comparable to the eRHIC vertical beam size at the interaction point (IP), thus avoiding luminosity reduction caused by the so-called "hourglass effect." In the inner part of the interaction region, the vertical beam size grows parabolically with distance away from the interaction point. In order to keep both colliding beams within the tightly focused area near the IP, thus maximizing the contribution to luminosity, the hadron bunch length has to be as short as possible. For this purpose 563 MHz cavities, the same frequency as the electron storage ring cavities, are being considered. The 336 MHz crab cavities should provide about 10 MV to the hadron beam.

*Polarization*

RHIC has already operated with great success as a polarized proton collider (see Chapter 5). The eRHIC physics program further requires polarized electrons with the possibility of opposite polarization directions from bunch to bunch. This can be achieved only with a full-energy polarized electron injector. Once the electron bunches are stored, their polarization evolves due to a spin-flip component of synchrotron radiation toward an equilibrium state direction that is opposite to the main bending field. This radiative self-polarization mechanism[3] deteriorates the polarization of those electron bunches that are initially oriented along the bending field on a time scale ranging from a few tens of minutes to a few hours, depending on the beam energy and magnetic field. Additionally, spin diffusion due to synchrotron radiation may enhance the polarization decay, especially near energies corresponding to specific resonance conditions between the spin precession and orbital oscillations. In order to maintain an adequate average polarization, the bunches must be replaced with fresh ones at a maximum rate of one bunch per second.

*Electron Injector*

A polarized source and recirculating electron linac could meet the eRHIC electron injector requirements. However, a more economical solution is under study. A rapid-cycling synchrotron could be installed in the RHIC tunnel. A recently invented special optics configuration could be used to preserve the polarization through the acceleration process.

## The JLEIC Conceptual Design

JLEIC is JLab's proposal for an EIC. It is the culmination of long and in-depth study of collider designs that would take full advantage of the existing electron accelerator facility—in particular, its recent upgrade to 12 GeV. It is a ring-ring collider designed to deliver high luminosity up to $10^{34}$ $cm^{-2}s^{-1}$ per interaction

[3] Radiative self-polarization, often associated with the names of Sokolov and Ternov, is a mechanism by which the polarization of a beam builds up through a subtle interplay of orbital motion and spin precessions. The physics is lucidly discussed in J.D. Jackson, 1976, On understanding spin-flip synchrotron radiation and the transverse polarization of electrons in storage rings, *Rev. Mod. Phys.* 48:417.

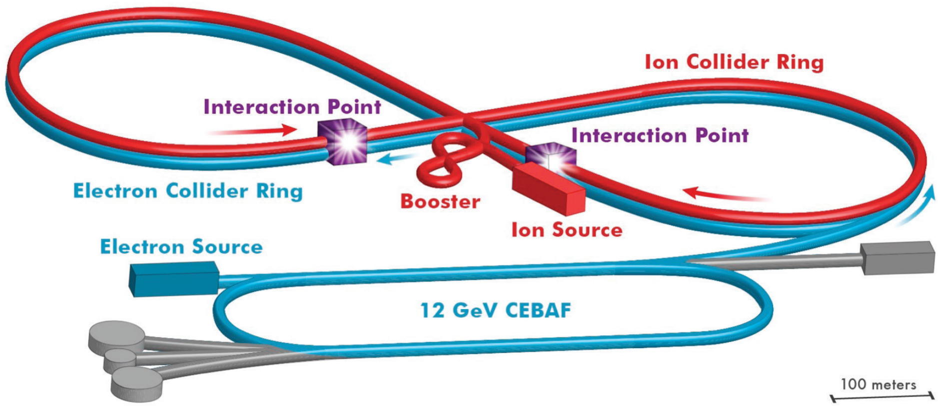


**FIGURE 4.4** Schematic layout of the Jefferson Laboratory EIC design. SOURCE: Thomas Jefferson National Accelerator Facility.

region over a broad center-of-mass energy range, high polarization in excess of 80 percent for both electron and light ion beams, and full detection acceptance and forward tagging.

The JLEIC baseline concept is illustrated in Figure 4.4. The central part of the facility is a set of two figure-8 shape collider rings, one for electrons and one for ions. The CEBAF SRF linac is a full-energy injector to the electron collider ring, which will store an electron beam of 3 to 10 GeV energy. The maximum stored electron current is 3 A. The new ion complex includes an ion injector (sources, a SRF linac, and a figure-8 booster) and an ion collider ring. The stored ion beam current is up to 0.75 A. The two collider rings are stacked vertically and housed in the same underground tunnel. They are about 2.2 km in circumference and fit in the JLab site.

*Energy*

The electron-nucleon center-of-mass energy, $\sqrt{s_{eN}}$ , of JLEIC is 15 to 65 GeV achieved by the following energy ranges of the colliding beams: from 3 to 10 GeV for electrons, from 20 to 100 GeV for protons, and up to 40 GeV per nucleon for ions. A center-of-mass energy of 100 GeV can be achieved by increasing the proton energy to 200 GeV (ion ring arc dipole field from 3 T to 6 T) and by taking full advantage of the 12 GeV CEBAF energy.

*Luminosity Concept*

While the key to high luminosity in JLEIC is high bunch repetition rate of the colliding beams, the JLEIC high-luminosity strategy is based on multiple factors, as follows:

- Ultra-high collision frequency;
- Very short bunches and very small transverse emittance for both electron and ion beams;
- Multistage electron cooling to achieve appropriate ion emittances;
- Very strong final focusing (very small beam size) at the interaction point;
- Large attainable beam-beam tune shift; and
- Large (50 mrad) crossing angle and crab crossing of colliding beams.

Specifically, both the electron and ion beams have very short bunch lengths and small transverse emittances to enable strong final focusing to reduce the beam spot sizes of a few micrometers (a micrometer is equal to $1 \times 10^{-6}$ m) at the collision point. This configuration, combined with a high bunch repetition rate, boosts the collider luminosity. A high bunch repetition rate enables a modest bunch charge to be used, allowing for relatively weak collective and intra-beam[4] scattering effects, particularly in the ion beams, while maintaining high beam current to provide high luminosity. This luminosity concept has been validated at today's lepton colliders such as the B-factories, which achieve luminosities above $10^{34}$ $cm^{-2}s^{-1}$.

An essential element of the JLEIC luminosity concept is electron cooling for reducing the ion beam emittance. To achieve the required high efficiency, JLEIC adopts a multi-phased cooling scheme, which utilizes two electron coolers, a magnetized DC cooler in the booster synchrotron, and a magnetized bunched-beam cooler based on an ERL for the collider ring.

*Polarization*

CEBAF is a fully polarized electron injector, and the polarization in the electron ring can be preserved by appropriate spin matching. A set of spin rotators with energy-independent geometry aligns the electron spins in the required longitudinal direction at the collision points and in the vertical direction in the arcs. The spin dynamics is entirely symmetric for oppositely polarized bunches. For energies above 7 GeV, the depolarization time of the JLEIC electron collider ring is very short, in the range of approximately 2 hours to 20 minutes (at 10 GeV). In order to

[4] Intra-beam scattering (IBS) refers to the effect of multiple small deflections of particles encountering each other within the beams, leading to a growth of the beam size and reduction of luminosity.

maintain high polarization (above 80 percent), the present JLEIC baseline utilizes a scheme of continuous injection of very low current (a few nA) electron beam with high polarization from the CEBAF linac to replace the electron bunches with the most degraded polarization already in the collider ring. This scheme is called "top-off" injection.

Achieving high polarization in the ion ring requires state-of-the-art polarized ion sources. In addition, the polarization must be preserved during acceleration. JLEIC uses a figure-8 layout for the booster and collider rings, in which spin precessions in the left and right half-rings are canceled, resulting in zero spin precession, effectively eliminating crossing of spin resonances during energy ramping. Moreover, only weak magnetic fields are necessary for spin control and manipulation, making possible colliding polarized deuterons.

*Magnets and RF System*

The bunch repetition rate of the JLEIC stored beams is 476 MHz, driven by the plan to reuse PEP-II warm RF cavities and RF stations for the electron collider ring. A conceptual scheme has been developed for injecting the electron bunches from the CEBAF SRF linac (which has a frequency of 1.497 GHz) into the collider ring. All new RF cavities and RF stations required for the ion collider ring will have a frequency of 952 MHz, thereby enabling cost effective future improvements in luminosity and energy. The designs of the booster and collider rings are based on super-ferric magnet technology, which offers substantial savings in capital and operating costs, but requires R&D, as elaborated below.

*Interaction Region*

The design of the JLEIC interaction region is aimed at achieving high luminosity in an integrated full-acceptance detector. The current JLEIC detector design requires a magnet-free space of 7 m for the ion beam on the downstream side, and after optimization, only 3.6 m on the upstream side. For the electron beam, the first final focusing elements are permanent magnets which, thanks to their small sizes, can be placed inside the main detector and very close to the interaction point. In the JLEIC design the beams collide at an angle to avoid all parasitic collisions. A local compensation scheme based on SRF crab cavities is utilized to restore head-on collisions thus recovering the loss of luminosity caused by the crossing angle. A relatively large crossing angle also enhances the detection of reacting particles. The interaction region (IR) design uses a combined local and global compensation scheme to control the chromatic aberrations.

**TABLE 4.2** Main Parameters of the Jefferson Laboratory Electron-Ion Collider for Collisions of Protons with Electrons for a Full Acceptance Detector

| Parameter | Units | Low Center-of-Mass Energy | | Medium Center-of-Mass Energy | | High Center-of-Mass Energy | |
|---|---|---|---|---|---|---|---|
| Particle | | Protons | Electrons | Protons | Electrons | Protons | Electrons |
| Center-of-mass energy | Gev | 21.9 | | 44.7 | | 63.3 | |
| Beam energy | Gev | 40 | 3 | 100 | 5 | 100 | 10 |
| Collision frequency | MHz | 476 | | 476 | | 476/4=119 | |
| Particles/bunch | $10^{10}$ | 0.98 | 3.7 | 0.98 | 3.7 | 3.9 | 3.9 |
| Beam current | A | 0.75 | 2.8 | 0.75 | 2.8 | 0.75 | 0.71 |
| Bunch length, RMS | cm | 3 | 1 | 1 | 1 | 2.2 | 1 |
| Emittance norm (x,y) | μm | 0.3/0.3 | 24/24 | 0.5/0.1 | 54/10.8 | 0.9/0.18 | 432/86 |
| Luminosity / IP | $10^{34}$ $cm^{-2}s^{-1}$ | 0.25 | | 2.14 | | 0.59 | |

NOTE: Three sets of parameters are given at different center-of-mass energies. RMS, root mean square.
SOURCE: Yuhong Zhang, talk at EIC Collaboration meeting, October 2017, Brookhaven National Lab, Upton, N.Y., https://indico.bnl.gov/getFile.py/access?contribId=2&sessionId=0&resId=0&materialId=slides&confId=3492, accessed August 13, 2018.

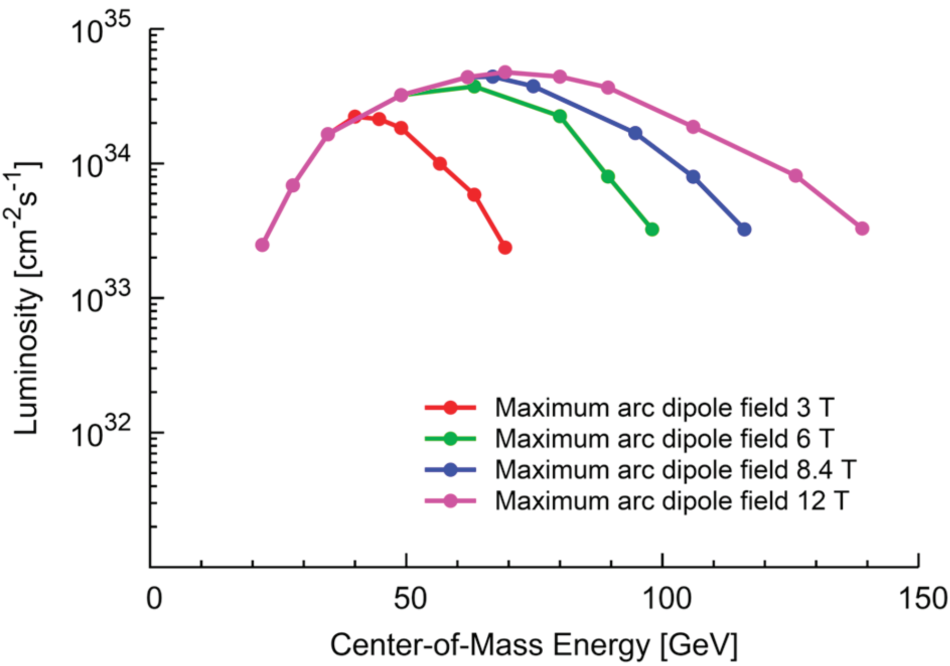


**FIGURE 4.5** Jefferson Laboratory Electron Ion Collider (JLEIC) e-p luminosity as a function of center-of-mass energy with the 3 T hadron arc magnets currently under development (red curve and the parameter sets in Table 4.2). The other curves show the potential of magnets with still higher fields. SOURCE: Y. Zhang, 2017, "Progress in JLEIC Design," EIC Accelerator Collaboration Meeting, Brookhaven National Laboratory, October.

### *JLEIC Parameters and Performance*

The JLEIC main design parameters are summarized in Table 4.2, and the luminosity performance for e-p collision is shown in Figure 4.5. The figure also shows the potential of a future energy upgrade by replacing the 3 T super-ferric magnets with higher field superconducting magnets. Similar high luminosities also can be achieved for various eA collisions. Without cooling during collisions, the expected luminosity is lowered to about 2 to 3 × $10^{33}$ $cm^{-2}s^{-1}$, assuming that one can refill the ion collider every 3 hours to counteract intra-beam scattering (IBS) emittance growth.

## ENABLING ACCELERATOR TECHNOLOGIES

To reach the performance goals of the proposed EIC conceptual designs, a number of accelerator advances are required. Several of these advances are common to all EIC designs and include the following: advanced magnet designs, strong hadron beam cooling, high-current (multiturn) ERL technology, crab cavity operation with hadron beams, the generation of polarized $^3$He beams, and development and benchmarking of simulation tools. The successful implementation of an EIC requires the successful validation of these key concepts through high-fidelity simulations and demonstration experiments. The following sections review these enabling technologies, the present state of the art, and required research and development to meet EIC facility specifications and realize EIC science.

### Magnet Technologies

Several magnet designs of both the JLEIC and eRHIC concepts are beyond state of the art. Magnet technology R&D is required for the JLEIC ion ring magnets, the interaction region magnets for both designs, and the solenoids for the electron cooler and spin control.

In the case of the eRHIC design, the crossing angle of 22 mrad calls for combination of active and passive shielding to provide a field-free pass of the electron beam inside the IR quadrupole (see Figure 4.6a). For other IR magnets, the penetration of the electron beam through the yoke of the ion magnets is arranged as shown in Figure 4.6b. Therefore, the eRHIC magnet R&D focuses on further developing active shielding technology, originally explored for the International Linear Collider (ILC) IR magnets, with a goal of fabricating and testing a short active-shielded magnet prototype.

In the case of JLEIC, fast-ramped 3 T super-ferric dipoles for the ion booster and collider rings represent both a cost-effective option and an advance in conductor technology. However, the technology is not well established or fully validated. The cable-in-conduit conductor technology (see Figure 4.7) developed by Texas A&M University's Accelerator Research Laboratory and utilized in these super-ferric magnets, can withstand the high ramp rate required in the ion booster magnets. The JLEIC magnet R&D program focuses on validating the super-ferric technology for 3 T and 6 T magnets, and on the development of IR magnets (final focus quadrupoles and dipoles), which are compact, high field, and robust in a high-radiation environment and have large aperture.

A key technical area common to all EIC concepts is the validation of magnet designs associated with high-acceptance interaction points by prototyping. In order to attain the high luminosity required, the final focus quadrupole magnets must be in close proximity to the interaction point. Large magnet apertures are required to

(a)

(b)

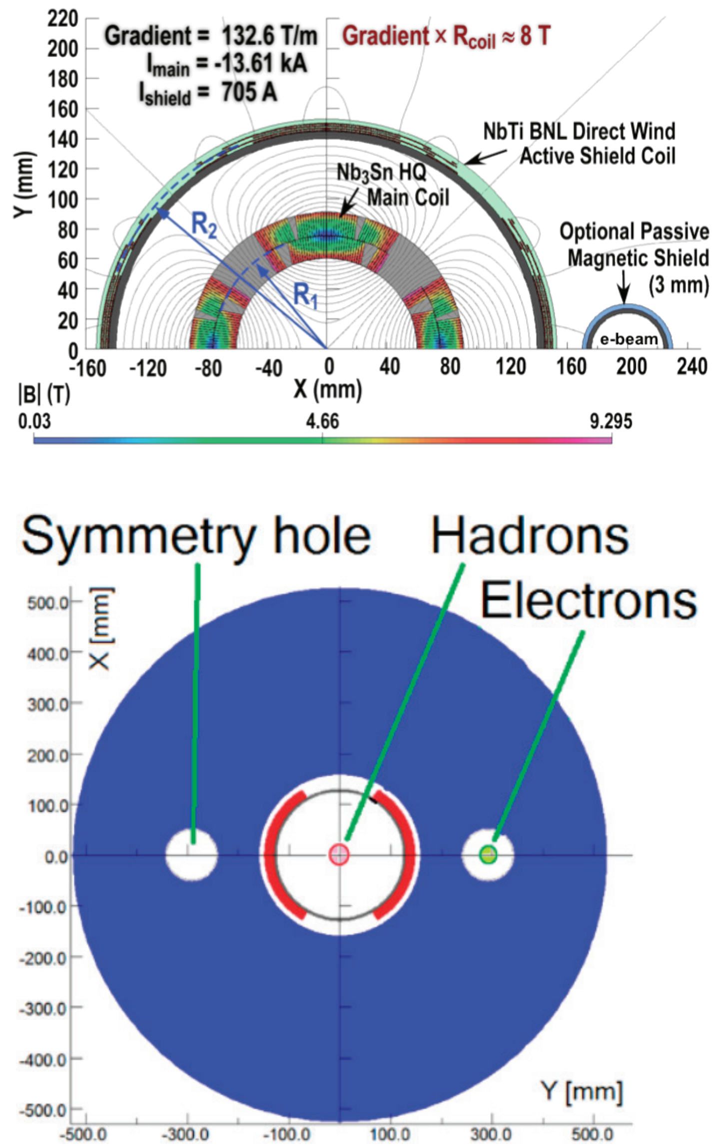


**FIGURE 4.6** eRHIC IR magnet concepts: (a) NbTi active shielding around NbSn3 magnet coil of the ion Q1 quadrupole; (b) electron passage through the yoke of the B1 dipole magnet. SOURCE: B. Parker, R.B. Palmer, and H. Witte, 2017, "The eRHIC Interaction Region Magnets," Proceedings of IPAC 2017, Copenhagen; V. Ptitsyn, 2017, "Progress in eRHIC Design," EIC Collaboration Meeting, October, Brookhaven National Laboratory, Upton N.Y.: https://indico.bnl.gov/conferenceDisplay.py?confId=3492, accessed August 13, 2018.

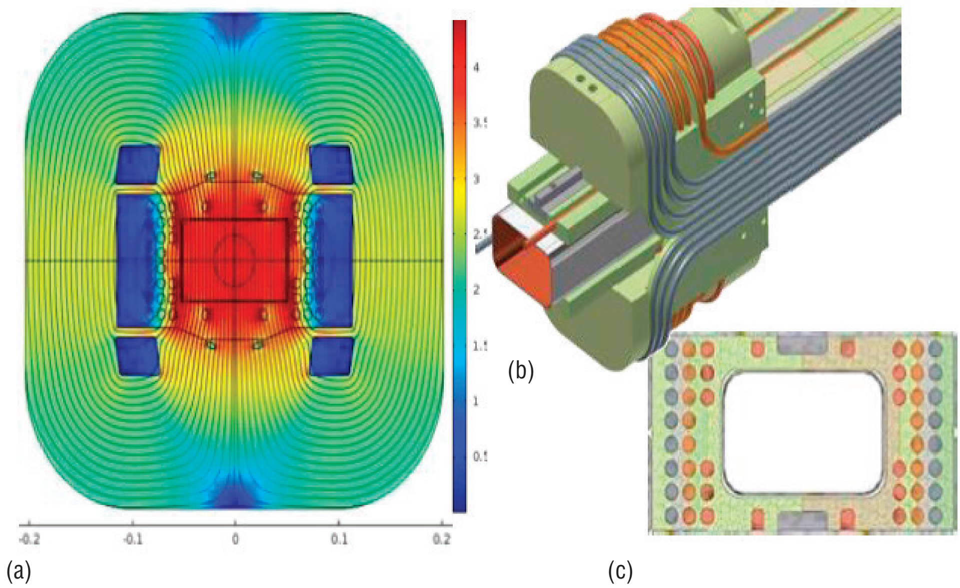


**FIGURE 4.7** The 3.5 T cable-in-conduit-based design for the ion ring arc dipole: (a) magnetic field design; (b) winding design; (c) cross section of winding structure. SOURCE: J. Breitschopf et al., 2016, "Superferric Arc Dipoles for the Ion Ring and Booster of JLEIC," Proceedings of NAPAC 2016, Chicago, http://accelconf.web.cern.ch/AccelConf/napac2016/papers/mopob54.pdf.

maximize acceptance by the detectors. The first spectrometer dipoles must also have large apertures for detector acceptance and accommodating the close proximity of the adjacent electron beam pipe.

## Strong Hadron Beam Cooling

Cooling of hadron beams is essential to achieving the highest luminosities demanded by the EIC science. Both the JLEIC and eRHIC concepts have adopted novel beam cooling techniques that require significant R&D. JLEIC employs a multiphased cooling scheme, while eRHIC considers various new approaches using electron beams. One of them, coherent electron cooling (CeC) is being subjected to a proof-of-principle test at RHIC.

### *JLEIC Multiphase Electron Cooling*

As a critical part of the luminosity concept, JLEIC employs conventional electron cooling technology for reducing the ion beam emittance. It also adopts a

**TABLE 4.3** Jefferson Laboratory Electron-Ion Collider Multiphase Electron Cooling

| | Phase | Functions | Proton Kinetic Energy (GeV/u) | Electron Kinetic Energy (MeV) | Cooler Type |
|---|---|---|---|---|---|
| Booster | 1 | Assisting accumulation of ions | 0.11 ~ 0.19 | 0.062 ~ 0.1 | DC |
| | 2 | Emittance reduction | 2 | 1.09 | |
| Collider ring | 3 | Suppressing IBS and maintaining emittance during stacking of beams | 7.9 | 4.3 | Bunched beam (ERL) |
| | 4 | Suppressing IBS and maintaining emittance during collision | 100 | 55 | |

NOTE: ELC, Energy recovery linac; IBS, intra-beam scattering.
SOURCE: Yuhong Zhang, talk at EIC Collaboration meeting, October 2017, Brookhaven National Laboratory, Upton, N.Y., https://indico.bnl.gov/getFile.py/access?contribId=2&sessionId=0&resId=0&materialId=slides&confId=3492, accessed August 13, 2018.

multiphased cooling scheme, as summarized in Table 4.3, to achieve the required high efficiency. The scheme utilizes two electron coolers, a magnetized DC cooler in the booster synchrotron, and a magnetized bunched-beam cooler based on an ERL for the collider ring, with its schematic design shown in Figure 4.8. The DC cooler is state-of-the-art, off-the-shelf technology. R&D is necessary in the area of magnetized bunched beam cooling.

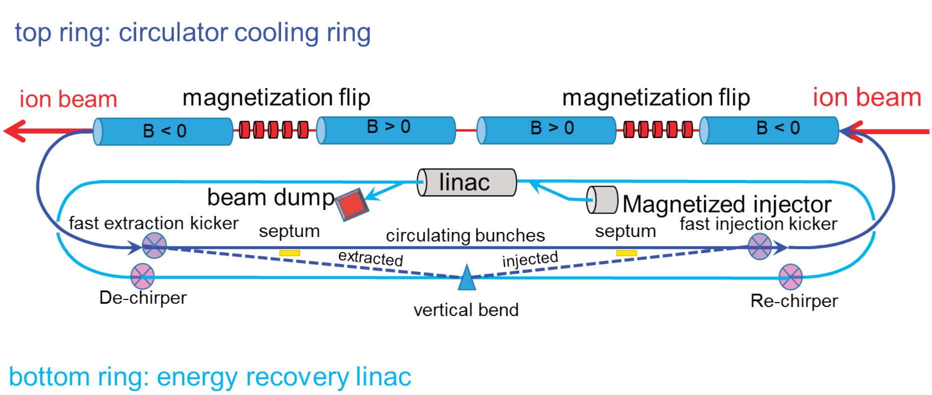


**FIGURE 4.8** Conceptual design of the Jefferson Laboratory Electron-Ion Collider bunched-beam energy recovery linac cooler. SOURCE: Stephen Benson, talk at EIC Collaboration Meeting, October 2017, Brookhaven National Laboratory, Upton, N.Y., https://indico.bnl.gov/getFile.py/access?contribId=30&sessionId=6&resId=0&materialId=slides&confId=3492, accessed August 13, 2018.

A single-turn ERL cooler enables luminosity of approximately 3 to 4 × $10^{33}$ $cm^{-2}s^{-1}$. The efficiency of electron cooling can be significantly enhanced by circulating the cooling beam a few times hence boosting the current, and enabling luminosity in excess of $10^{34}$ $cm^{-2}s^{-1}$. Circulating the cooling beam also relaxes the electron source requirements. One challenge of a multipass cooling scheme is the development of a fast kicker to switch the cooling bunches in and out of circulation. R&D on a fast kicker prototype is ongoing at JLab and is very promising. Further R&D requirements include ERL design for single-turn and multiturn operation; development of a high-current, magnetized source for the electron cooler; and electron cooling simulations.

*Coherent Electron Cooling, as Applied to eRHIC*

One of the most remarkable innovations at RHIC was the implementation of bunched-beam stochastic cooling of the heavy-ion beams at full energy in collision. Stochastic cooling, in which an RF "pick-up" measures fluctuations in the particle distribution that are later corrected in a subsequent kicker stage, has been effective in reversing the beam size increase due to intra-beam scattering and has resulted in an increase in luminosity and considerable increase in the physics reach of the RHIC collider. However, the full performance of eRHIC, with much higher peak currents than those of RHIC, requires improved cooling rates, therefore much higher bandwidth systems, beyond the capabilities of any established cooling technology. CeC, a promising new approach that uses an electron beam as both the pick-up and kicker, has been proposed.[5] Various high-bandwidth amplifiers have been proposed, including a free-electron laser[6] (FEL) and microbunching instability[7] (MBI). The FEL has received the most attention to date.

The principle of CeC is illustrated in Figure 4.9. In the first section, the Coulomb field of the ion modulates the electron energies. Electrons and ions take separate paths in the second section. Electrons go through an amplifier section, FEL or MBI, which converts the energy modulation to a density spike at the ion's former location in the electron beam. The ions go through a dispersive section, where an ion with lower than average energy falls behind the density spike it created, and an ion with above average energy slips ahead of its density spike. When the ion and electron beams are brought together again in the last section, a lower energy ion will have fallen behind and the Coulomb field of the density spike provides an energy boost; conversely, a higher energy ion will have slipped ahead and the col-

[5] V. Litvinenko and Y. Derbenev, 2009, Coherent electron cooling, *Phys. Rev. Lett.* 102:114801.

[6] D. Ratner, 2013, Microbunched electron cooling for high-energy hadron beams, *Phys. Rev. Lett.* 111:084802.

[7] Ibid.

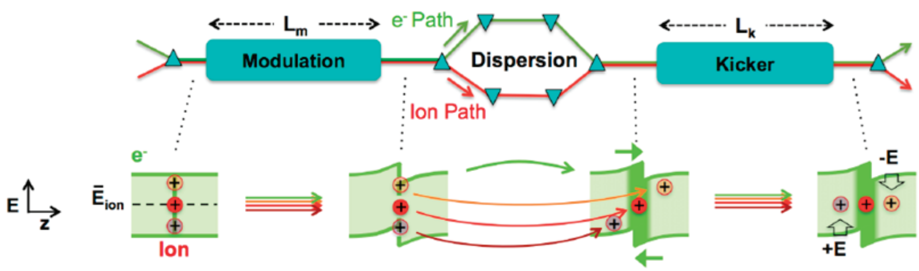


**FIGURE 4.9** Schematic of a one-dimensional model for coherent electron cooling. SOURCE: D. Ratner, 2013, Microbunched electron cooling for high-energy hadron beams, *Phys. Rev. Lett.* 111:084802.

lective electron field pulls the ion backward, reducing its energy. The net effect is to push all ions toward the average energy—that is, cooling. Theory suggests that cooling times of seconds to minutes are achievable.

While of great interest and promise, this technique still requires significant R&D and experimental validation. A proof of principle experiment is currently under way at RHIC.

### Energy Recovery Linacs

ERLs, a high-performance and high-efficiency type of recirculating linac, presently offer the only credible concept for electron cooling of high-energy colliding beams. The idea of energy recovery in a recirculating RF linac is based on the fact that the RF fields, by proper choice of the time of arrival of the electron bunches in the linac, may be used to both accelerate and decelerate the same beam. In an ERL, the electron beam is generated in a high-brightness electron source and injected into the linac, timed to be accelerated on the first pass through the linac. It is then transported through a magnetic arc to its point of use (e.g., the interaction region with protons or ions, in the case of an electron cooling device or an EIC) and then transported back to the entrance of the linac. If the recirculation path is chosen to be precisely an integer plus ½ RF wavelengths, then, on the second pass through the linac, the beam will be decelerated by the same RF field that accelerated it on the first pass. For the RF cavities within the recirculation loop, energy is directly transferred, via the RF field, from the decelerating beam to the accelerating beam; therefore, the RF power systems do not need to provide the energy to accelerate the first-pass beam. Indeed, the RF power draw becomes almost completely independent of beam current. ERLs can, in principle, accelerate very high currents with only modest amounts of RF power. This feature makes ERLs an attractive

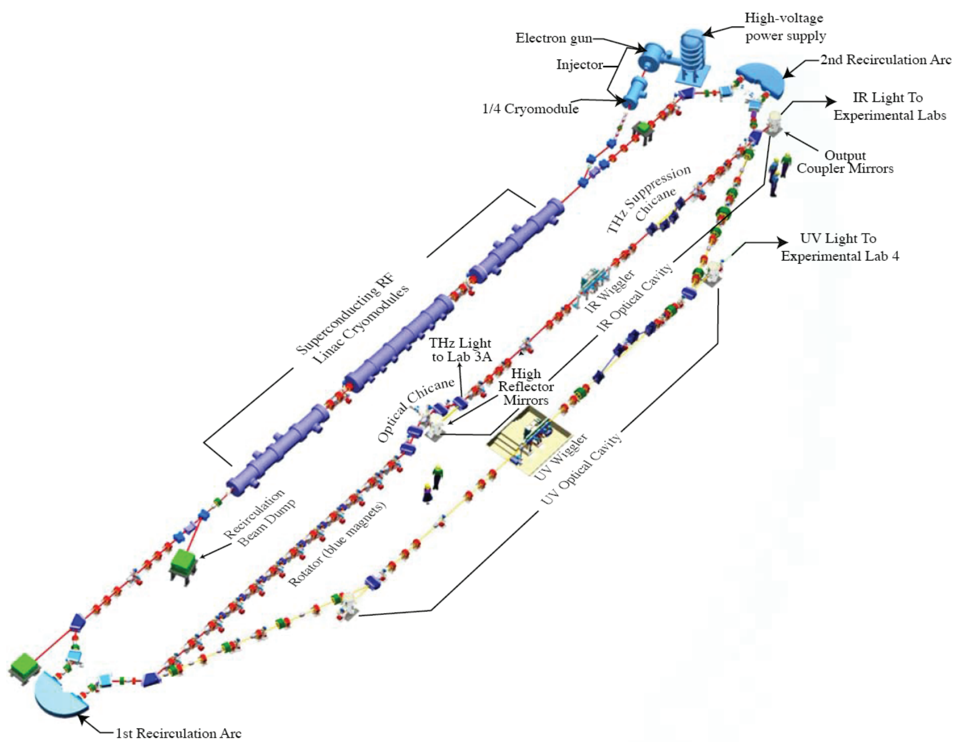


**FIGURE 4.10** The Jefferson Laboratory infrared and ultraviolet free-electron laser facilities, showing the electron source *(top right)*; injector cryomodule; and superconducting radio frequency (SRF) linac, which comprises three cryomodules (*left*), interaction region (IR) recirculator (*middle*), and ultraviolet UV recirculator with the UV wiggler and optical cavity (*right*). SOURCE: G. Neil, Thomas Jefferson National Accelerator Facility.

concept for a variety of applications, including higher-power FELs, synchrotron radiation sources, electron cooling devices, and high-luminosity EICs. The majority of operating and proposed ERLs are based on SRF linacs, due to their greater efficiency of energy recovery. Figure 4.10 illustrates the JLab IR and UV ERL-FEL.

To date, several ERLs have operated successfully and established the fundamental principles of energy recovery. The ERLs required for electron cooling are at scales much larger than supported by present-day experience, so a number of accelerator physics and technology challenges still need to be overcome with focused R&D and great attention to detailed simulations. The challenges center around the following three major areas:

- Achieving high electron source brightness;
- Maintaining high beam brightness through the accelerator transport (beam dynamics of an unprecedented number of spatially superposed bunches in the SRF linacs; very precise phase and amplitude control); and
- Dealing with unprecedented beam currents in SRF linacs (halo mitigation, beam breakup instabilities, higher order mode dissipation).

Many of these R&D issues are being investigated vigorously in dedicated test facilities under construction and commissioning in laboratories around the world. Specifically, the 4-pass Fixed-Field Alternating Gradient R&D loop for eRHIC (see

**BOX 4.2**
**CBETA and Fixed-Field Alternating Gradient Optics for Electron Acceleration**

The Brookhaven National Laboratory (BNL) has launched a collaboration with Cornell University to build a high-intensity multipass 150 MeV test energy recovery linac (ERL) with nonscaling fixed-field alternating gradient (NS-fixed-field alternating gradient) return arcs, called CBETA (for Cornell-BNL ERL Test Accelerator),[1] shown schematically in Figure 4.2.1. The large momentum acceptance of the NS-fixed-field alternating gradient optics could substantially reduce the number of return arcs and the cost of the 18 GeV injector of the eRHIC electron storage ring (or the 18 GeV ERL itself, in the case of the linac-ring design concept). Several beams of different energies could pass through the same arc structure on different orbits.

Like eRHIC, the Jefferson Laboratory Electron Ion Collider (JLEIC) design of an EIC also employs an ERL as an electron cooler to achieve low-emittance ion beams. These, and other future ERLs or recirculating linac accelerators, could also benefit from the fixed-field alternating gradient focusing principle.

CBETA will pioneer several energy-saving concepts in accelerator design. As an ERL, of course, it will recover the energy of the beam it accelerates and reuse it to accelerate new beams. It will be the first multiturn ERL to employ superconducting radio-frequency (SRF) accelerating cavities. The beam will pass four times through the single RF cryomodule. The fixed-field alternating gradient arcs will be constructed from permanent magnets, requiring no electrical power, instead of conventional electromagnets. The designs advance permanent magnet technology.

CBETA will exploit existing buildings, infrastructure, and completed research and development at Cornell University. A fully commissioned photoemission electron source, high-power injector, ERL accelerator module, and high-power beam stop are state-of-the-art components that are already available on the site. After a sequence of commissioning phases,[2] operation in the 4-turn ERL mode is foreseen in spring 2020.

Besides testing numerous accelerator physics and technology concepts, CBETA also has a number of potential applications. Its continuous wave high-brightness electron beams have the potential to perform dark matter searches with high luminosity on an internal target. A number of other nuclear physics experiments using polarized electron beams could be pursued. It could work as a compact Compton source for gamma rays or a THz laser (complementing the existing

Box 4.2) could illuminate key issues including multiturn beam-breakup instability thresholds for proof of possible cavity designs, halo and mitigation, beam-ion effects, and operational challenges such as instrumentation and stability of multiturn beams.

### Crab Cavity Operation in Hadron Ring

To reach the ultimate luminosity goals, both EIC design concepts require "crab crossing." In a storage ring collider with beams crossing at an angle, some luminosity is lost because the colliding bunches do not overlap completely. A crab crossing

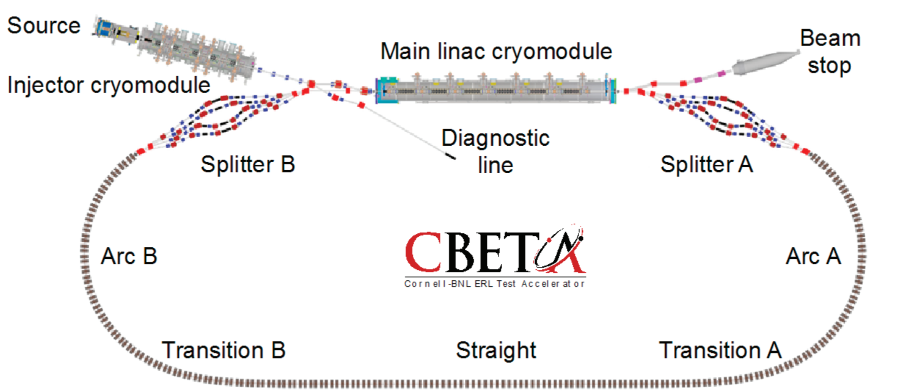


**FIGURE 4.2.1** Simplified schematic layout of the CBETA test accelerator. SOURCE: Georg Hoffstaetter of the Cornell Physics Department, https://www.classe.cornell.edu/, accessed August 13, 2018.

CHESS facility at Cornell). Detailed descriptions of these multiple potential uses are provided in the design report.[3]

[1] *CBETA Design Report*, 2017, principal investigators G.H. Hoffstaetter, D. Trbojevic, and E. Mayes, Cornell.

[2] G. Hofstaetter, 2017, "The 59th ICFA Advanced Beam Dynamics Workshop, the 7th International Workshop on Energy Recovery Linacs," CERN, June 18-23, 2017, https://indico.cern.ch/event/470407/, accessed August 13, 2018.

[3] *CBETA Design Report*, 2017.

scheme counteracts this by means of transverse RF deflectors placed at symmetric locations around the IP. These tilt the bunches in the crossing plane, by half the crossing angle, so that they collide head-on (in a frame moving transversely) at the IP without loss of luminosity. After the collision, the tilt angle is canceled by the crab cavities installed at the opposite side of the IP.

To date, the only operational implementation of crab crossing has been at the electron-positron collider (KEKB) at the High Energy Accelerator Research Organization (KEK) in Japan. Crab crossing has never been demonstrated in a hadron machine.

Supported by the U.S. LHC Accelerator Research Program, intense research and development of crab cavities for the High-Luminosity Large Hadron Collider (HL-LHC) has been ongoing at BNL and at Old Dominion University (ODU), near JLab. The BNL effort is focused the upcoming tests at CERN. Crab cavity work at ODU focuses on design and fabrication, and investigation of cavity shapes, cell apertures, and number of cells per cryomodule for JLEIC. Demonstration of hadron beam crabbing took place at the Super Proton Synchrotron (SPS) at CERN in May 2018.

Crab cavity operation at KEKB with high current (>0.5 A) was initially limited by large amplitude oscillations of beams and cavity fields resulting from a combination of beam loading in the crab cavities and the beam-beam force. The possibility of such an instability in the EIC needs to be investigated in combined simulations of beam-beam collisions and crab-cavity responses for the various EIC design concepts. Extensive simulations of hadron beams with crab cavities, long bunches, and beam-beam collisions are necessary to evaluate the performance of the proposed EICs. In addition, crab cavity tests with hadron or high current electron beams will be critical at the project definition stage of an EIC. The experiments could be done at several laboratories, including at a future bunch cooler ring test facility at JLab, at RHIC at BNL, or CBETA at Cornell, as well as at the SPS at CERN.

### Polarized $^3$He Source

A polarized neutron beam is essential for the EIC science program, discussed in Chapter 2. The neutron is the charge-neutral analogue of the proton and is an essential building block of nuclear physics. In addition, it could be used for important tests of the Standard Model. In practice, polarized $^3$He ion beams offer a technically feasible method to realize a polarized neutron beam at EIC. Development of such a beam has been identified as an R&D priority by the EIC Advisory Committee[8] and the Office of Nuclear Physics Community Review.[9]

A BNL-Massachusetts Institute of Technology (MIT) collaboration is working on development of a polarized $^3$He ion source using the existing EBIS at RHIC. $^3$He atoms are polarized via optical pumping[10] in a glass cell at a pressure of 1 mbar and directed into the EBIS vacuum system. An intense, 30 keV electron beam completely ionizes the polarized atoms, which are then electrostatically confined in the EBIS. By pulsing high voltage electrodes, $^3He^{++}$ ions can be extracted. The design goal for the source is $1 \times 10^{12}$ $^3He^{++}$/s at 70 percent polarization.

Successful tests of polarizing $^3$He in a high magnetic field have led to the development of the Extended EBIS upgrade where $^3$He is polarized in a second 5 T solenoid, as shown in Figure 4.11. This upgrade will also improve the ionized gold $Au^{32+}$ production, prompting the construction to be completed in two phases. Phase 1 will focus on a 50 percent increase in $Au^{32+}$ production and gas injection for the RHIC run starting January 2019. Phase 2 will be the polarized $^3He^{++}$ upgrade.

### Development and Benchmarking of EIC Simulations

An essential element of the EIC design process is the development of new and adaptation of existing simulation tools that can validate the many novel concepts of the proposed EIC designs, before critical technical decisions are taken. Both EIC accelerator designs require beam parameters and operational modes that present a significant extrapolation from state-of-the-art colliders and have never been demonstrated experimentally. To establish the feasibility of these concepts, validation through self-consistent, start-to-end simulations is essential. In turn, the simulation codes should be validated through benchmarking against experimental data. Specific modes of operation which require the development of new simulation codes include beam-beam interactions with crabbed beams in asymmetric e-p collisions and bunch-by-bunch swap out injections of high-intensity electron bunches during the collision process. The development of a central simulation toolbox that can be shared by all design teams is a worthwhile undertaking as it can be broadly applicable to other accelerator designs.

[8] Report of the Electron Ion Collider Advisory Committee, November 2-3, 2009.

[9] Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics, February 13, 2017.

[10] F.D. Colegrove, L.D. Schearer, and G.K. Walters, 1963, Polarization of $He^3$ gas by optical pumping, *Phys. Rev.* 132:2561.

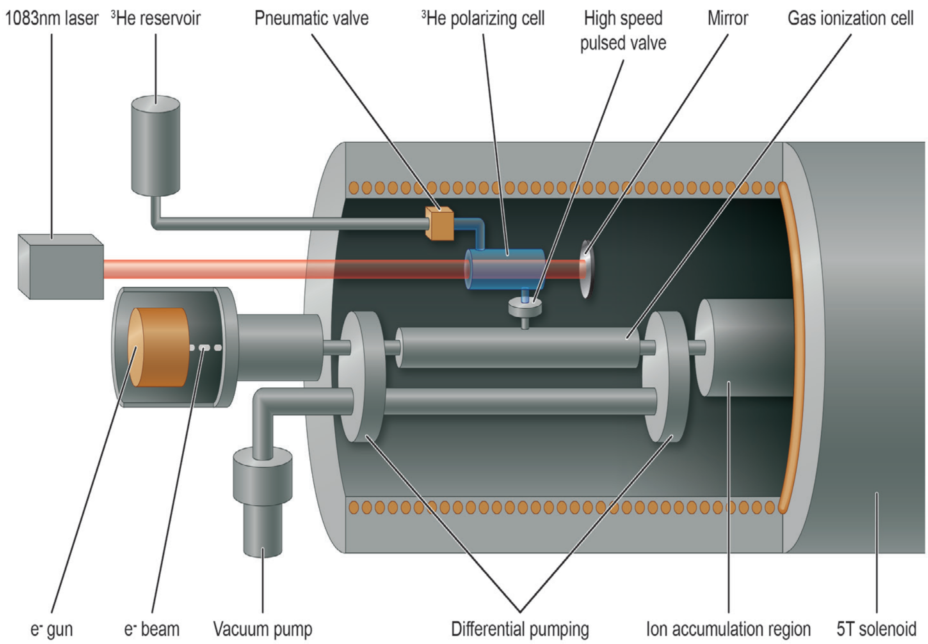


**FIGURE 4.11** Schematic layout of the extended Electron Beam Ionization Source. SOURCE: Brookhaven National Laboratory (2017).

## DETECTOR TECHNOLOGIES

Measurements at an EIC rely crucially on highly capable detectors to observe the scattered electrons and any other particles scattered or produced in the collisions of the electron and ion beams. The range of EIC beam energies, ion species, collision rates, and collision characteristics of the processes of interest each present particular challenges for the design of such detectors, as do the envisioned measurement accuracies, including those of luminosity and polarization. The successful development of suitable EIC detectors relies crucially on HERA experience and on technological developments for other large-scale detectors in high-energy and nuclear physics, in particular those at the LHC and those envisioned for the ILC. Many of the needed detector technologies will thus have been used or demonstrated prior to the EIC. Optimized and tightly integrated EIC detectors will nevertheless require a sustained program of dedicated R&D.[11]

[11] Brookhaven National Laboratory, in association with JLab and the DOE Office of Nuclear Physics, announced a generic detector R&D program in 2011 that has attracted active participation from the EIC user community.

The need for high luminosity at an EIC, for example, presents conflicting demands of having to position beam focusing elements close to the interaction point while also leaving enough space for a well-integrated set of instruments that jointly form the central detector to fully characterize the beam collision products or events. The key challenge is thus to make the central detector as compact as possible, while retaining large acceptance and the full suite of particle identification and measurement capabilities. The topology of the beam collision events presents further challenges. The particles are scattered or produced over a wide range of angles, ranging from just a few fractions of a degree from the ion beam direction to a few fractions of a degree from the electron beam direction, thus requiring a detector that covers a similarly wide range. This range, or acceptance, well exceeds that of the existing and planned detectors at JLab and at RHIC. Like the angles, the energies of the scattered electrons span a broad range from just a small fraction of the EIC electron beam energy up to the ion beam energy. The need for high fidelity in the measurements restricts the amount of material that can be used in the innermost parts of the central detector and imposes stringent demands on detector resolutions. Many measurements require that the handful of hadrons produced in a typical beam collision at the EIC are identified, posing yet further challenges. Several candidate detector concepts have been put forward to meet the science needs for both the JLEIC and eRHIC design options. Figure 4.12 shows an example of a central detector concept for the eRHIC design option. Its integration in the interaction region is shown in Figure 4.3.

Large acceptance "electromagnetic calorimetry" features prominently in each of the concepts, driven first and foremost by the need to measure the scattered electron energy. The technology choices are informed primarily by energy resolution requirements, which are most stringent in the region along the forward going electron beam. Dense and fast lead tungstate crystals ($PbWO_4$), studied extensively as part of R&D for the Compact Muon Solenoid (CMS) and Anti-Proton Annihilations at Darmstadt (PANDA) experiments, are a prime candidate for this region because of their superior energy resolution. Modules of tungsten powder with scintillating fibers, as developed initially within the Solenoidal Tracker at RHIC (STAR) collaboration, are being considered for the less demanding regions of the detector, as are more conventional choices. Established technologies are chosen typically also for hadronic calorimetry.

The detector concepts also feature large acceptance and low-mass "charged particle tracking" between the interaction point and the calorimeters. A high-rate time projection chamber (TPC), possibly complemented with large cylindrical MicroMegas detector elements, is an attractive option, as are barrel layers based on thinned complementary metal-oxide-semiconductor monolithic active pixel sensors (MAPS). MAPS have been studied extensively as part of the inner tracking systems of the STAR and A Large Ion Collider Experiment (ALICE) experiments

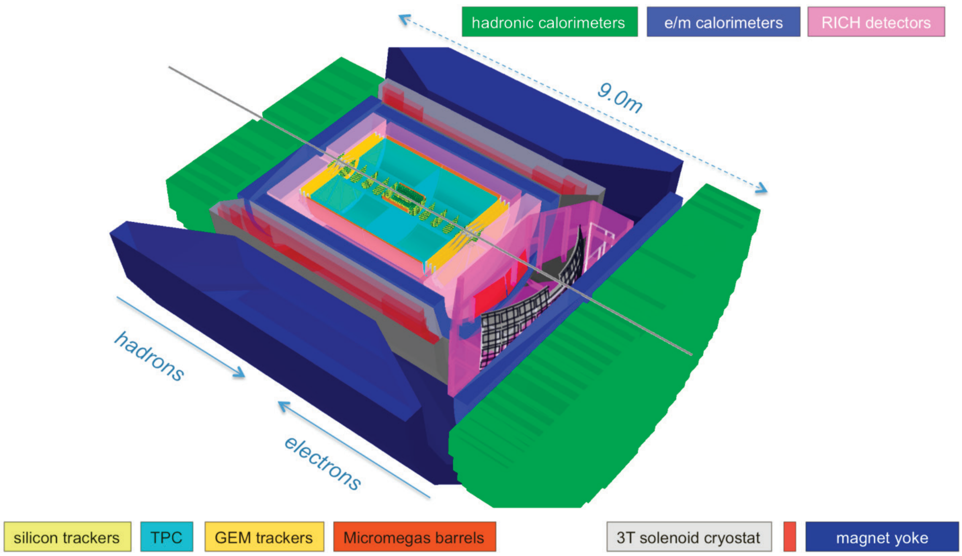


**FIGURE 4.12** Schematic view of candidate central EIC detector. SOURCE: Alexander Kiselev, presentation at the XXIV International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS16), April 2016, DESY, Hamburg, Germany, https://indico.desy.de/indico/event/12482/session/7/contribution/259/material/slides/1.pdf.

and for other applications—for example, in cryo-electron microscopy to study biomolecules. The tracking in the challenging regions along the EIC beam directions require suitably optimized arrays of disks. Options include the aforementioned MAPS as well as gas electron multiplier technology, which has been greatly developed since its inception and is now used in numerous applications.

The broad range of hadron total momenta and the relatively compact central detector designs require consideration of a similarly broad range of technologies for particle identification (PID), a key capability for essentially all but the inclusive measurements at the EIC. A TPC, a prime candidate for charged particle tracking, can also provide charged particle identification via measurements of the particle specific energy depositions as the particle traverses the TPC gas. A high-performance Detecting Internally Reflected Cherenkov light within a solid radiator, and high-resolution time-of-flight technologies are being pursued as well, as are Ring-Imaging Cherenkov technology with aerogel and gas radiators. Reaction channels producing hadrons containing charm or beauty quarks can be reconstructed topologically by observation of their displaced decay vertices with precision silicon vertex trackers, MAPS again being a prime technology candidate.

Such reaction channels can also be tagged via observation of the semi-leptonic decays into electrons, positrons, or muons. Some of the central detector design concepts thus entertain the possibility of muon chambers at the outermost radii.

In addition to the central detector, it is crucial to integrate far-forward instrumentation into the interaction region design of the collider (see Figure 4.3) for exclusive as well as diffractive measurements. The scattered proton in exclusive electron-proton reactions can be measured with silicon-based trackers in "Roman Pot" stations that are used to measure the total cross section of two particle beams in a collider. These stations are integrated into the ion beam-line design at carefully chosen locations where the beam size is minimized and the scattered protons can be analyzed from the dispersion through dipole magnetic fields of the ion ring. Instrumented Roman Pot stations with suitable acceptance can serve also to tag spectator protons from the break-up of deuterium or $^{3}$He ion beams, whereas heavier ion beams require a dedicated spectrometer or zero-degree hadronic calorimetry. Detailed study of the remnants of the beam ions after their collision with the beam electrons has thus far not been emphasized as a core part of the EIC science program, but would present further challenges for EIC instruments.

Precision measurements of electron and hadron beam polarization[12] and collision luminosity are essential to the EIC core science program and require ancillary instrumentation. The methods and techniques for these measurements appear known to be able to achieve the core EIC science objectives, although it should be noted that a number of EIC measurements are limited by systematic rather than statistical uncertainties. The instrumentation associated with luminosity and polarization measurements is typically located very close to the beams and can, in the case of the electron beam, be designed to considerably expand the acceptance of the central detector for scattered electrons to very shallow angles, a region of considerable scientific interest dominated by photo-production processes.

[12] Measurement of EIC hadron beam polarization is likely to adopt the methods employed at RHIC, which have achieved 3 to 4 percent accuracy and will take place in a dedicated location away from the central detectors.

# 5

# Comparison of a U.S.-Based Electron-Ion Collider to Current and Future Facilities

## INTRODUCTION

The physics program of an electron-ion collider (EIC) will be part of the worldwide activity in nuclear and elementary particle physics, although the EIC is proposed for construction in the United States. Furthermore, the EIC will serve the international physics community, just as other facilities do elsewhere. This chapter sets it in its international context by reviewing the capabilities and physics programs of other accelerators and colliders, starting with the Hadron-Electron Ring Accelerator (HERA), the only lepton-hadron collider that has operated to date, and moving on to survey other types of accelerators and colliders that are presently operating and whose physics programs are related to that of the EIC. Finally, other proposals for possible future machines are discussed. This will serve to highlight the unique capabilities and scientific value of an EIC and how that value will be preserved into the future.

## HERA AT DESY

Following its proposal in 1981,[1] the HERA collider[2,3] operated from 1991 to 2007 at the Deutsches Elektronen-Synchrotron (DESY) laboratory in Hamburg,

[1] G.A. Voss et al., 1981, "HERA—a proposal for a large electron-proton colliding beam facility at DESY, DESY report HERA 81/10.

[2] See HERA page at DESY website, http://www.desy.de/research/facilities_projects/hera/, accessed August 13, 2018.

[3] F. Willeke, 2016, The HERA lepton-proton collider, in *Challenges and Goals for Accelerators in the XXI Century*, World Scientific, Singapore.

Germany, colliding 27.5 GeV electron (or positron) beams with up to 920 GeV proton beams in its 6.3 km circumference ring, attaining a center-of-mass energy up to $\sqrt{s} = 318$ GeV. While its energy was higher than that of the EICs described in Chapter 4, its peak luminosity reached $5 \times 10^{31}$ cm$^{-2}$s$^{-1}$, a few hundred times less than the ultimate goals of the present EIC proposals. The total integrated e-p luminosity delivered to the H1 and ZEUS experiments was about $0.5 \times 10^{39}$ cm$^{-2}$, conventionally denoted as 0.5 fb$^{-1}$ each. Moreover, HERA only collided electrons with protons, never any other ions.

HERA pioneered the use of polarized stored electron beams in collisions. Unlike the EICs, transverse beam spin-polarization could be allowed to build up on a timescale of an hour by radiative self-polarization or Sokolov-Ternov polarization (see Chapter 4) and was maintained by the implementation of correction procedures in the ring optics to cancel small effects that tend to destroy the polarization. Movable spin rotator magnets were deployed to rotate the transverse polarization into the longitudinal direction at the collision point. Moreover, the hadron ring was one of the first to use superconducting magnets.

HERA was designed for the needs of the high-energy particle physics community, primarily to search for new physics beyond the Standard Model. However, given that it discovered no new physics, HERA is remembered mainly for the wealth of electroweak and quantum chromodynamics (QCD) measurements it performed (Figure 5.1).

As the first high-energy electron-proton collider, reaching beyond fixed-target experiments, HERA provided data in the H1 and ZEUS experiments on proton structure in unprecedented energy regimes, reaching $\sqrt{s} = 318$ GeV. With ample data well into the regime where theoretical techniques could be applied, HERA provided tremendously better constraints on parton distribution functions (PDFs) in the proton than were previously available. In turn, the availability from HERA of higher-precision data over a wider kinematic range helped to spur a number of the theoretical advances in QCD that took place throughout the 1990s and early 2000s.

While an EIC will revisit many of the QCD measurements that HERA already performed, it will be able to radically improve upon many of them, taking advantage of, among other factors, instantaneous luminosities at least two orders of magnitude higher than HERA, as discussed in Chapter 4. Further improvements will come, for example, from detector technology and design as well as the ability and intent to run an EIC at a wide range of center-of-mass energies in order to optimize QCD measurements. These are important for measurements sensitive to the gluon distribution. Other measurements performed by HERA that will be pursued further at an EIC include those of the inclusive neutral- and charged-current cross sections for electron-proton scattering at a range of energies, heavy flavor production in electron-proton scattering, and inclusive jet and dijet production.

Of particular relevance for an EIC are the measurements HERA performed of

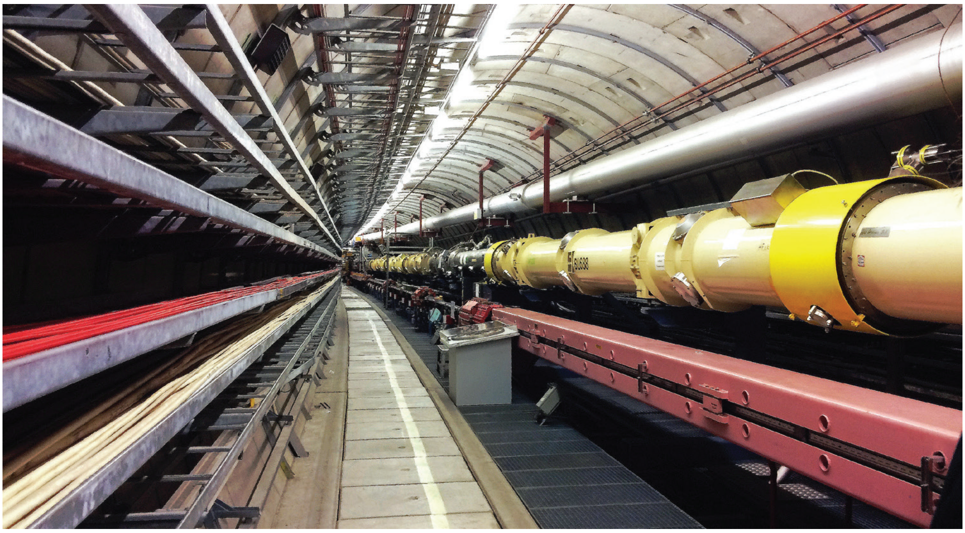

**FIGURE 5.1** The electron (*below*) and superconducting proton (*above*) rings in the tunnel of the Hadron-Electron Ring Accelerator. SOURCE: Simon Waldherr, File:DESY-HERA.jpg, Wikimedia, December 29, 2015, Creative Commons Attribution-Share Alike 4.0 International license, https://commons.wikimedia.org/wiki/File:DESY-HERA.jpg.

proton structure at low $x$ values, given their potential connection to a predicted regime where the density of gluons is so high that the gluons typically interact with each other rather than with quarks, which an EIC is being designed to explore (see the section "Gluons in Nuclei"). HERA data reached $x$ values less than $10^{-4}$ in the proton, a region where such nonlinear effects have been predicted. While the necessity of such effects to describe the HERA measurements has been hotly debated and remains inconclusive, the HERA data have prompted extensive theoretical advances of the field. An EIC will reach higher gluon densities than HERA by using beams of heavy nuclei as opposed to protons. Based on what has been learned from the relevant HERA measurements and the phenomenological efforts invested in interpreting them, a comprehensive suite of measurements is being planned for an EIC to study the gluon-dense regime of nuclear matter in depth.

In addition to the H1 and ZEUS experiments at HERA, the HERA Measurement of Spin (HERMES) fixed-target experiment used HERA's electron and positron beams on a variety of stationary targets, including longitudinally and transversely polarized proton targets and nuclear targets. The longitudinally polarized lepton beam in HERA permitted a variety of measurements on polarized targets in various configurations. In contrast to the collider experiments, HERMES was designed with a focus on QCD and the structure of the nucleon, particularly in terms of its spin. HERMES not only improved constraints on the polarized PDFs, in particular for quarks, but, critically for a future EIC, laid much of the initial groundwork for transverse momentum-dependent distributions (TMDs) describing spin-momentum correlations in the proton and added to the sparse world knowledge of nuclear PDFs and hadronization from nuclei.

In summary, while HERA was not primarily designed to study QCD, without it, knowledge of QCD and proton structure in particular would not be anywhere close to where it is today. The Relativistic Heavy Ion Collider (RHIC) spin program, using much more complicated proton-proton collisions to study proton structure, would not be nearly as fruitful without the availability of both unpolarized and polarized PDF constraints from HERA as input to the analysis. The EIC is being proposed in the context of everything that was learned, directly and indirectly, from the HERA measurements and the theoretical progress they sparked. Being designed some three decades after HERA, the EIC will not only exploit all the accelerator and detector technological advances of the intervening years, but will also be optimized for a broad and powerful QCD program. In addition to the polarized proton and light ion capabilities and the ability to accelerate heavy ions that are discussed in Chapter 4, other factors such as the optimal beam-crossing angle in the experimental interaction regions are being considered. Compared to the fixed-target HERMES experiment at HERA, which had both polarized and nuclear targets, analogous measurements at the EIC will offer cleaner interpretation thanks to the possibility of larger momentum transfers. In studies of hadronization, the more favorable geometry of interactions in a collider will provide cleaner separation of target and current fragmentation regions. At HERA, the QCD community acquired practical experience and learned lessons in carrying out measurements in an electron-hadron collider configuration. This is being incorporated into the designs of accelerator and detectors for an EIC. Examples include performing diffractive measurements in electron-proton collisions, constraining the longitudinal structure function $F_L$ by varying the center-of-mass energy, and accessing PDFs at high $x$ by measuring small-angle jets.

## CEBAF AT JLAB

The valence quark region, which will be a focus of the 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) science program, is an important bridge connecting to the gluon and sea quark region accessible by an EIC. Naturally, many of the some 1,600 physicists currently active at CEBAF form one of the communities driving the realization of an EIC. This section describes the past and present facilities and physics programs at the Thomas Jefferson National Accelerator Facility (JLab) and their relation to a future EIC.

CEBAF was built in the late 1980s to investigate the then largely unexplored transition between the nucleon-meson and the quark-gluon descriptions of nuclear systems. For transition-region experiments, the originally envisioned machine required a combination of the following characteristics: multi-GeV energy for spatial resolution and kinematic flexibility, high intensity for precise measurement of relatively small electromagnetic cross sections, high duty factor to allow coincidence experiments, and beam quality sufficient for use with high-resolution spectrometers and detectors.

The original CEBAF accelerator was a five-pass recirculating linac capable of simultaneous delivery to three end stations of continuous wave (CW) beams of up to 200 μA with 75 percent polarization, geometric emittance less than $10^{-9}$ m rad, and relative momentum spread of a few $10^{-5}$. The original design beam energy was 4 GeV with the possibility of a later energy upgrade.

The CEBAF accelerator design introduced a number of innovations, the most important ones being the choice of superconducting radio frequency (SRF) technology and the use of multipass beam recirculation. Neither had been previously applied on such a scale, and CEBAF remained the world's largest implementation of SRF technology until Large Electron Positron Collider 2 (LEP2) came into operation in the later 1990s. Beam recirculation was implemented with bend radii large enough to keep open the possibility of future energy upgrades. The CEBAF design included 42 cryomodules, each containing 8 SRF cavities, to achieve the design energy of 4 GeV. The cryomodules were evenly divided between two linacs, North and South, connected by magnetic spreaders, arcs, and recombiner sections. CEBAF reached its design energy of 4 GeV in 1995 and extended it to 6 GeV in 2000. It operated at energies up to 6 GeV until 2012. The beam parameters for the 6 GeV configuration can be found in Table 5.1. CEBAF supported simultaneous beam delivery to three experimental end stations, each receiving beams with a multiple of the one-pass energy, beam currents from below 1 nA to 190 μA, and beam polarization greater than 85 percent. During 6 GeV operations the users performed 178 experiments.

CEBAF was recently upgraded to deliver continuous electron beams to the experimental users at a maximum energy of 12 GeV. The 12 GeV upgrade design retained the same footprint as the original 4 GeV CEBAF, allowing the new accelerator to use the existing tunnel with the addition of a new extraction line transporting beam to a new end station named Hall D. To achieve the 12 GeV energy requirement, the design called for the following:

- An additional recirculating arc, Arc 10, to provide an additional pass of energy gain in the North Linac; and
- Additional cryomodules in each linac to increase the total energy gain in each linac from 600 to 1,100 MeV.

**TABLE 5.1** Delivered Beam Parameters for 6 GeV and 12 GeV Continuous Electron Beam Accelerator Facility

| Parameter | 6 GeV | 12 GeV |
|---|---|---|
| Maximum energy to Halls A, B, C | 6 GeV | 11 GeV |
| Maximum energy to Hall D | NA | 12 GeV |
| Duty factor | CW | CW |
| Maximum beam power | 1 MW | 1 MW |
| Bunch charge (minimum-maximum) | 0.004 fC-1.3 pC | 0.004 fC-1.3 pC |
| Hall repetition rate (minimum-maximum) | 31.2-499 MHz | 31.2-499 MHz |
| Nominal hall repetition rate | 499 MHz | 249.5/499 MHz |
| Number of experiment halls | 3 | 4 |
| Maximum number of passes | 5 | 5.5 |
| Emittance (geometric) at full energy | 0.1 nm-rad(X)/0.1 nm-rad(Y) | 3 nm-rad(X)/1 nm-rad(Y) |
| Energy spread at full energy | 0.002% | 0.018% |
| Polarization | 35% (initial), 85% (final) | >85% |

SOURCE: A. Freyberger, "Commissioning and Operation of 12GeV CEBAF," *Proceedings of the 6th International Particle Accelerator Conference* (IPAC2015), paper MOXGB2, http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/moxgb2.pdf.

The beam parameters for the 6 and 12 GeV designs are compared in Table 5.1. Apart from beam energy, the main difference is the increase in beam emittance and energy spread due to the copious synchrotron radiation in the high energy arcs.

JLab completed the accelerator upgrade and the associated experimental equipment upgrade in 2017, including a new experimental hall (Hall D). The energy-upgraded CEBAF accelerator is capable of delivering beams simultaneously to all four halls, up to 11 GeV electrons to Halls A, B, and C, and a 12 GeV electron beam to Hall D for producing 9 GeV tagged photons for meson spectroscopy, complementary to spectroscopy at the Large Hadron Collider (LHC) and possibly at the future EIC (Figure 5.2). The JLab Hall D program will investigate the role of gluonic excitations in the spectroscopy of light mesons by searching for states with exotic quantum numbers involving excitations of the gluonic field, states not taken into account in studying only quark and antiquark degrees of freedom. The discovery of such exotic states will elucidate the nature of quark confinement.

Owing to the limited kinematical reach of the upgraded JLab beam,[4] $0.05 < x < 0.8$ and $Q^2$ up to some 17 $GeV^2$, the upgraded JLab beam will study the valence

[4]J. Dudek et al., Physics opportunities with the 12 GeV upgrade at Jefferson Lab, *Eur. Phys. J. A* 48: 187(2012).

**FIGURE 5.2** A view of the Continuous Electron Beam Accelerator Facility accelerating structures, recently upgraded to provide 12 GeV beams. SOURCE: Thomas Jefferson National Accelerator Facility, https://www.jlab.org/, accessed August 13, 2018.

quark region at relatively low $Q^2$. By comparison, an EIC will be able to extend the study in the valence quark region up to $Q^2$ of order 1,000 $GeV^2$.

The original proton "spin crisis" discovered by the European Organization for Nuclear Research (CERN) European Muon Collaboration (EMC) experiment motivated experimental and theoretical activities worldwide in understanding the source of the proton spin. These studies also led to a more complete description of the partonic structure of the nucleon through three-dimensional (3D) distribution functions, generalized parton distributions (GPD) and TMD distributions, discussed in Chapter 2. The GPDs are accessed in exclusive scattering processes such as deeply virtual Compton scattering and deeply virtual meson production. The TMDs can be accessed in coincidence measurements in which the nucleon no longer remains intact, and one of the produced hadrons is detected together with the scattered electron. The resulting multidimensional distribution functions provide tomographic imaging of the nucleon and insight into the QCD dynamics inside the nucleon. Extensive programs on GPDs and TMDs are planned for Halls A, B, and C in the large *x*, also called "valence quark," region with a 12 GeV CEBAF.

An ultimate goal of nuclear physics is to be able to predict and describe nuclear properties and reactions from the first principles of QCD. Understanding the structure of the nucleon from QCD is an important step toward this goal. Apart from the study of the structure of the nucleon, the 12 GeV CEBAF provides significant opportunities to study QCD effects in nuclei. At the same time, nuclei also provide a unique laboratory to study QCD. Multinucleon correlations observed in nuclei at the 6 GeV CEBAF pave the way to addressing fundamental nuclear physics questions: Is there is a relation between short-range nucleon-nucleon correlations and the partonic structure of nuclei? What is the importance of the nucleon-nucleon wave function at short distances, the origin of the nucleon-nucleon force and effects of color transparency (the predicted vanishing of initial or final nuclear state rections)? Do hidden color configurations (not described by the usual color singlet nucleon states) exist in nuclei?

Precision intensity frontiers are complementary to energy frontiers in discovering new physics beyond the Standard Model of particle physics. The high-intensity polarized CEBAF beam is a powerful intensity frontier tool that offers discovery potential for physics beyond the Standard Model by utilizing precision measurements of mirror symmetry (parity) violation in electron scattering. Very precise measurements of parity violating asymmetries at the 6 GeV CEBAF have been performed to study the strangeness form factors and the weak charge of the proton in elastic electron-proton scattering. The energy upgraded CEBAF offers new opportunities using parity-violating electron scattering off atomic electrons and nuclei to probe new physics at energy scales of 10 to 20 TeV.

## THE COMPASS EXPERIMENT AT CERN

The measurements performed by Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) have improved knowledge of nucleon structure and helped to drive theoretical work, in particular related to both momentum and spatial imaging, setting the stage for much of the nucleon imaging physics program to be executed at the EIC.

The COMPASS experiment at CERN began running in 2002 and has physics programs involving both a muon beam and a hadron beam on fixed targets, with beam energies ranging from 160 to 200 GeV, and a muon-hadron luminosity of a few times $10^{31}$ cm$^{-2}$s$^{-1}$ (Figure 5.3). COMPASS builds upon a long legacy of fixed-target experiments at CERN using muon beams on polarized targets, following the EMC and Spin Muon Collaboration experiments. Continued running is currently planned through 2018, and there is a proposal to extend COMPASS data taking through 2021. The muon beam physics program includes lepton scattering and exclusive measurements on nuclear targets containing both longitudinally and transversely polarized nucleons. These measurements focus on the spin structure of the nucleon, as well as on momentum and spatial imaging of polarized and unpolarized nucleons. In the hadron-beam physics program, most of the data have been taken with pion beams. Negative pion beams are used to perform momentum imaging of transversely polarized protons, and to test understanding of color


**FIGURE 5.3** View of the COMPASS experiment in a target hall of the Super Proton Synchrotron accelerator at the European Organization for Nuclear Research (CERN). SOURCE: CERN, "View from the Crane of the COMPASS Experiment Facility," © 2011-2018 CERN, http://cds.cern.ch/record/1370231, accessed August 13, 2018.

interactions and how they differ in the related processes of lepton scattering and lepton production via quark-antiquark annihilation.

An EIC, with its variable energy and almost hermetic detectors, will greatly extend the kinematic coverage for lepton-nucleon scattering beyond that accessible by COMPASS, reaching larger center-of-mass energies, lower $x$ and higher $Q^2$, and accumulating much larger data samples, with uniquely abundant statistics, especially in the gluon-dominated regime. The EIC will additionally perform a comprehensive program of lepton scattering and exclusive measurements on nuclei.

## RHIC AT BROOKHAVEN NATIONAL LABORATORY

### RHIC Collider

The RHIC, which has operated at Brookhaven National Laboratory (BNL) since 2000, was the first hadron collider to collide heavy nuclei and it also collides polarized protons (Figure 5.4). It is expected to operate into the 2020s. Most of the RHIC runs have collided gold ions, but numerous other combinations including gold on deuterons or protons, as well as a range of nuclei from copper to uranium have been collided.[5]

RHIC built on the alternating gradient synchrotron (AGS; constructed in the late 1950s) and other machines at BNL, which now form its injector chain. The collider itself consists of two 3.8 km circumference rings of superconducting magnets, in which protons can be accelerated to energies of 255 GeV and heavy ions to 100 GeV/nucleon. BNLs long and distinguished record of innovation in accelerator physics and technology, with a strong orientation to the needs of physics programs, has continued with the RHIC machine.

Among numerous innovations enabling continual performance upgrades beyond design expectations, the heavy-ion luminosity was substantially upgraded, at low cost, with the implementation of bunched beam stochastic cooling. RHIC remains the only hadron collider that has succeeded in accelerating and colliding polarized proton beams. This experience is a crucial foundation for an EIC that must also accelerate and store polarized proton beams.

Projections for the RHIC collider extending to 2027, with a variety of nuclei and further polarized proton performance, have been given.[6]

## The RHIC Physics Program Within the Context of the EIC

In operation since 2000, RHIC was designed to study QCD, with focus on high energy densities, the creation and study of a quark-gluon plasma, and the polarized structure of the proton. The current RHIC community is one of the principal communities interested in realizing an EIC. With a user community of approximately 1,000 scientists, RHIC has had two large, multipurpose experiments, the Solenoidal Tracker at RHIC (STAR) and the Pioneering High Energy Nuclear Interaction Experiment (PHENIX), involved in the full breadth of its physics program. PHENIX concluded operations in 2016, and the sPHENIX experiment is anticipated to start taking data in 2023. STAR will continue to run until at least the early 2020s. Two smaller experiments, BRAHMS and PHOBOS, finished operations in the mid-2000s.

There are many connections between the RHIC program, the proton structure part in particular, and that envisioned at an EIC. RHIC's high-energy polarized proton beams and collider configuration allow the spin structure of the proton

[5] W. Fischer and J.M. Jowett, 2014, Ion colliders, *Reviews of Accelerator Science and Technology* 7:49.

[6] W. Fischer, M. Blaskiewicz, A. Fedotov, H. Huang, C. Liu, G. Marr, M. Minty, V. Ranjbar, and D. Raparia, 2017, RHIC Collider Projections (FY 2017-FY 2027), Brookhaven National Laboratory Note, May 2017.

**FIGURE 5.4** Aluminum tubes with spiraling grooves were used for the construction of 48 full-twist superconducting helical dipoles for the Siberian snakes and spin rotators that allowed the acceleration and collision of up to 250 GeV polarized protons at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. SOURCE: Brookhaven National Laboratory.

to be studied at large $Q^2$ compared to polarized fixed-target experiments, over a relatively wide range of $x$, including significant overlap with the expected EIC kinematic coverage. The RHIC spin program was originally designed with a focus on determining the polarization of gluons in the polarized proton, and on delineating the polarizations of the up and down quark and antiquarks. The main probes sensitive to gluon spin at RHIC are inclusive hadron production, jets, and dijets. In 2014, RHIC announced the discovery of a moderate positive contribution from gluon spin to the spin of the proton; however, uncertainties remain relatively sizable and the measurements are sensitive only to a modest range of gluon momentum fractions $x$. The efforts to constrain the flavor-separated light sea quark helicity distributions at RHIC are based on the production of W-boson in polarized proton collisions and their subsequent decay into electrons, positrons, and muons, taking advantage of both the parity-violating nature and the flavor sensitivity of the weak interaction. RHIC has found evidence for a flavor-asymmetric polarized sea, which is presently stimulating further theoretical work. Measurements with transversely polarized beams at RHIC made the surprising discovery that the large spin-momentum correlations in forward hadron production initially observed with low-energy polarized hadronic collisions in the 1970s persist up to the maximum RHIC center-of-mass energy of 510 GeV and at hard scales of up to $Q^2 \sim 50$ GeV$^2$. The large size of these asymmetries and their intricate relationships to the typically smaller transverse spin effects observed in polarized deep-inelastic lepton-nucleon experiments have contributed considerably to the renewed interest in QCD phenomena with transverse spins and to advances in their understanding. The EIC will combine the strengths of the kinematic reach at a collider with the discriminating power of a lepton probe to elucidate the nucleon's internal spin structure.

The study of the quark-gluon plasma and exploration of the QCD phase diagram are not part of the EIC physics program; however, improving knowledge of the partonic structure of nuclei is part of both the RHIC heavy ion and EIC physics programs. RHIC, in a similar spirit to an EIC, was designed to perform measurements with pp, p/dA, and AA collisions (where A denotes nuclei heavier than the deuteron) in matching kinematics, so that nuclear effects could be understood in relation to the proton. Deuteron-nucleus collision data from RHIC (as well as proton-nucleus data from the LHC, see later) have already been included in global fits of nuclear PDFs,[7] with recent RHIC proton-nucleus measurements to be included in future fits. The kinematic reach of RHIC and its experiments is predicted to include a regime in which gluon distributions in nuclei saturate, and measurements for hadron production in dA, particularly in forward kinematics,

[7] K.J. Eskola, P. Paakkinen, H. Paukkunen et al., 2017, EPPS16: Nuclear parton distributions with LHC data, *Eur. Phys. J. C* 77:163, Table 1 and Figure 2, https://doi.org/10.1140/epjc/s10052-017-4725-9, accessed August 13, 2018.

have been cited as evidence for gluon saturation. However, with multiple effects potentially contributing to measurements in the complex environment of p/dA collisions, definitive interpretations of the data have proven elusive. An EIC, with a lepton beam on a variety of light and heavy nuclei at a range of center-of-mass energies, would make precision measurements of the flavor-separated partonic structure of nuclei through inclusive, semi-inclusive, and exclusive observables, comparable to similar measurements performed on protons. In the clean environment of lepton-nucleus collisions, and with critical kinematic coverage allowing calculations of observables sensitive to gluon saturation effects using both theoretical techniques specific to a saturation regime and traditional perturbative methods of calculation in QCD, definitive studies of gluon saturation will be possible at an EIC. RHIC has additionally performed a handful of diffractive measurements in ultraperipheral collisions and plans to make further measurements over the next several years. Such measurements are expected to offer insight on the magnitude of certain diffractive observables planned for an EIC.

## LHC AT CERN

The LHC is the largest and highest energy particle collider in the world. It is operated by CERN at its laboratory near Geneva, Switzerland. CERN, is an international organization with 22 Member States but serves the global particle and nuclear physics community. The United States, along with Japan and Russia, has long been an Observer State, and physicists from U.S. universities and national laboratories are major participants in the LHC program. In 2016 the 1,925 U.S.-based users were the largest national contingent at CERN.[8]

The first feasibility study of the LHC took place in 1983 and the machine was turned on in 2008, after many years of R&D on the technologies required for the accelerator and its experiments. The two rings of the LHC are composed of superconducting magnets in an approximately circular tunnel of 27 km circumference that previously housed the LEP electron-positron collider. Its injector complex includes several preexisting accelerators that have served many physics programs since the late 1950s. Decades of operation and continual improvement has allowed these machines to far exceed their initially foreseen capabilities.

The LHC spends most time colliding beams of protons for the elementary particle physics program. A major result of the pp program was the discovery of the Higgs boson in 2012. Proton beam operations have also led to a vast wealth of high-energy QCD results and the first exotic hadronic states have now been observed conclusively. In addition, a typical operating year includes 1 month devoted

[8] "CERN Users by Institute and Nationality 2016," http://usersoffice.web.cern.ch/annual-statistics, accessed August 13, 2018.

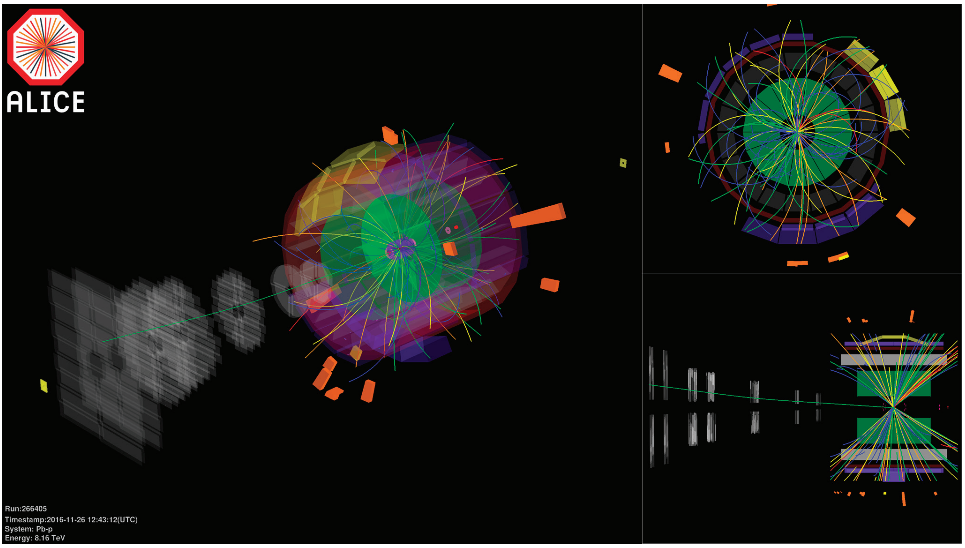


**FIGURE 5.5** A collision between a lead nucleus, with a total energy of 533 TeV and a proton of energy 6.5 TeV, yielding an average 8.16 TeV per colliding nucleon pair, recorded in detail by the ALICE detector at the Large Hadron Collider in late 2016. SOURCE: ALICE Experiment, European Organization for Nuclear Research (CERN).

to the nuclear (or "heavy-ion") collision program.[9] So far, lead nuclei have been collided with each other (PbPb) or with protons (pPb). A short pilot run colliding xenon nuclei (XeXe) took place recently, demonstrating the capability of the CERN complex to accelerate and collide other species if required in the future.

The total energy concentrated into nuclear volumes in the LHC's Pb-Pb collisions, at over 1,000 TeV, is by far the highest achieved to date in any human-made particle collision. In nuclear physics the convention is to quote the center-of-mass energy per colliding nucleon-pair, which is at present 13, 8.16, and 5.02 TeV for pp, pPb, and PbPb collisions, respectively. After a total of about 11 weeks operation for Pb-Pb and 8 weeks for p-Pb collisions, solutions have been found to most of the expected performance limits and peak luminosity levels are already far beyond design.

The heavy-ion program of the LHC is largely driven by the specialized experiment A Large Ion Collider Experiment (ALICE), but all other large experiments, ATLAS, CMS, and LHCb (originally conceived for flavor physics), now participate in this program (Figure 5.5).

In addition to the nucleus-nucleus (AA) collisions, pp and pA collisions at

[9] W. Fischer and J.M. Jowett, 2014, Ion colliders, *Reviews of Accelerator Science and Technology* 7:49.

equivalent energies play a vital role in the experiments' programs. The forward region of pA collisions may probe the very small $x$ region of a nucleus and has implications for cosmic ray experiments. These pp, pA, and AA studies have stimulated much excitement and controversy concerning possible effects arising from effect of high gluon density, and studies at an EIC would do much to resolve various interpretations.

Although no electron-hadron collider is presently foreseen in Europe (see the discussion of the Large Hadron-Electron Collider later in this chapter), the continued running of the LHC above design luminosities in these modes in the coming years and decades will bring many results complementary to but relevant to an EIC. The general reason for this connection is that, at the very high (10 TeV) energy scale of the LHC, the bulk of all particles produced in all three collision combinations originate from processes involving gluons, a consequence of the dominance of gluons at low $x$ in hadrons. Furthermore, because of the very high LHC energy, very low $x$ values, down to the range of $x = 10^{-6}$ are reachable, albeit not in the same clean and controlled conditions as at an EIC. This means, in particular, it is generally very difficult to determine precisely the important scale parameters $Q^2$ and $x$ in hadronic collisions.

Recent studies at LHC energy of pp and pPb collisions as a function of charged particle multiplicity have revealed interesting and unexpected features. As the multiplicity increases to and beyond several times the average (inclusive) multiplicity, the collisions exhibit signs of apparent collective behavior. These include azimuthal anisotropies and azimuthal correlations that are smaller in magnitude but similar in shape to the hydrodynamic flow distributions observed dramatically in PbPb collisions. Some, but not all, of these results can be well described in models based on gluon saturation, where the hadronic wave functions are described in the framework of a color-glass condensate (see Chapter 2). At transverse momenta of the order of a few GeV, $x$ values in the range of and below $10^{-4}$ can be reached, especially at forward rapidity (very close to the forward-going proton-beam direction).

Another area where low $x$ gluon distributions can be probed is open charm (i.e., hadrons with nonzero net charm) production at forward rapidity. First results from the LHCb collaboration indicate that such data will be very valuable to constrain the magnitude of gluon PDFs at low $x$. These studies are being extended to pPb collisions leading to results on gluon distributions in heavy nuclei at low $x$, that is, deep into the saturation region. Unfortunately, $Q^2$ cannot be varied independently. Nevertheless, such data will be very valuable to test predictions from models based on gluon saturation.

Furthermore, open charm and open bottom production will also be studied in eA collisions at an EIC. Together with the results from the pPb program at the LHC this should allow fundamental tests of high-energy QCD predictions for energy loss of heavy quarks in a dense (gluonic) medium.

An emerging program at the LHC is the study of ultra-peripheral collisions in pPb and PbPb. These collisions (or, rather, near-misses) are experimentally defined such that the impact parameter is large compared to the sum of the radii of the colliding hadrons or nuclei. In such collisions, a photon from one of the colliding particles can penetrate into the other, providing an effective means to study photon-nucleus collisions at very high energy. Of particular interest are photonuclear collisions involving the exclusive production of light vector mesons ($\rho$, $\omega$, $\Phi$) and of heavy quarkonia ($J/\psi$ and $\Upsilon$ particles). All of these can, and will, be studied with precision at the LHC, in particular in the ALICE and LHCb experiments. Since photonuclear cross sections scale, at leading order, as the square of the gluon distribution in the relevant nucleus, they provide an excellent tool to probe gluon distributions at low $x$, albeit at fixed (low) $Q^2$. First results have been presented,[10,11,12,13,14,15] and many more are to come.

The future operation of the LHC and its upgrading to the High-Luminosity LHC (HL-LHC) is a central plank of the European Strategy for Particle Physics:[16]

> Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade program will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

The HL-LHC upgrades will be implemented in the 2020s and are expected to be exploited until around 2035. The upgrades include improvements to the injector complex and the LHC itself that will allow the heavy-ion program at the LHC to exceed its initial luminosity goal of 1 $nb^{-1}$ in two experiments (ALICE and CMS) to 10 $nb^{-1}$ in three experiments (ALICE, ATLAS, and CMS) plus LHCb. The present heavy-ion program is foreseen to continue until 2029.

The Nuclear Physics European Collaboration Committee (NuPECC), essentially the analogue of the Nuclear Science Advisory Committee (NSAC) in Europe,

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10 H. Paukkunen, 2017, Status of nuclear PDFs after the first LHC p-Pb run, *Nucl. Phys.* A967:241.

11 S. Klein, 2017, Ultra-peripheral collisions and hadronic structure, *Nucl. Phys.* A967:249.

12 E. Kryshen, 2017, Photoproduction of heavy vector mesons in ultra-peripheral Pb-Pb collisions, *Nucl. Phys.* A967:273.

13 M. Dyndal, 2017, Electromagnetic processes in ultraperipheral Pb-Pb collisions with ATLAS, *Nucl. Phys.* A967:281.

14 H. Mäntysaari et al., 2017, Proton structure fluctuations: Constraints from HERA and applications to pA collisions, *Nucl Phys.* A967:317.

15 D. d'Enterria et al., 2017, Physics with ions at the Future Circular Collider, *Nucl. Phys.* A967:888.

16 "The European Strategy for Particle Physics Update 2013," CERN-Council-S/106, http://cds.cern.ch/record/1567258/files/esc-e-106.pdf?subformat=pdfa.

recently published its 2017 long-range plan.[17] NuPeCC considers it "crucial that all aspects of the LHC heavy-ion program, including manpower support and completion of the detector upgrades, are strongly supported."

## OTHER FUTURE ELECTRON-HADRON COLLIDER PROPOSALS

### LHeC

The Large Hadron-Electron Collider (LHeC) has been proposed[18] as an extension of the present LHC that would provide ep or eA collisions simultaneously with the LHC's pp or AA collisions. To achieve this, a large energy recovery linac (ERL) would have to be constructed in a new 9 km racetrack-shaped deep-underground tunnel. The electron-hadron collisions would occur at one of the present interaction points of the LHC, requiring the replacement of one of the present experiments with a new detector designed for these collisions. Parameters of the LHeC for ep collisions are given in the first two columns of Table 5.2.

The LHeC is designed to have 10 to 20 times higher center-of-mass energy, and nearly 1,000 times higher luminosity, than HERA. Therefore, the LHeC extends the kinematic range accessed with HERA on the proton from a maximum momentum transfer squared, $Q^2$, of about 0.03 $(\text{TeV}/c)^2$ to above 1 and from a maximum $x$ of about 0.6 to 0.9. Furthermore, the low $x$ range extends down to $10^{-6}$. In addition, the LHeC would have the ability to study nuclei in electron-ion collisions, which was not possible at HERA.

Selected science highlights of the LHeC Study Group[19] are described in the following sections.

#### *High-Precision Studies of QCD and Electroweak Physics*

Thanks to the wide kinematic range, high luminosity, and possibility of beam variations, the LHeC would provide the necessary constraints on all parton (quark and gluon) distributions to determine PDFs completely, free of conventional QCD fit assumptions, which has hitherto not been possible.

The strong coupling constant $\alpha_S(M_Z^2)$ can be measured to parts-in-a-thousand precision, as compared to the percent level today. Such a measurement would put attempts to study whether the strong, electromagnetic, and weak forces become

[17] A. Bracco et al., eds., 2016, "NuPECC Long Range Plan 2017 Perspectives in Nuclear Physics," European Science Foundation, http://www.nupecc.org/lrp2016/Documents/lrp2017.pdf.

[18] The LHeC Study Group, 2012, A Large Hadron Electron Collider at CERN, *J. Phys. G: Nuclear and Particle Physics* 39:075001.

[19] Ibid.

**TABLE 5.2** Baseline Parameters for e-p Collisions at Three Potential Future Lepton-Hadron Colliders that might be built as Extensions of the CERN Complex

| Parameter | LHeC CDR | ep at HL-LHC | ep at HE-LHC | FCC-he |
|---|---|---|---|---|
| $E_p$ [TeV] | 7 | 7 | 12.5 | 50 |
| $E_e$ [GeV] | 60 | 60 | 60 | 60 |
| $\sqrt{s}$ [TeV] | 1.3 | 1.3 | 1.7 | 3.5 |
| Bunch spacing [ns] | 25 | 25 | 25 | 25 |
| Protons per bunch [$10^{11}$] | 1.7 | 2.2 | 2.5 | 1 |
| $\gamma\varepsilon_p$ [μm] | 3.7 | 2 | 2.5 | 2.2 |
| Electrons per bunch [$10^9$] | 1 | 2.3 | 3.0 | 3.0 |
| Electron current [mA] | 6.4 | 15 | 20 | 20 |
| IP beta function $\beta^*_p$[cm] | 10 | 7 | 10 | 15 |
| Hourglass factor $H_{geom}$ | 0.9 | 0.9 | 0.9 | 0.9 |
| Pinch factor $H_{b-b}$ | 1.3 | 1.3 | 1.3 | 1.3 |
| Proton filling $H_{coll}$ | 0.8 | 0.8 | 0.8 | 0.8 |
| Luminosity [$10^{33}$ cm$^{-2}$s$^{-1}$] | 1 | 8 | 12 | 15 |

NOTE: This reference also provides parameters for electron-ion collisions. With the proton and heavy-ion beams foreseen for the future High-Luminosity Large Hadron Collider (HL-LHC) (third column), it would be possible to provide higher luminosity than foreseen at the time of the Large Hadron-Electron Collider (LHeC) Critical Design Review (CDR) (second column). Realizations of an electron-hadron collider by constructing a large energy recovery linac (ERL) next to the High-Energy LHC (HE-LHC) or Future Circular Collider (FCC) hadron colliders could yield the performance indicated in the fourth and fifth columns.

SOURCE: O. Bruning, J.M. Jowett, M. Klein, D. Pellegrini, D. Schulte, and F. Zimmermann, 2017, "Future Circular Collider Study FCC-he Baseline Parameters," CERN-ACC-2017-0019, April, http://cds.cern.ch/record/2260408, accessed August 13, 2018.

comparable in strength at the grand unification scale, some $10^{16}$ GeV, on a firm footing.

### *Low* x *Physics*

The most pressing issue in low *x* physics is the need for a mechanism to tame the growth of the parton density, which, from very general considerations, is expected to be modified in the region of LHeC sensitivity. There is a wide, though nonuniversal, consensus that nonlinear contributions to parton evolution (e.g., via gluon recombination gg $\rightarrow$ g) eventually become relevant and the parton densities saturate. The LHeC offers the unique possibility of observing these nonperturbative dynamics at sufficiently large $Q^2$ for weak-coupling theoretical methods to be applied, suggesting the exciting possibility of an understanding at the parton-level of the collective properties of QCD.

*Nuclear Structure at High Energy*

Structure function measurements and their flavor decompositions in eA will allow nuclear parton densities at small $x$ to be measured, testing current methods of extraction, particularly for the gluon density for $x < 10^{-2}$, and the unknown charm and beauty densities in nuclei, quantities which are presently almost unconstrained by experimental data.

Exclusive vector meson production in eA collisions will offer a handle complementary to ep, on the possible evidence of nonlinear dynamics and saturation of partonic densities, as these effects increase with A.

The dynamics of hadronization and QCD radiation will be clarified in e-A collisions through semi-inclusive measurements of both particles and jets, of which large yields will be produced up to high transverse momenta. The effects of the nuclear environment will be explored through the modification of yields, the variety of hadron species produced, jet substructure, and so on, compared to equivalent ep measurements.

The science motivating the LHeC has significant overlap with that motivating the EIC. However, there is also substantial complementarity between the projects both in terms of scientific motivation and timescale for realization. While the LHeC would push to lower $x$, an EIC would have high luminosity polarized electron and nucleon beams. In electron-ion collisions, an EIC will probe the approach to saturation while the LHeC would be more likely to reach the saturation regime. Reasonably, an EIC would be realized first and a later LHeC would still have a first-rate science case.

## Status of the LHeC Proposal

In Europe, there is currently no plan for an EIC-like facility. After the 2013 European Strategy for Particle Physics process, the plans for the LHeC project at CERN were not pursued actively. However, a significant amount of work is ongoing to prepare discussions on such an accelerator for the upcoming 2019-2020 European Strategy for Particle Physics deliberations. In any case, such a facility could only be realized for the final phase of LHC operations in the 2030s.

## HE-LHC-he

The High-Energy LHC (HE-LHC)[20] is another potential future hadron collider based on replacing the present LHC superconducting magnets with higher-field

[20] O. Bruning, J.M. Jowett, M. Klein, D. Pellegrini, D. Schulte, and F. Zimmermann, 2017, *Future Circular Collider Study FCC-he Baseline Parameters*, CERN-ACC-2017-0019, April, http://cds.cern.ch/record/2260408, accessed August 13, 2018.

magnets, employing Nb-Sn technology, in the existing LHC tunnel. It could potentially provide ep and eA collisions simultaneously with pp or AA collisions. It would use the same ERL to provide electron beams similar to those envisaged for the LHeC but would collide them with hadron beams of up to twice the energy. This might succeed the LHC to become operational in the late 2030s.

### FCC-he

A further potential long-term step at CERN is the Future Circular Collider (FCC-hh) a hadron collider built with Nb-Sn magnets in a new 100 km tunnel in the Geneva area. It would use the existing CERN complex as its injectors. This collider might succeed the LHC to become operational in the 2040s. Again, with the additional construction of a large ERL, it could provide ep and eA collisions simultaneously with pp or AA collisions.

## ELECTRON-POSITRON COLLIDERS

The majority of particle colliders built for elementary particle physics research since the early 1960s have been electron-positron colliders. In terms of energy reach, these culminated in the Large Electron Positron Collider (LEP) at CERN which attained a center-of-mass energy of 200 GeV thanks to massive deployment of superconducting RF cavities. Its 27 km tunnel is now occupied by the LHC. More recent $e^+e^-$ colliders, such as DAΦNE in Frascati (Italy), and the B-factories at SLAC and KEK (Japan), have been built to explore the intensity frontier by revisiting lower energies with much higher luminosity than their predecessors. Indeed, these machines have pioneered much of the technology needed for the present EIC proposals: high-intensity, multibunch electron rings, SRF technology, crab cavities, electron-cloud mitigation, and advanced interaction region designs. The electron rings of the EIC design concepts have much in common with them.

The $e^+e^-$ colliders, LEP in particular, have among numerous other achievements made a profound impact on the understanding of how color-carrying quarks transform into color-neutral hadrons. This knowledge, encoded in what are called "fragmentation functions," is essential in relating observations at other facilities to the underlying physics. The knowledge of fragmentation functions has made it possible, for example, to relate neutral pion production in polarized proton collisions to the gluon spin distribution in the polarized proton, thereby complementing the insights gained from jet measurements at RHIC. Recent fragmentation measurements with Belle at the KEK B-factory have revealed a rich interplay between spin and transverse momenta, which enable determinations of quark transversity, a quark spin distribution related to the nucleon tensor charge and electric dipole moment from the azimuthal distributions of hadrons produced in polarized deep-inelastic lepton-nucleon collisions, such as those at JLab. These and other fragmentation measurements will continue to have important roles at a future EIC, where they form also the vacuum baseline for studies of hadronization in nuclei (see Figure 2.3.1 in Box 2.3).

## RELATED NUCLEAR PHYSICS FACILITIES

The preceding sections covered facilities whose scientific programs have quite direct relations to that of the proposed EICs. Among facilities, existing, planned, or proposed worldwide, there are a few others that have some less direct connections. For the sake of completeness, they are covered in this section.

### FAIR at GSI

The Facility for Antiproton and Ion Research (FAIR) is currently under construction at the GSI Helmholtz Center for Heavy Ion Research at Darmstadt, Germany. It will come online around 2024, while a phase-0 program of experiments using the detectors and accelerators already available will start in 2018. The FAIR accelerators will provide intense beams of heavy ions and antiprotons in a wide energy range up to 10 GeV/nucleon. Its main physics focus will be in four research areas: atomic physics, plasma physics, and applications; nuclear matter physics with the High Acceptance Dielectron Spectrometer and Compressed Baryonic Matter detectors; nuclear structure, astrophysics, and reactions with the Nuclear Structure, Astrophysics, and Reactions detectors; and physics with high-energy antiprotons with the PANDA detector.

While much of the FAIR physics program is concentrated on areas outside the focus of an EIC, the PANDA experiment plans to measure processes like proton + antiproton → 2 photons and proton + antiproton → dileptons. The resulting data should be interesting for and complementary to EIC physics in that they open new avenues to measure deeply virtual Compton scattering and to probe distributions in the nucleon that change sign under time reversal.

### HIAF and an EIC in China

In the past decade or so, the Chinese central and local governments started to make major investments in large-scale accelerator-based facilities. One such example is the Shanghai Synchrotron Radiation Facility, which was built and supported jointly by the Chinese Academy of Sciences and the Shanghai government. The High Intensity Heavy-Ion Accelerator Facility (HIAF), officially approved by the Chinese government at the end of 2015, is one of the 16 large-scale research facilities proposed to boost China's capabilities in basic science research during the country's twelfth 5-year plan. HIAF will address a number of important questions in nuclear physics and nuclear astrophysics such as the following: What are the limits to nuclear existence? What are new forms of nuclear matter far from stability? How were elements from carbon to uranium created? How is energy generated in stars and stellar explosions? The construction of HIAF is currently under way in Huizhou, a city in the southeast part of China.

In the past several years, Chinese physicists, together with collaborators in the United States, proposed a concept of a polarized EIC at HIAF. EIC@HIAF would be an extension to the originally proposed HIAF. The China EIC would include 3 to 5 GeV polarized electrons on 12 to 23 GeV polarized protons (and ions about 12 GeV/nucleon), with luminosities of 1 to $2 \times 10^{33} cm^{-2}\ s^{-1}$ for stage 1 design. Such a facility would allow for the studies of the spin and the exploration of three-dimensional nucleon structure in both the valence and sea quark regions, the studies of QCD dynamics, and advance understanding of the strong force. While this plan for an EIC in China received strong support from the Chinese high-energy and nuclear physics communities, the project has not been funded, and the timing for its construction is uncertain.

## J-PARC

The Hadron Experimental Facility of the Japan Proton Accelerator Research Complex (J-PARC) provides the world's highest-power beams for particle and nuclear experiments. The primary proton beam of 30 GeV at J-PARC is slowly extracted from the Main Ring accelerator and transported to the production target in the experimental hall. Various secondary particles, such as K and $\pi$ mesons produced in the target, are transported through the secondary beam lines to the experimental area and are used for particle and nuclear physics experiments. The construction of the facility was started in 2004, and the first beam was extracted to the hall on January 27, 2009. The formal beam operation for users started in January 2010.

The J-PARC particle physics experiments on rare decay and searches for lepton flavor violation will shed light on unanswered fundamental questions, such as the mechanism to realize the dominance of matter over antimatter in the universe and the nature of dark matter. Nuclear physics experiments investigate the nature of hadrons and nuclear matter in various environments—such as the high temperature in the early universe and the high density in the core of neutron stars—to clarify the origins of matter in stars (as well as in humans) in the universe.

Plans in the original J-PARC conceptual designs to extend the Hadron Experimental Facility and construct new beam lines for future upgrade are currently being updated and revised. They will include the extension of the experimental hall, additional targets for producing secondary beams, new beam lines and the increase of secondary beam intensities to maximize the physics impact from both nuclear and particle experiments.

### The NICA Project at JINR, Dubna, Russia

The Nuclotron-Based Ion Collider Facility (NICA) at the Joint Institute for Nuclear Research (JINR) is a new superconducting accelerator complex under construction at Dubna, Russia, and is expected to be in operation by about 2020. Beams will be injected into NICA from the existing nuclotron machine. NICA will deliver intense beams of ions from protons to gold as well as polarized protons and deuterons with maximum energy $\sqrt{s_{NN}} = 11$ GeV (for $Au^{79+}$) and 27 GeV (for protons). The expected luminosity is $10^{27}$ $cm^{-2}s^{-1}$ for gold and $10^{32}$ $cm^{-2}s^{-1}$ for protons.

The scientific motivation is to study hot, dense baryonic matter and to investigate polarization phenomena, including nucleon spin structure. NICA will explore the QCD phase diagram in the terra incognita of highest net baryon density and will be complementary to RHIC, LHC, and FAIR. It will have the potential to discover a critical end-point, the restoration of chiral symmetry, and a hypothetical "quarkyonic phase" in the phase diagram of dense matter. Together with FAIR, it can be regarded as part of a third generation of heavy ion experiments.

A general multi-purpose detector (MPD) concept has been developed. The MPD Collaboration consists of about 200 physicists from 19 institutions in 9 countries. Furthermore, a consortium has been established between the experimental collaborations from Compressed Baryonic Matter/FAIR and MPD/NICA. The MPD detector includes a 0.5 T superconducting solenoidal magnet, charged particle tracking, particle identification, and calorimetry. Design constraints include hermeticity, homogeneous solenoidal field, good tracking performance, high event rate capability, and careful event characterization. It is planned to measure hadrons ($\pi$, K, anti-p, anti-hyperons, light anti-nuclei), and dilepton spectra as a function of energy, system size, centrality, transverse momentum $p_T$, rapidity and azimuthal angle. By about 2020, it is the aim of the MPD Collaboration to localize the QCD critical end point (if it exists) and to investigate it in detail. Measurements of low mass dileptons will also be a priority with the aim to probe for evidence of chiral symmetry restoration.

A second experiment with the aim of studying nucleon spin structure is also under development. It is planned to study the spin-dependent Drell-Yan process using both longitudinally and transversely polarized protons and deuterons to extract new parton distribution functions in a much lower kinematic range than at an EIC.

# 6

# Impact of an Electron-Ion Collider on Other Fields

As a major new scientific instrument, the design, construction, and operation of an electron-ion collider (EIC) would offer significant benefits to other fields of science and to society. In this chapter, these contributions and benefits are summarized.

## ROLE OF AN EIC IN U.S. ACCELERATOR SCIENCE

Chapter 4 described two concepts to realize an EIC accelerator that have been developed: one based on the existing Relativistic Heavy Ion Collider (RHIC) complex at Brookhaven National Laboratory (BNL), called eRHIC; and a second based on the existing Continuous Electron Beam Accelerator Facility (CEBAF) accelerator at the Thomas Jefferson National Accelerator Facility (JLab), called the Jefferson Laboratory Electron Ion Collider (JLEIC). Ring-ring concepts have been developed for both eRHIC and JLEIC. An advanced linac-ring concept using an energy-recovery linac (ERL) has also been developed for eRHIC although the ring-ring option is now preferred by BNL. All EIC concepts are technically challenging and motivate a significant research and development (R&D) effort in the United States. This effort addresses fundamental issues in accelerator physics that are of broad interest beyond the nuclear physics community. Several examples of EIC R&D research are highlighted here.

## Specific Benefits of EIC R&D

*Applications of ERLs*

Compact and cost-effective ERLs can be used as drivers for high-power free-electron lasers (FELs), which are photon sources with applications in many fields of scientific research and industry. A number of ERLs have already been constructed around the world and there are plans for more in several laboratories.[1] The ERLs required for the EIC are among the most demanding designs under consideration.

*Strong Hadron Beam Cooling*

High-energy bunched-beam cooling was a spectacularly cost-effective upgrade to the luminosity performance of RHIC. However, the stochastic cooling technique used at RHIC is not powerful enough for the requirements of future hadron colliders such as an EIC. The novel concept of coherent electron cooling (CeC), developed by scientists at BNL and JLab, holds the promise of a very high-bandwidth and a fast method to cool hadron beams and achieve high luminosity. If the proof-of-principle experiment at BNL eventually leads to successful implementation, it would potentially be of very high interest for other future hadron colliders in a range of energies, perhaps up to that of the Large Hadron Collider (LHC).[2] Even if no such colliders are envisaged, beyond an EIC itself, establishing this principle and rendering it operational would be a tour de force of advanced accelerator technology, which would surely have multiple indirect benefits.

*Superconducting RF Technology*

Particle acceleration by means of superconducting radio frequency (SRF) cavities is an established technology with over 30 years of application. Early deployments included the recyclotron at the Hansen Experimental Physics Laboratory (HEPL), the microtrons at Illinois, in the United States, and Darmstadt, Germany, and the Cornell Electron Storage Ring at Cornell University, as well as large systems in the electron-positron colliders TRISTAN (at High Energy Accelerator Research Organization [KEK], Japan) and LEP (at the European Organization for Nuclear Research [CERN]), which allowed high energies to be reached without prohibitive power consumption. In the United States, the CEBAF accelerator pioneered

[1] "The 59th ICFA Advanced Beam Dynamics Workshop, the 7th International Workshop on Energy Recovery Linacs," CERN, June 18-23, 2017, https://indico.cern.ch/event/470407/.

[2] Coherent electron cooling is not obviously useful at higher energy colliders like FCC-hh, discussed in Chapter 5, where the beam energies are so high that natural synchrotron radiation damping already provides sufficient cooling.

the application of SRF technology on a large scale and JLab is a national center of expertise for SRF. The technology continues to evolve to meet the challenges of very high current beams and the R&D for machines like B-factories, light sources, and the EICs. Considering the acceleration systems required for the eRHIC storage ring and the injector ERL, there are clear synergies and common developments in the areas of multicell superconducting cavities and high-power adaptive couplers.

Besides the main accelerating cavities, the EICs require crab cavities installed close to their interaction points to locally rotate both beams and enhance the luminosity when they collide. Here there is a very strong synergy with the developments under way at BNL of similar devices for installation in the High-Luminosity Large Hadron Collider (HL-LHC). Crab cavities were operated successfully in a hadron accelerator, the SPS at CERN, for the first time only very recently.

*Electron Cloud Mitigation*

Electron clouds are a major challenge for all accelerators with positively charged high intensity beams. Operating accelerators (e.g., RHIC, LHC, and Super KEK-B) devote significant time to "scrubbing" the vacuum chamber to reduce secondary electron yield and there are well-established collaborations performing R&D to mitigate this problem. To achieve a further factor of 2 in proton beam intensity beyond RHIC, in situ coating techniques are under development for eRHIC at BNL. This technology would apply a low-impedance 10 μm copper layer to the present stainless-steel RHIC beam pipe which would then be further coated with carbon to reduce the secondary electron yield. Related developments for the HL-LHC are under way at the Cold Bore Experiment (COLDEX) facility in the CERN SPS. Progress in this effort will benefit future facilities with intense hadron beams in cold-bore beam pipes and, possibly, those with intense positron beams.

*Magnet Technology*

The interaction regions of the present EIC design concepts have to accommodate and strongly focus incoming and outgoing beams of very different energies; allow the installation of crab cavities, spin-rotators, and other elements; and minimize the exposure of the detector to synchrotron radiation. These requirements result in complex and highly constrained geometries and optics, which require special magnets. In the EIC concepts, the fields of the large-aperture high-gradient superconducting quadrupoles that focus the hadron beams have to fall away sharply in the transverse direction to avoid disturbing the electron beam. The design solution has the electron beam passing through special "hoses" in the return yokes of these quadrupoles. These have clear synergies with magnets proposed for the Large Hadron-Electron Collider (LHeC) and Future Circular Collider (FCC-eh) whose design faces similar problems at still higher energies. The electron beam's own focusing has to be provided within actively shielded quadrupoles similar to those proposed for the International Linear Collider (ILC). Bending of that beam will likely require actively shielded super-ferric dipoles.

More generally, the development of the numerous special magnets required for an EIC will build on and sustain the world-leading capabilities of the Magnet Division at BNL, an important resource for accelerator developments in the United States. Magnets using $Nb_3Sn$ superconductors are foreseen to have many applications and are already being applied to the HL-LHC in particular.

*High-Current Polarized Electron Source*

R&D is in progress at BNL and the Massachusetts Institute of Technology on the development of a high-current (50 mA), polarized (80 percent) electron gun that would be needed by the ERL-based design of eRHIC. Although reaching a goal so far beyond the present state of the art was identified as the major technical risk motivating the switch to the storage ring design, the outcome of this R&D could be of importance for future linear collider projects and the existing CEBAF facility. Were it to proceed rapidly enough to permit a switch to the alternative ERL design, it could reduce the costs of construction and operation of the EIC.

## WORKFORCE

A highly qualified workforce trained in nuclear science is vital to the nation's health, economy, and security. Nuclear science is especially relevant to confronting some of the most pressing issues facing humanity. Nuclear weapons control, carbon-free energy production on a large scale, counter-terrorism, and nuclear medicine are all areas where nuclear physicists play a leadership role. Furthermore, nuclear physicists serve in governments worldwide in leadership positions that address these critical issues. Figure 6.1 shows the distribution of careers of nuclear science Ph.D. recipients from 2006 to 2009.

A landmark study of education in U.S. nuclear science in 2004 recommended an increase of about 20 percent in 5 years in the production of Ph.D.'s in the field. This was significantly motivated by critical needs for nuclear expertise in the area of national security. The most recent assessments report that, at best, U.S. Ph.D. production has been flat. Increasingly, individuals who receive their Ph.D. outside the United States fill positions for young nuclear physicists. Furthermore, the most recent assessments specifically identify workforce challenges in the areas of accelerator science and high performance computing. An EIC can play a very valuable role in sustaining the U.S. nuclear physics workforce for the coming decades.

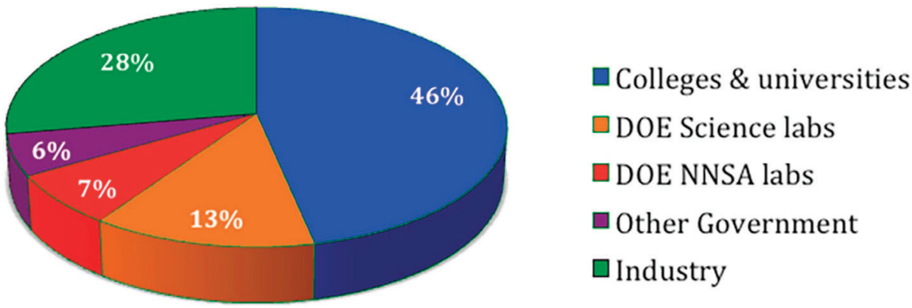


**FIGURE 6.1** Distribution of careers of nuclear science Ph.D. recipients from 2006 to 2009. SOURCE: U.S. Department of Energy and National Science Foundation, *Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science*, October 2015, https://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf.

### Importance of Sustaining a Healthy U.S. Accelerator Community

World-leading discovery science in the United States requires that the nation's accelerator-based, national user facilities have world-leading capabilities to answer the important, open questions in nuclear and high energy physics, in materials, biological and chemical sciences, as well as in applications of these fundamental fields. Next-generation accelerators in the United States such as an EIC will be more challenging to build and to operate safely and cost-effectively than earlier accelerators and detector systems. Highly reliable, small accelerators are also central to advances in medicine and industry, constituting a multibillion-dollar enterprise with over 30,000 particle accelerators in the world.[3] Many of the most exciting innovations in medicine and commerce arise from small commercial companies located contiguous to the accelerator laboratories and universities.

A sustainable supply of highly skilled scientists and engineers is required to meet the challenges in developing accelerators for fundamental science and applied research and development. As the most critical areas of relevant technical expertise are rarely taught in U.S. universities, the Department of Energy (DOE) Office of Science and the National Science Foundation (NSF) must provide workforce development opportunities to ensure rigorous, structured training for graduate students and post-doctoral scholars and the staff already at its national laboratories.[4]

[3] U.S. Department of Energy, *Accelerators for America's Future*, Office of Science, Washington, D.C., 2010.

[4] *Assessment of Workforce Development Needs in the Office of Nuclear Physics Research Disciplines*, Report to NSAC from the Subcommittee on Workforce Development, J. Cizewski (Chair), July 18, 2014.

The U.S. accelerator physics community numbers about 1,100,[5] including staff at the accelerator laboratories and in private industry, and about 35 tenured or tenure-track faculty, staff, and students at about 15 universities. The scarcity of formal Ph.D. programs and lack of advanced graduate-level courses in accelerator science and technology in U.S. universities is directly addressed by the U.S. Particle Accelerator School (USPAS), an effective partnership of major research universities and DOE laboratories. The USPAS plays a particularly important role in educating and training young scientists by providing high-quality courses on essential topics in the physics and technology of beams delivered by world experts at locations around the country on a semiannual basis. Although USPAS courses are typically not held in a traditional campus setting, training modules are academically rigorous and carry direct university graduate credit from the host university for each session.

In nuclear physics, the user facilities at BNL, JLab, and Michigan State University (MSU) retain the vast majority of accelerator physics scientists and engineers in support of operations at RHIC and CEBAF, and of the construction of Facility for Rare Isotope Beams (FRIB) at MSU, respectively. All three of these institutions have active programs in accelerator physics with support coming from DOE/Nuclear Physics, DOE/High Energy Physics, and NSF. The BNL and JLab programs are both supporting relevant R&D for the EIC (and the development of highly trained Ph.D.'s in accelerator science) through the associated Old Dominion University (ODU) and Stony Brook University accelerator physics programs (the Center for Accelerator Physics at ODU and the Center for Accelerator Science and Education that is joint between BNL and Stony Brook). These efforts are important and should receive continued support as preparations are made for the construction of EIC. The 2014 Nuclear Science Advisory Committee (NSAC) subcommittee report on workforce needs in nuclear physics identified[6] significant challenges in attracting and developing a talented U.S. workforce in accelerator science and associated technologies. It recommended an expansion of USPAS courses.

Essential to the vitality of the U.S. accelerator community is the need for R&D on cutting-edge technical challenges. This research both engages the best talent and attracts the brightest young minds to the field. In this regard, the high-priority accelerator R&D identified for an EIC—for example, crab cavity operation in a hadron ring, development of ERLs, strong hadron cooling, magnet design, and polarized source development—demands an intensive and systematic focus by the U.S. particle accelerator community. Clearly, success will demand the participation of scientists and engineers across all of the nation's accelerator laboratories

[5] Official Unit membership of the American Physical Society, 2017.

[6] *Assessment of Workforce Development Needs in the Office of Nuclear Physics Research Disciplines*, Report to NSAC from the Subcommittee on Workforce Development, J. Cizewski (Chair), July 18, 2014.

for an extended period. Furthermore, it presents a highly leveraged opportunity to grow the small university research community. The design and realization of a high-luminosity, polarized EIC represents a singular opportunity for the U.S. accelerator community in that it will demand that core capabilities are kept at the cutting edge and hence position the United States for other future large-scale accelerator projects.

## EIC AND ADVANCED SCIENTIFIC COMPUTING

The goal of understanding how protons, neutrons, their interaction, and nuclei emerge from the strong interaction at a fundamental level calls for the combined strengths of accelerator science, large experiment collaborations and detectors, and theory, each of which are increasingly incorporating advanced scientific computing resources, techniques, and associated research. Nuclear physics, high energy physics, and computing have traditionally had strong synergies driven by mutual interests in high-performance calculations and simulations, in vast data rates and volumes with commensurate analysis demands, and in advanced networking and data sharing. The experiments at the LHC are prime examples, and have been characterized as a resounding success of bold extrapolations and numerous technological breakthroughs.[7] The LHC experiments have collectively been at the forefront of beam-collision rate and event-size right from their start, and will continue to push these boundaries well into the LHC era with high-intensity hadron beams and beyond the scale of the envisioned EIC.

The continued rapid pace of technological development is starting to enable a transition from the event-oriented and triggered data-acquisitions of past and current experiments in nuclear and high energy physics to data models where detector subsystems deliver time-stamped streams of data for processing with increasingly integrated and advanced computing resources in real time. The LHCb experiment, for example, is preparing for triggerless readout for LHC run 3 (2021-2023, prior to an EIC) and will process a data rate of about 5 TB/s in real time on its online central processing unit farm. In view of the inherent advantages, as well as new opportunities, this trend is being pursued broadly in nuclear physics, including for example, for experiments with the future Gamma-Ray Energy Tracking Array instrument to be deployed at FRIB.[8]

Lepton-nucleon scattering experiments past and present provide further con-

[7] S. Cittolin, 2012, The data acquisition and reduction challenge at the Large Hadron Collider, *Phil. Trans. R. Soc. A* 370:954.

[8] See for example, the U.S. Department of Energy, *DOE Exascale Requirements Review—NP/ASCR*, an Office of Science review sponsored jointly by Advanced Scientific Computing Research and Nuclear Physics, Washington, D.C.

text for a future EIC. The completed Hadron-Electron Ring Accelerator (HERA) collider program is of particular relevance. Besides the scientific insights it has delivered and the scientific role it has played, the HERA program also yielded benchmark data on cross-sections and event topologies for projections and advanced simulations for an EIC, as well as invaluable experience for the accelerator, the experiment detectors, and their all-important integration.

EIC luminosities will exceed those achieved at HERA by two to three orders in magnitude. EIC science furthermore requires polarization, heavy-ion beams, a wide range of center-of-mass collision energies, and experiment capabilities to measure a broad range of interaction channels with numerous correlations and in multiple dimensions. Each of these aspects calls for new and detailed simulations to develop full-fledged and optimized designs for the facility as well as the experiments. An EIC will be among the first facilities to come online in the era of exa-scale computing, an era that will see unprecedented integration of computing in the collider and experiments. These developments, combined with continued advances in machine learning and other areas, will open up opportunities for truly new approaches to nuclear physics experiments and analyses of scale, perhaps removing altogether the current distinction between acquiring the data from the instruments and their subsequent analysis.

## LATTICE QCD

The exact theory of the strong interaction is thought to be that provided by quantum chromodynamics (QCD), which has the remarkable property of confinement, in which interacting colored quarks and gluons produce colorless nucleons and nuclei as composite bound states. The complex nature of this continuum theory—it does not lend itself to analytic approximation—rules out any direct solution. However a discrete version of this theory, where space and time coordinates become points on a four-dimensional finite lattice, can be solved given sufficient computing resources. Despite the many technical issues that must be addressed—including the choice of how QCD is adapted to the lattice, the consequences of the finite lattice spacing, and extrapolation from finite computable volumes to infinite volume—lattice QCD (LQCD) can yield effectively exact results with known error bars in many applications.

Ken Wilson formulated QCD on a lattice in 1974, arguing that this discrete restriction of the theory could succeed. In the 40+ years that have passed since his formulation, both LQCD algorithms and computing power have advanced by many orders of magnitude. Over the past 20 years, machine speeds have increased from the terascale—$10^{12}$ flops—to within an order of magnitude of the exascale—$10^{18}$ flops. Remarkably, algorithm advances spurred on by efforts to solve LQCD have contributed equally to the progress. Today, with "cold" LQCD techniques, hadron masses and certain weak interaction couplings can be calculated to a precision of 1 percent. The RHIC program motivated an entirely new thrust of the field—the exploration of the phases of QCD with "hot" LQCD methods.

The EIC comes at an interesting time: A new generation of supercomputers with novel architectures are being installed at Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, and Argonne National Laboratory, and entirely new approaches to the solution of field theories are being considered, such as Hamiltonian methods adaptable to quantum computers. The more challenging problems that the EIC will pose are guaranteed to continue to drive important advances in hardware and algorithms.

The EIC, with its luminosity and polarized beam capabilities, will allow us to look at nucleons and nuclei in much greater detail than is now possible, imaging the transverse momenta and positions of quarks and gluons in relativistic hadrons. EIC experiments will tell us how the nucleon's spin is distributed among its constituents, including the role of sea quark and gluon orbital angular momentum. It will help us learn how gluons interact with each other, fusing and splitting. The committee expects that qualitatively new regimes will be found where the gluons reach an asymptotic density and dominate the dynamics. The EIC will also determine how quark and gluon distributions are altered when nucleons are bound in the nuclei. Such EIC measurements will provide a large set of new challenges for theory generally, and specifically for LQCD.

The parton distribution functions (PDFs) that will be measured at the EIC pose particular challenges for LQCD. The mathematical calculations that arise in LQCD formulations, which are evaluated using simulations on computers, are carried out using a mathematical trick of "imaginary times." This procedure forces the amplitudes associated with quantum states to decay exponentially, with excited state components diminishing faster than in the ground state. This use of imaginary time allows one to "filter out" excited states until only the ground state remains.

However, this procedure fails for PDFs—which describe the longitudinal momentum structure of the nucleon—as these quantities are defined using a time-dependent correlation between quarks and gluons. The LQCD rotation to imaginary time rules out a direct calculation of such time-dependent correlations. Consequently, until recently, calculations have been limited to evaluations of moments (or certain integrals) of PDFs,[9] which can be calculated in LQCD. Unfortunately,

[9] G. Martinelli and C. T. Sachrajda, 1987, Pion structure functions from lattice QCD, *Phys. Lett.* B196:184; M. Göckeler et al., 2001, Lattice calculations of the nucleon's spin-dependent structure function g2 reexamined, *Phys. Rev.* D63:074506, and Investigation of the second moment of the nucleon's g1 and g2 structure functions in two-flavor lattice QCD, 2005, *Phys. Rev.* D72:054507; D. Dolgov et al., 2002, Moments of nucleon light cone quark distributions calculated in full lattice QCD, *Phys. Rev.* D66:034506; Ph. Hägler et al., 2008, Nucleon generalized parton distributions from full lattice QCD, *Phys. Rev.* D77:094502.

technical problems associated with the reduced symmetry of LQCD lattice, relative to real space-time, have so far limited calculations to the first few such moments.[10]

Recently, however, a promising new strategy[11] for directly calculating the PDFs has been proposed. It involves carrying out the LQCD calculation of a modified PDF (called a "quasi-PDF") and then relating it to the true PDF iteratively, using a tool of theoretical physics known as "effective field theory."[12] This feasibility of quasi-PDF calculations in LQCD has been demonstrated in prototype investigations.[13] There are technical issues in the procedure that require further exploration—for example, determining if the lattice extrapolations to infinite volume and vanishing lattice spacings are properly handled through this two-step procedure—but so far studies have supported the soundness of the approach.[14]

Even with this new procedure, LQCD calculations of hadrons carrying large momenta will be computationally challenging. However, there is great optimism in the field that the theoretical quantities most relevant to the EIC program are now within reach of the technique. This means that LQCD could become the standard tool for interpreting EIC measurements and for guiding its future program. Anticipated algorithmic and hardware improvements over the next decade will help the field reach this goal.

## CONNECTION TO CONDENSED MATTER AND ATOMIC PHYSICS

Condensed matter physics is concerned with emergent behavior in many-body systems of atoms and electrons. Historically, nuclear physicists have studied the many-body properties of nuclear matter and finite nuclei. Many of these studies

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[10] W. Detmold, W. Melnitchouk, and A.W. Thomas, 2001, Parton distributions from lattice QCD, *Eur. Phys. J. Direct* 3:1; J. W. Negele, 2002, Understanding parton distributions from lattice QCD: Present limitations and future promise, *Nucl. Phys.* A711:281; Ph. Hägler et al., 2008, Nucleon generalized parton distributions from full lattice QCD, *Phys. Rev. D* 77:094502; Z. Davoudi and M. J. Savage, 2008, Restoration of rotational symmetry in the continuum limit of lattice field theories, *Phys. Rev. D* 86:054505.

[11] X. Ji, 2013, Parton physics on a Euclidean lattice, *Phys. Rev. Lett.* 110:262002.

[12] X. Xiong, X. Ji, and Y. Zhao, 2014, One-loop matching for parton distributions: Nonsinglet case, *Phys. Rev.* D90:014051; X. Ji, A. Schafer, X. Xiong, and J.-H. Zhang, 2015, One-loop matching for generalized parton distributions, *Phys. Rev.* D92:014039; X. Ji, 2014, Parton physics from large-momentum effective field theory, *China Phys. Mech. Astron.* 57:1407.

[13] C. Alexandrou et al., 2015, Lattice calculation of parton distributions, *Phys. Rev.* D92:014502; J.-W. Chen, S.D. Cohen, X. Ji, H.-W. Lin, and J.-H. Zhang, 2016, Nucleon helicity and transversity parton distributions from lattice QCD, *Nucl. Phys.* B911:246.

[14] R.A. Briceno, M.T. Hansen, and C.J. Monahan, 2017, The role of the Euclidean signature in lattice calculations of quasi-distributions and other non-local matrix elements, *Phys. Rev.* D96:014502.

were strongly influenced by advances in condensed matter theory—for example, the discovery of pairing in nuclei and the development of Landau Fermi liquid theory.

Emergent phenomena described by these theories include superfluidity in neutron stars and nuclear collective motion. With the development of QCD, new types of many-body effects were discovered. An important example is chiral symmetry breaking, which is associated with the condensation of quark-antiquark pairs, and which can be understood in analogy with pair condensation or magnetization in metals and nuclei.

Indeed, at this point, with a deeper understanding of QCD, scientists are poised to view nucleons and nuclei as collective many-body systems in which quark and gluon interactions lead to new emergent phenomena. One of these is nucleon itself: 99 percent of the interaction energy of a nuclear system is carried by the simple masses of these "composite fermions," bound states of quarks interacting through gluon exchange. QCD gives rise to completely new many-body phenomena, which are intimately tied to the fact that the gluon interacts with itself, unlike the photons that mediate electromagnetic interactions. One remarkable consequence of this nonlinearity is confinement, the absence of isolated color charges.

An EIC will refine understanding of confinement, but it will also study completely new types of many-body phenomena, those associated with saturation in dense gluonic matter. Saturated gluonic matter is a transient state, which, in collisions of hadrons or nuclei, eventually decays into a quark-gluon plasma. This transition is a new, far-from equilibrium, intrinsically quantum mechanical, and strongly coupled many body phenomenon that promises to reveal new effects that have not been seen in other systems to date. For example, it has been suggested that the decay of saturated gluonic matter into a gluon plasma seeds the formation of topological defects, which create an asymmetry in the handedness of produced quark-antiquark pairs. This handedness manifests itself in heavy ion collisions through interesting transport phenomena, known as "chiral magnetic effects." Analogues of chiral magnetic effects have been discovered in condensed matter systems—for example, in the semi-metal $ZrTe_5$, where they may lead to novel spintronic devices. The initial formation of topological defects in heavy ion collisions is related to the structure of the color field in saturated gluonic matter. Unraveling the structure of these fields is a central goal of an EIC, as described in detail in Chapter 2. The rapid pace at which novel topological materials are being developed suggests that the interaction between QCD and condensed matter physics will continue to be fruitful.

## CONNECTION TO HIGH ENERGY PHYSICS

HERA has played essential roles in the development of QCD. The insights it has given in the gluonic content of the proton, for example, are integral to the physics program at the LHC. Where the LHC is now probing QCD at the energy frontier and challenging the limits of QCD calculations when the color interactions are weak, the EIC will provide essential connections to QCD in regimes that are inaccessible with such techniques. At the most basic level, the EIC will expand understanding of the gluonic content of the proton and extend it to nuclei, which is relevant to present and future high energy physics pursuits at colliders, with neutrinos, or in space. More broadly, the richness of QCD phenomena eludes explanation at present by means of first-principle calculations, and advances continue to require the interplay of experiment and theory. As much of the theoretical work to develop physics beyond the Standard Model centers on Yang-Mills theories, QCD plays a special role in nuclear and particle physics as the only Yang-Mills theory within the Standard Model that admits relativistic bound states.

## CONNECTION TO ASTROPHYSICS

One of the most interesting questions in astrophysics is the high-energy limit of our universe: What kinds of natural accelerators exist in nature, and what can be learned about astrophysical acceleration mechanisms by measuring the high-energy neutrinos, nucleons, and nuclei that reach Earth? In recent years, new kinds of astrophysical observatories have been constructed to answer such questions. The Pierre Auger Observatory,[15] located in the Mendoza region of Argentina near the base of the Andes, was completed in 2008. The observatory detects the collisions of ultra-high-energy cosmic rays—energetic nucleons or nuclei—with atmospheric nuclei through the air showers that such collisions produce (Figure 6.2). The energy of the collision is dissipated in the atmosphere through the production of vast numbers of photons, electrons, and muons. As this particle shower travels from the upper atmosphere toward Earth, it causes the atmosphere to fluoresce. The ultraviolet light is recorded in the Pierre Auger Observatory's array of fluorescence telescopes, which can detect showers originating from an area of the sky in excess of 1,000 square miles. In addition, the energetic secondary particles that reach Earth's surface can be directly detected in the observatory's array of water Cherenkov detectors.

The Pierre Auger Observatory has recorded over 50,000 ultra-high-energy events with $E > 5 \times 10^{18}$ eV, corresponding to $\sqrt{s} > 100$ TeV for proton primaries.

[15] Pierre Auger Collaboration (A. Aab et al.), 2015, The Pierre Auger Cosmic Ray Observatory, *Nucl. Instrum. Meth.* A798:172.

**FIGURE 6.2** Artist's depiction of an atmosphere shower initiated by a cosmic ray event in the upper atmosphere, with a Pierre Auger Observatory detector in the foreground. SOURCE: W. Haxton.

More than 220 events have energies in excess of $5 \times 10^{19}$ eV. This energy is close to what is known as the Greisen-Zatsepin-Kuzmin cutoff—the energy above which cosmic ray protons and nuclei can no longer propagate long distances, due to their interactions with the cosmic microwave background left over from the Big Bang. The high-energy events are only slightly perturbed by their passage through the galactic magnetic field, and thus can be correlated with possible point sources.[16] Investigators have observed a change from a proton-dominated composition at a few times $10^{18}$ eV toward heavier nuclei as the energy increases. Moreover, taking benefit of their hybrid data, they found a ~30 percent excess of muons in extensive air showers with respect to shower simulations.[17] More recently, they also reported large-scale anisotropies toward the nearby distribution of extragalactic matter.[18]

An important goal of Pierre Auger and other high-energy cosmic ray studies is to understand the composition of the cosmic rays as a function of energy, as noted above. The composition must be deduced from a comparison of specific properties of the observed air showers, such as mean depth of the shower maximum, and its

[16] Pierre Auger Collaboration (A. Aab et al.), 2015, Searches for anisotropies in the arrival directions of the highest energy cosmic rays detected by the Pierre Auger Observatory, *Astrophys. J.* 804:15.

[17] Pierre Auger Collaboration (A. Aab et al.), 2016, Testing hadronic interactions at ultrahigh energies with air showers measured by the Pierre Auger Observatory, *Phys. Rev. Lett.* 117:192001.

[18] Pierre Auger Collaboration (A. Aab et al.), 2015, Large scale distribution of ultra high energy cosmic rays detected at the Pierre Auger Observatory with zenith angles up to 80°, *Astrophys. J.* 802:111.

dispersion, relative to expectations based on air shower simulations.[19] Key input to the latter are hadronic interaction models tuned to describe scattering data from accelerators such as the Hadron-Electron Ring Accelerator and the Large Hadron Collider, which are then used in extrapolations to higher center-of-mass energies relevant to Pierre Auger. One of the specific difficulties in relating subtle changes in shower properties to evolving compositions is that the hadronic cross sections may be changing in an unexpected way—for example, because of the onset of saturation—making such extrapolations unreliable. Constraints from EIC data could help reduce the uncertainties in cosmic ray composition analyses.[20,21]

[19] Pierre Auger Collaboration (A. Aab et al.), 2014, Depth of maximum of air-shower profiles at the Pierre Auger Observatory. I. Measurements at energies above 1017.8 eV, *Phys. Rev.* D90:122005.

[20] L.A. Anchordoqui, A.M. Cooper-Sarkar, D. Hooper, and S. Sarkar, 2006, Probing low-*x* QCD with cosmic neutrinos at the Pierre Auger Observatory, *Phys. Rev.* D74:043008.

[21] E.M. Henley and J. Jalilian-Marian, 2006, Ultrahigh energy neutrino-nucleon scattering and parton distributions at small *x*, *Phys. Rev.* D73:094004.

# 7

# Conclusions and Findings

The Committee on U.S. Based Electron Ion Collider Assessment finds that the science questions that an electron ion collider (EIC) would answer are central to completing our understanding of atomic nuclei as well as being integral to the agenda of nuclear physics today. These questions, about the fundamental building blocks of nuclei—neutrons and protons—and how they are held together in nuclei, are compelling. An EIC would build upon the heritage of more than a century of scattering experiments, discoveries, as well as on the insights and advances in accelerator science and technology. The increased understanding of nucleons, nuclei, and the underlying theory quantum chromodynamics (QCD) that an EIC would bring would have direct impact on particle physics, and improve our understanding of the most beautiful of all Yang Mills theories, QCD.[1] Design and construction of an EIC would keep the United States at the forefront of new collider technologies. An EIC would contribute to basic energy sciences through the EIC goal of understanding the emergent behavior of dense gluonic systems, and to plasma physics and astrophysics, through the creation of a state with enormous but saturated gluon density, resembling but differing from the radiation dominated plasmas of explosive astrophysics.

The committee was tasked with evaluating the importance and urgency of the science that an EIC addresses to both nuclear science and the physical sciences more broadly. The committee's task also included assessing the role of an EIC in

[1] D. Gross, 2016, Quantum chromodynamics—The perfect Yang-Mills gauge theory, *Int. J. Mod. Phys. A* 31:1630008.

the global context, including its relationship to other facilities within the United States and around the world. Lastly, the committee was asked to assess the broader impacts of an EIC, including on U.S. science leadership. The full statement of task is included in Appendix A.

The committee had a wide range of scientific expertise, from nuclear physics, particle physics, astrophysics, accelerator science, and condensed matter physics. The committee also invited speakers from the nuclear physics, accelerator physics, and particle physics communities to provide additional expert input and insights. To better understand its task, the committee met with representatives of the Department of Energy (DOE) and the National Science Foundation and a congressional staffer.

During its deliberations, the committee studied long-range plans in nuclear and particle physics relevant to EIC science, not only in the United States but also in the Asian and European communities, and surveyed existing and planned facilities around the world that can address science similarly to an EIC. Accelerator and collider experts from the United States and the international community were consulted. Discussion of design specifications as they related to achieving the scientific goals was explored, but no detailed comparisons were made between the two existing designs.

The committee's conclusions are organized into a set of nine findings, which it summarizes here.

**Finding 1:** An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- 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?

A better understanding of the weak and strong forces—two of four fundamental forces of nature—is central to nuclear physics. The strong force, so named because it holds together neutrons and protons tightly in the nuclei of atoms, is a subtle aspect of a more fundamental force, the color force, described by the well-established theory of QCD. These three questions are at heart of understanding how QCD shapes nuclei and their building blocks, nucleons; answering these questions is necessary to complete our understanding of the chemical elements, the elementary constituents of our physical world. The third question is perhaps the most exciting to nuclear scientists because it offers the opportunity for the most surprises, including new phases of matter and deep insights about quantum field theory.

**Finding 2:** These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

Based on documents the committee reviewed, input from speakers, and committee expertise, the committee concluded that, pending future machine and science studies, Figure 7.1 (cf. Figure 2.4) well summarizes the requirements on an EIC needed to answer the three compelling science questions discussed above. In addition to highly polarized beams, high luminosity—as shown in Figure 7.1—is needed to answer, by means of imaging, the question of how the spin and mass of the nucleon arise; and a high and variable center-of-mass energy, as shown in Figure 7.1 is essential to understanding the nature of gluons in nuclei. As the figure indicates, an EIC would also be useful in studying nuclear structure in terms of quarks and gluons—with the gluon saturation region explored at highest energies.

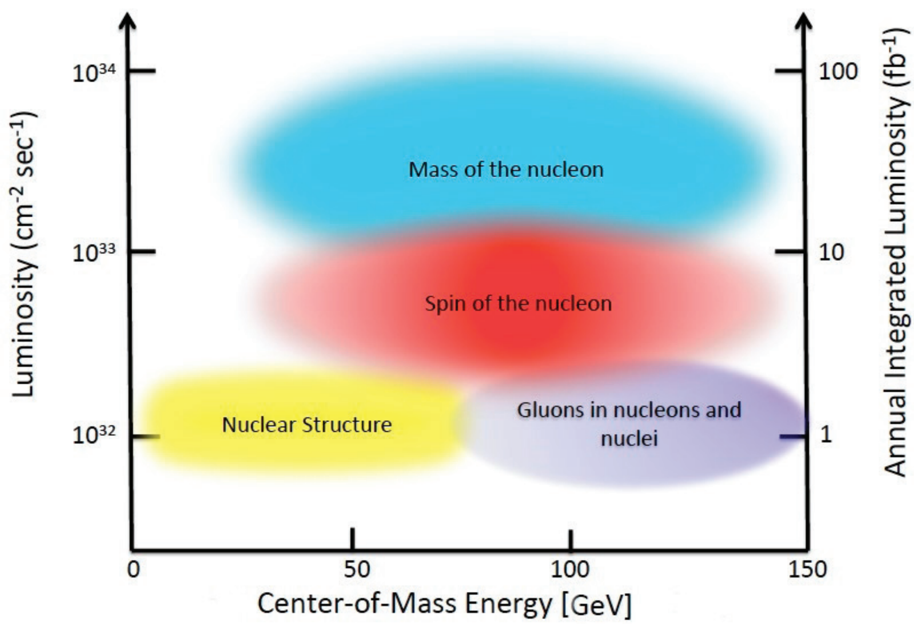


**FIGURE 7.1** Energy and luminosity requirements for answering the three questions—How does the mass of the nucleon arise? How does the spin of the nucleon arise? What are the emergent properties of dense systems of gluons?—are spin, mass, and gluons. SOURCE: Based on Figure 2.4; adapted from A. Deshpande, EIC Science, presentation on behalf of the EIC Users Group.

**Finding 3:** An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.

The committee did a comprehensive survey of existing and planned accelerator facilities in both nuclear and particle physics around the world. An EIC, with its high energy and luminosity and highly polarized electron and ion beams, would be unique, from both the accelerator point of view and the science that it can address.

**Finding 4:** An EIC would maintain U.S. leadership in the accelerator science and technology of colliders and help to maintain scientific leadership more broadly.

The EIC is the only high-energy collider being planned for construction in the United States. Furthermore, its high design luminosity and highly polarized beams would push the frontiers of accelerator science and technology. For these reasons, building the EIC would also maintain U.S. leadership in accelerator collider science. Because of the importance of accelerators, this would broadly benefit the physical sciences.

**Finding 5:** Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

Significant accelerator infrastructure and expertise exists at both the Brookhaven National Laboratory (BNL) and the Thomas Jefferson National Accelerator Facility (JLab). In particular, JLab has just completed the 12 GeV upgrade of its Continuous Electron Beam Accelerator Facility (CEBAF), which employs a polarized electron beam and uses superconducting accelerator technology. The Relativistic Heavy Ion Collider (RHIC) at BNL is able to collide a large variety of heavy ions over a wide range of energies and has pioneered collisions of high-energy polarized protons. Both BNL and JLab have proposed design concepts for an EIC that use existing infrastructure and both laboratories have significant accelerator expertise and experience.

**Finding 6:** The current accelerator R&D program supported by DOE is crucial to addressing outstanding design challenges.

While well-developed designs for an EIC exist at both BNL and JLab, design challenges remain for each. Neither of the existing designs can fully deliver on the three compelling science questions. The DOE research and development (R&D) investment has been and will continue to be crucial to retiring design risk in a timely fashion.

**Finding 7:** To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD and, furthermore, to glean the fundamental insights into QCD that an EIC can reveal.

QCD provides the mathematical description of how quarks and gluons assemble nucleons and nuclei, as well as the other hadrons, and a full understanding of how it does so will complete our understanding of the building blocks of our physical world, atoms. In so doing, other insights and surprises about this rich theory are likely to be revealed, some with broad implications in our understanding of the quantum world. In order to take advantage of the full potential of the EIC, a theory program to match its scope is essential, comprising both continuum and lattice QCD.

**Finding 8:** The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high-luminosity polarized EIC as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

The 2015 Long Range Plan for Nuclear Science[2] provided a clear and compelling discussion of the scientific scope of the field and a ranked list of priorities for the field. The frontiers of nuclear science encompass understanding the implications of QCD for nucleons and nuclei, nuclear structure and nuclear astrophysics, neutrinos, and insights from nuclear physics into the fundamental symmetries of nature. Because an EIC can answer fundamental questions in the first of these frontiers, the 2015 Long Range Plan made an EIC the highest priority for a new facility after the completion of FRIB. The importance of an EIC to the frontiers of nuclear science was also recognized in the 2007 Long Range Plan,[3] where accelerator R&D for an EIC was recommended and has since been supported by DOE.

**Finding 9:** The broader impacts of building an EIC in the United States are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

Beyond its impact on nuclear science, an EIC will help to maintain international leadership in accelerator science and technology of colliders. The accelerator-collider expertise in the United States now resides within the DOE Office of Nuclear

[2] U.S. Department of Energy and National Science Foundation, *Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science*, October 2015, https://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf.

[3] U.S. Department of Energy and National Science Foundation, *The Frontiers of Nuclear Science: A Long Range Plan*, December 2007, https://science.energy.gov/~/media/np/nsac/pdf/docs/nuclear_science_low_res.pdf.

Physics, following the closing of the Fermilab Collider facilities and the absence of a plan by DOE/High Energy Physics to construct a new collider. Any future accelerator facilities with high energy or high luminosity will benefit significantly from the expertise developed for an EIC.

An EIC would have impact on other research areas including particle physics, astrophysics, theoretical and computational modeling as well as rich intellectual connections to atomic and condensed matter physics.

Lastly, with the exciting physics frontier program enabled by an EIC, nuclear science will continue to attract outstanding graduate students, more than half of whom will go on to science, technology, engineering, and mathematics jobs in industry and DOE National Nuclear Security Administration and Office of Science laboratories.

The committee concludes that the science questions regarding the building blocks of matter are compelling and that an EIC is essential to answering these questions. Furthermore, the answers to these fundamental questions about the nature of the atoms will also have implications for particle physics and astrophysics and possibly other fields. Because an EIC will require significant advances and innovations in accelerator technologies, the impact of constructing an EIC will affect all accelerator based sciences.

In summary, the committee concludes that an EIC is timely and has the support of the nuclear science community. The science that it will achieve is unique and world leading and will ensure global U.S. leadership in nuclear science as well as in the accelerator science and technology of colliders. The latter, the committee notes, would position the United States for future high-energy collider projects in other fields.

# Appendixes

# A

# Statement of Task

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

In particular, the committee will address the following questions:

- What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron ion collider? What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to U.S. leadership in nuclear physics if a domestic electron ion collider were constructed?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?

# B

# Committee and Staff Biographical Information

GORDON BAYM, *Co-Chair*, is research professor and professor emeritus at the University of Illinois at Urbana-Champaign. Professor Baym received his bachelor's degree in physics from Cornell University in 1956, his A.M. in mathematics from Harvard in 1957, and his Ph.D. in physics from Harvard in 1960. He joined the Department of Physics at the University of Illinois as an assistant professor in 1963, where he has been since. Professor Baym has been a leader in the study of matter under extreme conditions in astrophysics and nuclear physics. He has made original, seminal contributions to our understanding of neutron stars, relativistic effects in nuclear physics, condensed matter physics, quantum fluids, and ultracold atomic systems. His work is characterized by a superb melding of basic theoretical physics concepts, from condensed matter to nuclear to elementary particle physics. Professor Baym is a member of the National Academy of Sciences (NAS), where he served as chair of the Physics Section from 1995-1998, and the American Philosophical Society, and is a fellow of the American Academy of Arts and Sciences, the American Physical Society (APS), and the American Association for the Advancement of Science (AAAS). He has received numerous awards and honors, including the Hans A. Bethe Prize of the APS in 2002 "for his superb synthesis of fundamental concepts which have provided an understanding of matter at extreme conditions, ranging from crusts and interiors of neutron stars to matter at ultrahigh temperature," and he shared the Lars Onsager Prize of the APS in 2008 "for fundamental applications of statistical physics to quantum fluids, including Fermi liquid theory and ground-state properties of dilute quantum gases, and for bringing a conceptual unity to these areas." He has served on numerous National Academies of Sciences, Engineering, and Medicine committees (in addition to many such committees outside the National Academies), including the Board on Physics and Astronomy, the Committee on an Assessment and Outlook for Nuclear Physics, the Committee on AMO2010, the Committee on Burning Plasma Assessment, the Committee on Nuclear Physics, and the Committee on Atomic, Molecular, and Optical Sciences.

ANI APRAHAMIAN, *Co-Chair*, is a professor of experimental nuclear physics in the Department of Physics at the University of Notre Dame. She received her Ph.D. from Clark University in 1986. Professor Aprahamian's research focuses on the study of nuclear structure effects (shapes, masses, decay lifetimes, and probabilities) and how they can influence stellar evolution as well as explosive astrophysical scenarios such as accretion disks of binary neutron star systems or shock fronts of core collapse supernova. Professor Aprahamian is the secretary general of the International Union of Pure and Applied Physics Commission on Nuclear Physics (C-12) and a member of the AstroParticle Commission (C-10). She was vice chair of the Committee on an Assessment and Outlook for Nuclear Physics (the 2010 nuclear physics decadal survey). She has served as co-chair of the Department of Energy's (DOE's) Nuclear Science Advisory Committee's (NSAC) subcommittee on isotope production and applications, and has been a National Science Foundation (NSF) program director for nuclear physics and nuclear astrophysics. She was chair of the APS Division of Nuclear Physics from 2014-2016. Professor Aprahamian is a member of the NSF-funded Frontier Center on Nuclear Astrophysics: The Joint Institute of Nuclear Astrophysics Center for the Evolution of the Elements, the Facility for Rare Isotope Beams (FRIB) Science Advisory Committee, as well as numerous other international advisory committees. She is a fellow of the AAAS and the APS, and an elected foreign member of the Science Academy of the Republic of Armenia.

CHRISTINE AIDALA is an associate professor of physics at the University of Michigan. She obtained her bachelor's in physics from Yale University in 1999 and her Ph.D. from Columbia University in 2005. She works in experimental high-energy nuclear physics, on the border between nuclear and particle physics. Her research is focused on nucleon structure and quantum chromodynamics (QCD), the theory of the strong force. She is particularly interested in spin-momentum correlations inside the proton, loosely analogous to the quantum electrodynamical spin-orbit and spin-spin couplings in the hydrogen atom. She currently carries out her research as part of three international collaborations, working on the fixed-target E906/SeaQuest experiment at Fermilab since 2010 as well as the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) since 2001, the fixed-target E906/SeaQuest experiment at Fermilab since 2010, and the LHCb experiment at the European Organization for Nuclear Research (CERN) since 2017. She joined the faculty of University of

Michigan in 2012. She has served on the executive committee of the APS Topical Group on Hadronic Physics and the program committee of the Division of Nuclear Physics and has worked extensively in the field of physics for minority causes and public outreach.

PETER BRAUN-MUNZINGER is the scientific director of the ExtreMe Matter Institute at GSI. He received his B.S. in physics from Heidelberg University in 1970 and his Ph.D. in 1972. His research focuses on the use of heavy-ion accelerators for studies of nuclear physics and particle physics. He was a postdoctoral researcher at the Max Planck Institute for Nuclear Physics in Heidelberg from 1973-1976 and was on the faculty of the University of Stony Brook from 1976-1995. From 1984-1999, he was spokesperson of AGS experiments E814 and E877. From 1996-2011, he was on the faculty of the Technical University of Darmstadt as full professor and at GSI Darmstadt as leading scientist. From 2011-2014, he was the Helmholtz Professor. He was the project leader of the Time Projection Chamber (TPC) of ALICE at CERN from 1998-2010 and from 2011-2016 has been chair of the ALICE collaboration board. He is a fellow of the APS and a member of the Academia Europaea. In 2014, he received the Lise Meitner Prize for Nuclear Physics of the European Physical Society. In 2015, he was appointed Honorary Professor at the University of Heidelberg.

HAIYAN GAO is a professor of physics at Duke University and vice chancellor for academic affairs at Duke Kunshan University in China. She received her B.S. in physics from Tsinghua University in 1988 and her Ph.D. in physics from California Institute of Technology (Caltech) in 1994. Her research interests cover structure of the nucleon, search for QCD exotics, fundamental symmetry studies at low energy, and the developments of polarized targets. She was on the faculty at the Massachusetts Institute of Technology (MIT) from 1997-2002 before she joined the physics faculty of Duke in 2002 and became a full professor in 2008. She was named the Henry Newson Professor of Physics in 2012 at Duke. She was the chair of the Physics Department from 2011 to 2014 and has been the vice chancellor for academic affairs at Duke Kunshan University since January 2015. She is a fellow of the APS. She chaired and co-chaired many workshops and conferences, and she has served on many international advisory committees and panels and a number of editorial boards of journals.

KAWTAR HAFIDI is the director of the Physics Division at Argonne National Laboratory. She received her B.S. in theoretical physics from Mohammed V University in Morocco in 1995 and her Ph.D. in physics from Paris Sud University in France in 1999. She conducts experimental research into QCD in the strong (nonperturbative) regime. She was a postdoctoral appointee at Argonne National

Laboratory from 1999 to 2002 and eventually became an assistant and full physicist in 2002 and 2006 respectively. She was named the associate chief scientist in 2015. From 2013-2014, she was a detailee to the DOE Office of Nuclear Physics. She conducts her experiments at Jefferson Lab, Deutsches Elektronen-Synchrotron (DESY), and Fermilab. She is a fellow of the APS and currently a member of the DOE NSAC. She has chaired/co-chaired a number of conferences and workshops and served on numerous international advisory committees.

WICK HAXTON is a professor of physics at University of California, Berkeley (UC Berkeley). Dr. Haxton received his B.A. from UC Santa Cruz in 1971 and his Ph.D. from Stanford in 1976. His research interests include neutrino physics, nuclear astrophysics, tests of fundamental symmetries, and many-body theory. He spent most of his early research career in the Los Alamos Theory Division, where he was a J. Robert Oppenheimer fellow and later a staff member. He moved to the University of Washington in 1984 as professor and, for 15 years, was director of DOE's Institute for Nuclear Theory there. In 2009, he joined UC Berkeley as professor of physics and the Lawrence Berkeley National Laboratory (LBNL) as a senior faculty scientist. He is a member of the NAS and a fellow of the American Academy of Arts and Sciences, the Washington State Academy of Sciences, the AAAS, and the APS. He received the Hans Bethe Prize from the APS in 2004. He has held visiting fellowships from the Guggenheim, Miller, and Alexander von Humboldt Foundations and the Phi Beta Kappa Society.

JOHN JOWETT is a principal accelerator physicist at CERN. He received a B.Sc. in mathematical physics from the University of Edinburgh in 1976 and a master's and a Ph.D. in mathematical and theoretical physics from the University of Cambridge. He joined CERN to take up particle accelerator physics in 1980 and developed a special interest in the effects of strong synchrotron radiation on high-energy electron beams. He contributed to the feasibility study of the Large Hadron Collider (LHC) in 1983 and worked on many aspects of the Large Electron Positron Collider (LEP) and other electron-positron colliders (including a year at the Stanford Linear Accelerator Center [SLAC]) until the late 1990s. He designed and commissioned the LEP "pretzel" luminosity upgrade. He has been responsible for heavy-ion beams in the LHC since 2003 and led the commissioning of lead-lead and proton-lead collisions. He has supervised a number of students and served on many international advisory and review committees, including, in the United States, an NSAC subcommittee on relativistic heavy-ion physics and chairing the Collider-Accelerator Department's Machine Advisory Committee at BNL. He is a fellow of the APS, past chair of the ICFA Beam Dynamics Panel, past member of the editorial board of *Physical Review Accelerators and Beams*, and present member of the High Energy and Particle Physics Board of the European Physical Society.

LARRY McLERRAN is the director of the Institute for Nuclear Theory at the University of Washington. He received his B.S. in physics from University of Washington in 1971 and his Ph.D. in 1975. His research focuses on hot and dense matter and high-energy nuclear physics. He was theory group leader at the Brookhaven Research Center at BNL from 2003-2015. Previously, he had worked as a research associate at SLAC and MIT and has taught at University of Washington, University of Illinois, University of Minnesota, and the Nordic Institute for Theoretical Physics. He has received numerous accolades and awards. He is a fellow of the APS and foreign member of the Finnish Academy of Arts and Sciences, and was named an Alfred P. Sloan Foundation fellow in 1983. He received the Alexander von Humboldt Prize in 1988 and the Brookhaven Science and Technology Award in 2007, among others. He has served on numerous committees, including the DOE's Nuclear Science Advisory Committee.

LIA MERMINGA is project director of PIP-II, the SRF proton linac under development at Fermilab, that will deliver high-intensity beams to LBNF/DUNE and future physics experiments. Prior to this appointment, she was associate laboratory director for accelerators at SLAC and professor at Stanford University, and before that she was head of the Accelerator Division at TRIUMF, Canada. She is a member of the Scientific Council of DESY, the Jefferson Science Associates Science Council, and the Scientific Advisory Council of Helmholtz-Zentrum Berlin. She has served on three U.S. National Academies committees, on the P5 panel, the 2007 NSAC Long Range Plan Writing Group, and the Physical Review Accelerators and Beams Editorial Board. Dr. Merminga is a fellow of the APS and is chair of the IUPAP Working Group on Accelerator Science.

ZEIN-EDDINE MEZIANI is a professor of physics at Temple University. He earned his bachelor's degree in theoretical physics from the University of Algiers, and his master's and doctoral degrees in nuclear and particle physics from the University of Paris XI, Orsay, France. Dr. Meziani joined Temple from Stanford University in 1993 after starting his spin structure studies of the neutron and proton at Stanford Linear Accelerator Center. He has become a leading researcher in trying to understand the spin structure of the neutron while conducting the majority of his research at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia. He co-chaired a 2007 town meeting to help set the priorities of the DOE's Division of Nuclear Physics and was at the forefront of the effort to upgrade the Jefferson Lab's Continuous Electron Beam Accelerator Facility. He is a fellow of the APS and has published numerous publications in peer-reviewed journals.

RICHARD MILNER is a professor of physics at MIT and has worked there since 1988. He did his undergraduate studies at University College Cork, Ireland, and received his Ph.D. in 1985 from Caltech. His research focuses on understanding nucleon and nuclear structure using the lepton probe, frequently using spin observables. He has proposed and led experiments at SLAC, IUCF, MIT, DESY, and Jefferson Lab. He has served as director of the MIT-Bates Linear Accelerator Center from 1998 to 2006 and director of MIT's Laboratory for Nuclear Science from 2006 to 2015. He has served on numerous international advisory committees, was chair of the Division of Nuclear Physics of the APS in 2007, and served as chair of the International Spin Physics Committee from 2014 to 2017. He is a fellow of the APS and recipient of an award from the Alexander von Humboldt Foundation, Germany.

THOMAS SCHAEFER is the Wesley O. Doggett distinguished professor of physics at North Carolina State University, a member of the Nuclear Theory Group at North Carolina State, and a former fellow at the RIKEN-BNL Research Center. He received his bachelor's in physics at the University of Giessen in 1989 and his Ph.D. from the University of Regensburg in 1992. His work is focused on QCD, many body effects in atomic, nuclear, and particle physics, as well as transport theory. From 1998-1999 he was a member of the Institute for Advanced Study in Princeton before joining the faculty at Stony Brook University as an assistant professor in 2000. He was promoted to the rank of associate professor in 2003 and joined the faculty of North Carolina State University the same year. He was promoted to full professor in 2006. From 2000-2004, he was also a fellow at the Riken-BNL research center at BNL. Dr. Schaefer received a Fedor Lynen Fellowship from the Alexander von Humboldt Foundation in 1992, an Outstanding Junior Investigator Award from DOE in 2002, and was elected a fellow of the APS in 2006. He served as an associate editor of *Physical Review Letters.*

ERNST SICHTERMANN is a senior scientist at LBNL. He received his master's in physics from Utrecht University and his Ph.D. in physics from Vrije Unversiteit Amsterdam in 2001 on research performed with the Spin Muon Collaboration at CERN. He then took a postdoctoral position at Yale University, where he studied the precision measurement of the anomalous magnetic moment of positive and negative muons with experiment E821 at BNL. He joined LBNL as a division fellow in 2003 and was promoted to senior scientist in early 2009. At LBNL, he pursues spin measurements in collisions of high-energy polarized protons with the STAR experiment at the Relativistic Heavy Ion Collider and its collaboration, of which he was a deputy spokesperson. Recent STAR data have revealed that gluon polarization forms an essential part of nucleon spin structure and that the polarizations of antiquarks are flavor-asymmetric. He was elected a fellow of the APS in 2017.

MICHAEL TURNER is the Rauner Distinguished Service Professor at the University of Chicago and director of the Kavli Institute for Cosmological Physics. He earned his Ph.D. from Stanford University in 1978 and his B.S. from Caltech in 1971. Dr. Turner's research focuses on the application of modern ideas in elementary particle theory to cosmology and astrophysics. He is a member of the NAS and has made seminal contributions to the current cosmological paradigm, known as the Lambda Cold Dark Matter. From 2003 to 2006, Dr. Turner was the assistant director for mathematical and physical sciences at NSF. He chaired the National Academies' Committee on the Physics of the Universe, which in 2003 published *Connecting Quarks with the Cosmos.* He has served on numerous other National Academies committees, including the past two astronomy and astrophysics decadal surveys, and is currently a member of DEPSCOM.

# C

# Acronyms

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|---|---|
| 2D | two dimensional |
| 3D | three dimensional |
| AAAS | American Association for the Advancement of Science |
| AGS | alternating gradient synchrotron |
| ALICE | A Large Ion Collider Experiment |
| APS | American Physical Society |
| ATLAS | A Toroidal LHC Apparatus |
| BNL | Brookhaven National Laboratory |
| BRAHMS | Broad Range Hadron Magnetic Spectrometers Experiment |
| Caltech | California Institute of Technology |
| CBETA | Cornell-BNL ERL Test Accelerator |
| CDR | critical design review |
| CEBAF | Continuous Electron Beam Accelerator Facility |
| CeC | coherent electron cooling |
| CERN | European Organization for Nuclear Research |
| CHESS | Cornell High Energy Synchrotron Source |
| CMS | Compact Muon Solenoid |
| COLDEX | Cold Bore Experiment |
| COMPASS | Common Muon and Proton Apparatus for Structure and Spectroscopy |

| | |
|---|---|
| CW | continuous wave |
| DESY | Deutsches Elektronen-Synchrotron (German Electron Synchrotron) |
| DIS | deep-inelastic scattering |
| DOE | Department of Energy |
| EBIS | Electron Beam Ionization Source |
| EIC | electron-ion collider |
| EMC | European Muon Collaboration |
| EPS | European Physics Society |
| ERL | energy recovery linac |
| FAIR | Facility for Antiproton and Ion Research in Europe |
| FCC | Future Circular Collider |
| FEL | free-electron laser |
| FRIB | Facility for Rare Isotope Beams |
| GPD | generalized parton distributions |
| GSI | GSI Helmholtzzentrum für Schwerionenforschung (formerly Gesellschaft für Schwerionenforschung) |
| HE-LHC | High-Energy Large Hadron Collider |
| HEPL | Hansen Experimental Physics Laboratory |
| HEPP | High Energy Particle Physics |
| HERA | Hadron-Electron Ring Accelerator |
| HERMES | HERA Measurement of Spin |
| HIAF | High Intensity Heavy-Ion Accelerator Facility |
| HL-LHC | High-Luminosity Large Hadron Collider |
| IBS | intra-beam scattering |
| ILC | International Linear Collider |
| IP | interaction point |
| IPAC | International Particle Accelerator Conference |
| IR | interaction region |
| JINR | Joint Institute for Nuclear Research |
| JLab | Thomas Jefferson National Accelerator Facility |
| JLEIC | Jefferson Laboratory Electron Ion Collider |
| J-PARC | Japan Proton Accelerator Research Complex |

| | |
|---|---|
| KEK | High Energy Accelerator Research Organization |
| KEKB | High Energy Accelerator Research Organization (B-factory) |
| | |
| LBNL | Lawrence Berkeley National Laboratory |
| LEP | Large Electron Positron Collider |
| LHC | Large Hadron Collider |
| LHeC | Large Hadron-Electron Collider |
| LQCD | lattice quantum chromodynamics |
| | |
| MAPS | monolithic active pixel sensor |
| MBI | microbunching instability |
| MIT | Massachusetts Institute of Technology |
| MPD | multipurpose detector |
| MRI | magnetic resonance imaging |
| MSU | Michigan State University |
| | |
| NAS | National Academy of Sciences |
| NICA | Nuclotron-Based Ion Collider Facility |
| NS | nonscaling |
| NSAC | Nuclear Science Advisory Committee |
| NSF | National Science Foundation |
| NuPECC | Nuclear Physics European Collaboration Committee |
| | |
| ODU | Old Dominion University |
| | |
| PANDA | Anti-Proton Annihilations at Darmstadt |
| PDF | parton distribution function |
| PEP | Positron Electron Project |
| PHENIX | Pioneering High Energy Nuclear Interaction Experiment |
| PHOBOS | One of two detectors at RHIC to measure Au ion collisions |
| PID | particle identification |
| | |
| QCD | quantum chromodynamics |
| Q-WEAK | Experiment to determine the weak charges of the quarks through parity violating electron scattering |
| | |
| R&D | research and development |
| RF | radio frequency |
| RHIC | Relativistic Heavy Ion Collider |
| RIKEN | Institute of Physical and Chemical Research, Japan |

| | |
|---|---|
| SIDIS | semi-inclusive deep-inelastic scattering |
| SLAC | Stanford Linear Accelerator Center |
| SPS | Super Proton Synchrotron |
| SRF | superconducting radio-frequency |
| STAR | Solenoidal Tracker at RHIC |
| TMD | transverse momentum-dependent distributions |
| TPC | time projection chamber |
| USPAS | U.S. Particle Accelerator School |
| ZEUS | Detector at HERA |