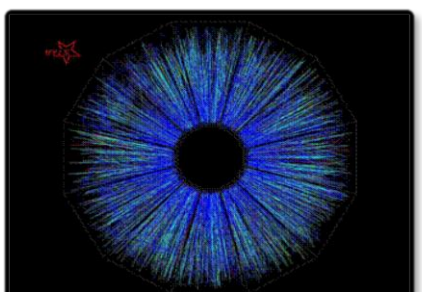
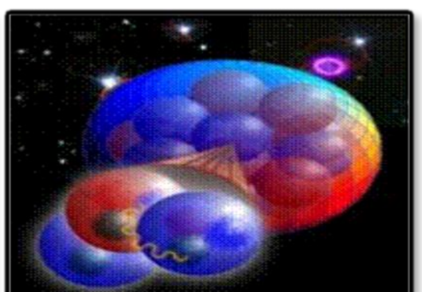
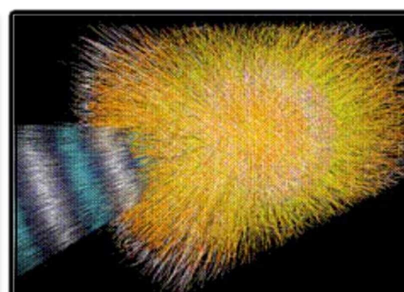
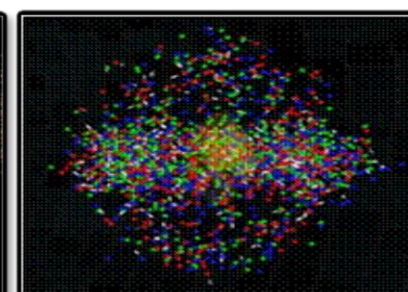
DOE NP Perspectives on a Possible Future Electron Ion Collider

NAS EIC Science Assessment

February 1-2, 2017

Dr. T. J. Hallman
Associate Director for Nuclear Physics
DOE Office of Science

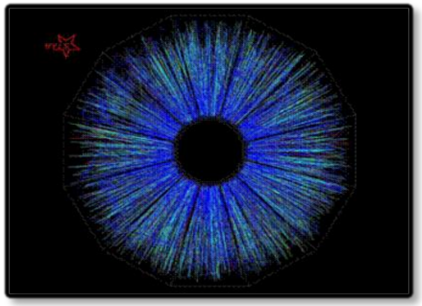
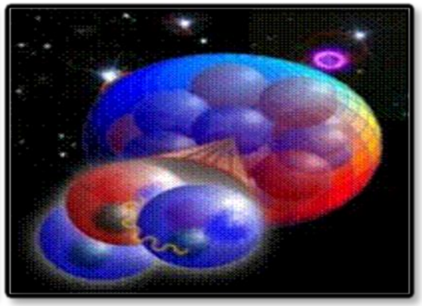
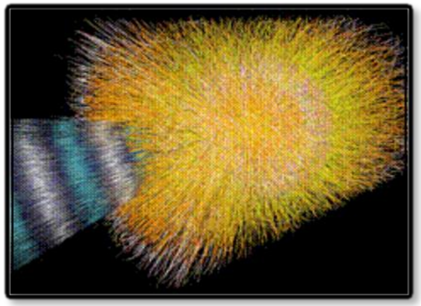
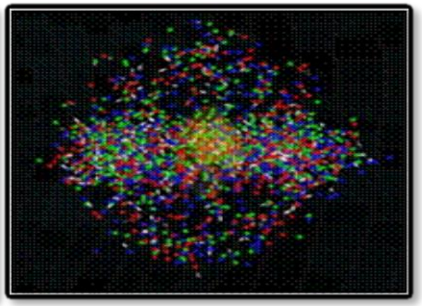





EIC Relevance to DOE Nuclear Physics' Mission

Discovering, exploring, and understanding all forms of nuclear matter

The Scientific Challenges

- The existence and properties of nuclear matter under extreme conditions, including that which existed at the beginning of the universe
- The exotic and excited bound states of quarks and gluons, including new tests of the Standard Model
- The ultimate limits of existence of bound systems of protons and neutrons
- Nuclear processes that power stars and supernovae, and synthesize the elements
- The nature and fundamental properties of neutrons and the neutrino and their role in the evolution of the early universe

EIC Relevance to DOE Nuclear Physics' Mission

Quantum Chromodynamics (QCD) seeks to develop a complete understanding of how quarks and gluons assemble themselves into protons and neutrons, how nuclear forces arise, and what forms of bulk strongly interacting matter can exist in nature, such as the quark-gluon plasma.

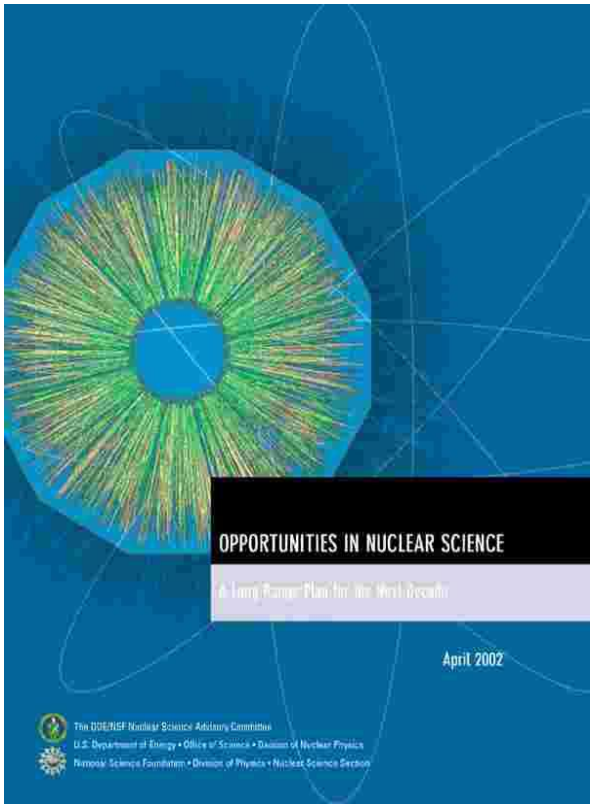
Nuclear Structure and Nuclear Astrophysics seeks to understand how protons and neutrons combine to form atomic nuclei, including some now being observed for the first time, and how these nuclei have arisen during the 13.8 billion years since the birth of the cosmos.

Fundamental Symmetries of neutrons and nuclei seeks to develop a better understanding of fundamental interactions by studying the properties of neutrons and targeted, single focus experiments using nuclei to study whether the neutrino is its own anti-particle.

A strong community emphasis on the need for a machine capable of illuminating the dynamical basis of hadron structure in terms of the fundamental quark and gluon fields exploring has been a persistent message for more than a decade and a half.

Discussion of an EIC in the 2002 Long Range Plan

2002



The Electron-Ion Collider (EIC). The EIC is a new accelerator concept that has been proposed to extend our understanding of the structure of matter in terms of its quark and gluon constituents. Two classes of machine design for the EIC have been considered: a ring-ring option where both electron and ion beams circulate in storage rings, and a ring-linac option where a linear electron beam is incident on a stored ion beam.

These first two initiatives, in particular, require ongoing R&D. For the field to be ready to implement the RHIC upgrade later in the decade, essential accelerator and detector R&D should be given very high priority in the short term. Likewise, there is a strong consensus among nuclear scientists to pursue R&D over the next three years to address a number of EIC design issues. In parallel, the scientific case for the EIC will be significantly refined.

Discussion of the EIC in the 2007 Long Range Plan

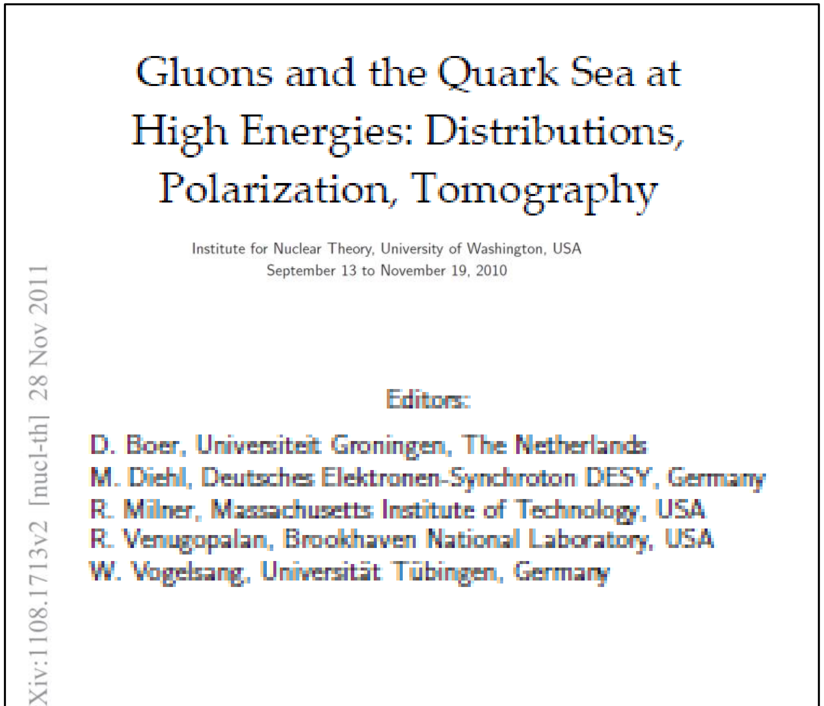
"Gluons and their interactions are critical to QCD. But their properties and dynamics in matter remain largely unexplored. Recent theoretical breakthroughs and experimental results suggest that both nucleons and nuclei, when viewed at high energies, appear as dense systems of gluons, creating fields whose intensity may be the strongest allowed in nature. The emerging science of this universal gluonic matter drives the development of a next-generation facility, the high-luminosity Electron-Ion Collider (EIC). The EIC's ability to collide high-energy electron beams with high-energy ion beams will provide access to those regions in the nucleon and nuclei where their structure is dominated by gluons. Moreover, polarized beams in the EIC will give unprecedented access to the spatial and spin structure of gluons in the proton."

2007

While significant progress has been made in developing concepts for an EIC, many open questions remain. Realization of an EIC will require advancements in accelerator science and technology, and detector research and development. The nuclear science community has recognized the importance of this future facility and makes the following recommendation."

"We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton."

Significant Community Effort Has Been Made To Document the EIC Science Case



2010 INT Workshop & Report

Executive summary

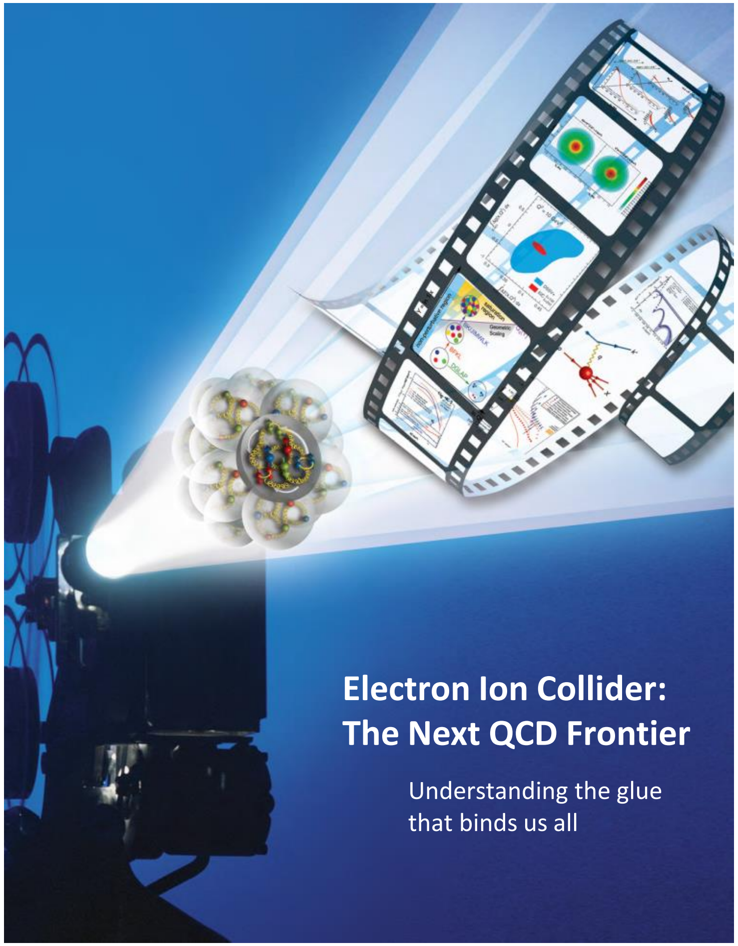
Understanding the fundamental structure of matter in the physical universe is one of the central goals of scientific research. Strongly bound atomic nuclei predominantly constitute the matter from which humans and the observable physical world around us are formed. In the closing decades of the twentieth century, physicists developed a beautiful theory, Quantum Chromodynamics (QCD), which explains all strongly interacting matter in terms of point-like quarks interacting by the exchange of gauge bosons, known as gluons….

However, more than thirty years after QCD was first proposed as the fundamental theory of the strong force...the understanding of how QCD works in detail remains an outstanding problem in physics. Very little is known about the dynamical basis of hadron structure in terms of the fundamental quark and gluon fields of the theory. How do these fundamental degrees of freedom dynamically generate the mass, spin, motion, and spatial distribution of color charges inside hadrons with varying momentum resolution and energy scales? Deep Inelastic Scattering (DIS) experiments at the HERA collider revealed clearly that at high momentum resolution and energy scales, the proton is a complex, many-body system of gluons and sea quarks, a picture very different from a more familiar view of the proton as a few point-like partons… each carrying a large fraction of its momentum. This picture, which is confirmed at hadron colliders, raises more questions than it answers about the dynamical structure of matter.

For instance, how is the spin-1/2 of the proton distributed in this many-body system of sea quarks and gluons? In the early universe, how did the many-body plasma of quarks and gluons cool into hadrons with several simple structural properties? Recreating key features of this quark-hadron transition in heavy ion collisions has been a major activity in nuclear physics, with several surprising findings including the realization that this matter flows with very little resistance as a nearly perfect fluid. A deep understanding ultimately requires detailed knowledge of the quark-gluon structure of hadrons and nuclei.

The Most Recent Community Articulation of the Science Case: EIC, the Next QCD Frontier

- Proton (and nuclei) and black holes are the only fully relativistic (high enough energy density to excite the vacuum) stable bound systems in the universe. Protons can be studied in the laboratory.
- Protons are fundamental to the visible universe (including us) and their properties are dominated by emergent phenomena of the self-coupling strong force that generates high density gluon fields:
  - The mass of the proton (and the visible universe)
  - The spin of the proton
  - The dynamics of quarks and gluons in nucleons and nuclei
  - The formation of hadrons from quarks and gluons
- The study of the high density gluon field that is at the center of it all requires a high energy, high luminosity, polarized Electron Ion Collider



2012 Report

An EIC Was Also Identified by NSAC as “Absolutely Central” to the Future of NP

Major Nuclear Physics Facilities for the Next Decade

Report of the NSAC Subcommittee on Scientific Facilities

March 14, 2013

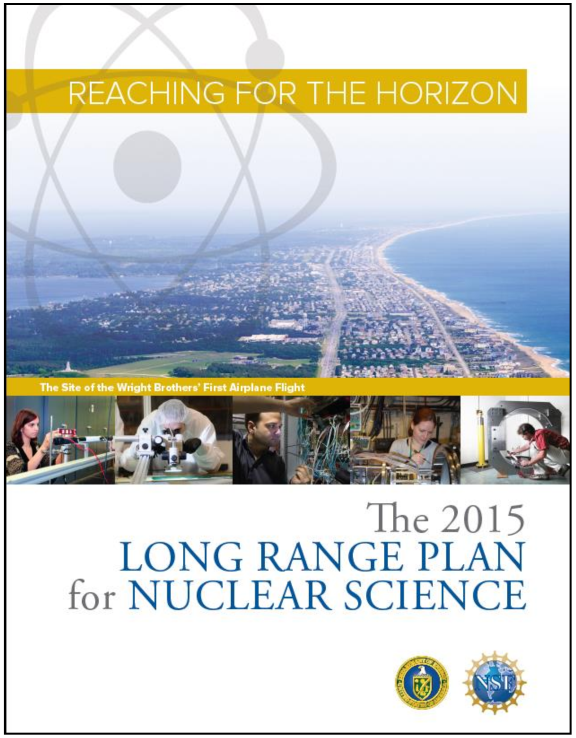
In December 2012 the Nuclear Science Advisory Committee was charged by Dr. William Brinkman, Director of the Office of Science at the Department of Energy, to help with the task of assessing proposed major scientific user facilities. In this case “major” is defined as new facilities or upgrades with a total cost of at least $100M. Dr. Brinkman asked that current user facilities and major proposed facilities and upgrades be assessed for their “ability to contribute to world-leading science in the next decade (2014-2024).”

The 2013 NSAC *Subcommittee on Future Facilities* identified an Electron-Ion Collider as ***absolutely central*** to the nuclear science program of the next decade.

The EIC in the 2015 Long Range Plan

Recommendations:

- The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. ***The highest priority in this 2015 Plan is to capitalize on the investments made.***
- The observation of neutrinoless double beta decay in nuclei would…have profound implications.. ***We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.***
- Gluons…generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain…. These can only be answered with a powerful new electron ion collider (EIC). ***We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.***
- ***We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.***



NP is working to implement these recommendations

Consistent with the community's advice, NP has also supported pre-conceptual accelerator R&D essential to inform the feasibility of future design concepts

Funding Opportunity Announcements (FOA)

- Published bi-annually since 2010
- These FOAs are in support of pre-conceptual accelerator R&D aimed at technological challenges for the next generation NP facilities. Accelerator R&D intended for this announcement should fall in the following general categories: **(National Labs, Universities; and Industry):**

  - Accelerator R&D with the potential for the development of a future generation of NP accelerators not under construction or design.

  - Accelerator R&D with the potential for improved performance and/or upgrades to existing NP scientific user facilities that will lead to new capabilities

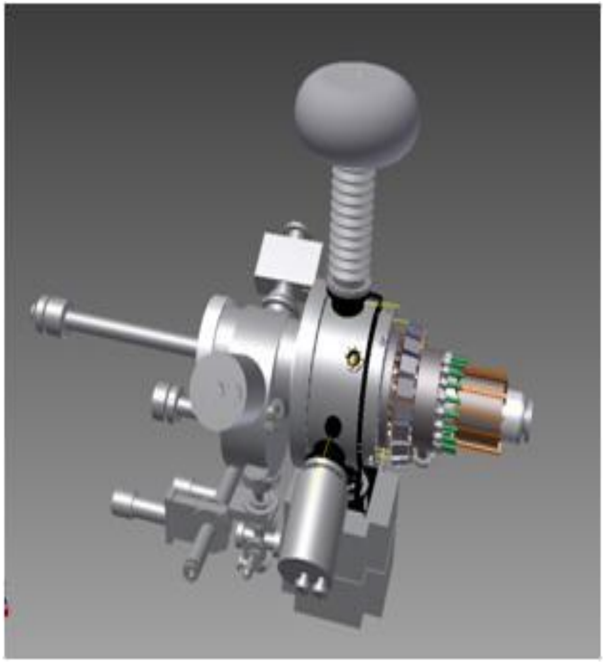
- Proposals were evaluated with the help of a review panel using both a set of Merit Review Criteria and a set of NP Program Policy Factors.

EIC Related University Competitive Accelerator R&D Awards From FY10 – FY16

Accelerator R&D University Grants			
Institution	**PI**	**Title**	**EIC**
Cornell University	Bazarov, Ivan	Next generation robust polarization photocathodes for EIC	EIC
Cornell University	Bazarov, Ivan	Physics and technology of high-brightness high-power photoinjectors for beam coolers and EIC	EIC
Cornell University	Talman, Richard	Planning and Prototyping for a Storage Ring Measurement of the Proton Electric Dipole Moment (EDM)	EDM
		2012 FOA	EDM
	Milner, Richard	Development of a Polarized 3He Ion Source for RHIC	eRHIC
MIT		2012 FOA	
		2014 FOA	
		2016 FOA	
MIT	Redwine, Robert	High Intensity Polarized Electron Gun	eRHIC
MIT		2012 FOA	
		2014 FOA	
		2016 FOA	
Northern Illinois U	Erdelyi, Bela	Studies of Conventional and ERL-Based Recirculator Electron Cooling for an EIC	JLEIC
		2012 FOA	
		2014 FOA	
		2016 FOA	

Generic Detector R&D for an Electron Ion Collider

In January 2011 Brookhaven National Laboratory, in association with Jefferson Lab announced a generic detector R&D program to address the scientific requirements for measurements at a future Electron Ion Collider (EIC). The primary goals of this program are to develop detector concepts and technologies that have particular importance for experiments in an EIC environment, and to help ensure that the techniques and resources for implementing these technologies are well established within the EIC user community.



(https://wiki.bnl.gov/conferences/index.php/Meetings)

EIC Accelerator R&D Supported By NP Since 2010

- Competitive FOA Funds
  - Coherent Electron Cooling BNL
  - High Current Polarized Electron Sources MIT, TJNAF, Cornell
  - Polarized ^{3}He Source MIT
  - Design of JLAB EIC TJNAF, ANL, TAMU, SLAC
  - High Current Unpolarized Photoinjector Cornell
  - Photocathode Developments W&M, Cornell (2016)
- Laboratory and Facility Operation Accelerator R&D

  BNL eRHIC
  - Coherent Electron Cooling (work force)
  - Gatling gun LDRD funds

  TJNAF MEIC/JELIC
  - Design of JLAB EIC

In response to the community's persistent strong emphasis on the need for the capabilities of an electron-ion collider and the significant effort already made on pre-conceptual R&D, NP is implementing the following strategic plan in discussion and coordination with EIC stakeholders. It is pursuing:

- An independent science assessment of a US-based EIC by the National Academy of Sciences
- A major NP Community EIC Accelerator R&D Panel Review this year
- A mechanism for increased accelerator R&D funding for FY17 and beyond

NP Goals for The NAS EIC Study Are Embodied in the SOT

U.S.-Based Electron Ion Collider Science Assessment

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?

Toward The Second NP R&D Thrust: Community Review of EIC R&D Status and Needs

Kevin Jones, Chair (ORNL), Oliver Bruning (CERN), John Corlett (LBNL), George W. Dodson (ORNL), Oliver Kester (TRIUMF), John Lewellen (LANL), Daniela Leitner (MSU), Sergei Nagaitsev (FNAL), Alexander Romanenko (FNAL), John Seeman (SLAC), John P. Tapia (LANL), Jie Wei (MSU), Ying Wu (Duke), Frank Zimmermann (CERN)

The Review took place Nov 29-Dec 2 at the Hilton Washington DC/Rockville, Rockville, MD.

It will center around EIC design concepts: JLEIC Concept, Linac-Ring eRHIC Concept, Ring-Ring eRHIC Concept

As appropriate, Laboratories and Universities have been asked by the Chair to submit documents describing:

- their concept(s)
- a prioritized R&D list for the proposed concept
- related technical and planning documents.

Charge Elements

Status of EIC R&D to date:	Evaluate current state of EIC-related accelerator R&D supported to date.
EIC design concepts:	Examine the current EIC design concepts under consideration and identify a risk level (High, Medium or Low) for each.
Technical feasibility:	Identify key areas of accelerator technologies that must be demonstrated or advanced significantly in order to realize the technical feasibility of each concept;
Priority list of R&D:	Generate a list of R&D areas for each EIC design concept, prioritized (High, Medium, Low) in the context of associated risk and impact of activity to value engineering and technical feasibility. Identify R&D items that have relevance to multiple EIC design concepts; and
Cost and schedule range:	To the extent possible and within the time constraints of the meeting, provide an estimate of cost and schedule range for each item on the R&D list above.

FY17 FOA and Funding

Current NP plan

- NP Community EIC R&D panel review to generate a report with EIC R&D priority list: February 2017.
- Subject to FY2017 funding constraints, NP to publish a new FOA based on EIC R&D priorities set by the Review Report above: March-April 2017
- Proposals to be reviewed by a new Review panel and awardees selected mainly based on priorities set by this panel: May-June 2017.
- Planning for ~$7M total funding for FY17 and finalized after enactment of an appropriation.
- Considering publishing this FOA for 2-year funding. This would require dealing with forward funding of university awards that are over $1M.

Current Status of Machine Concepts

Current Machine Concepts for EIC

eRHIC:

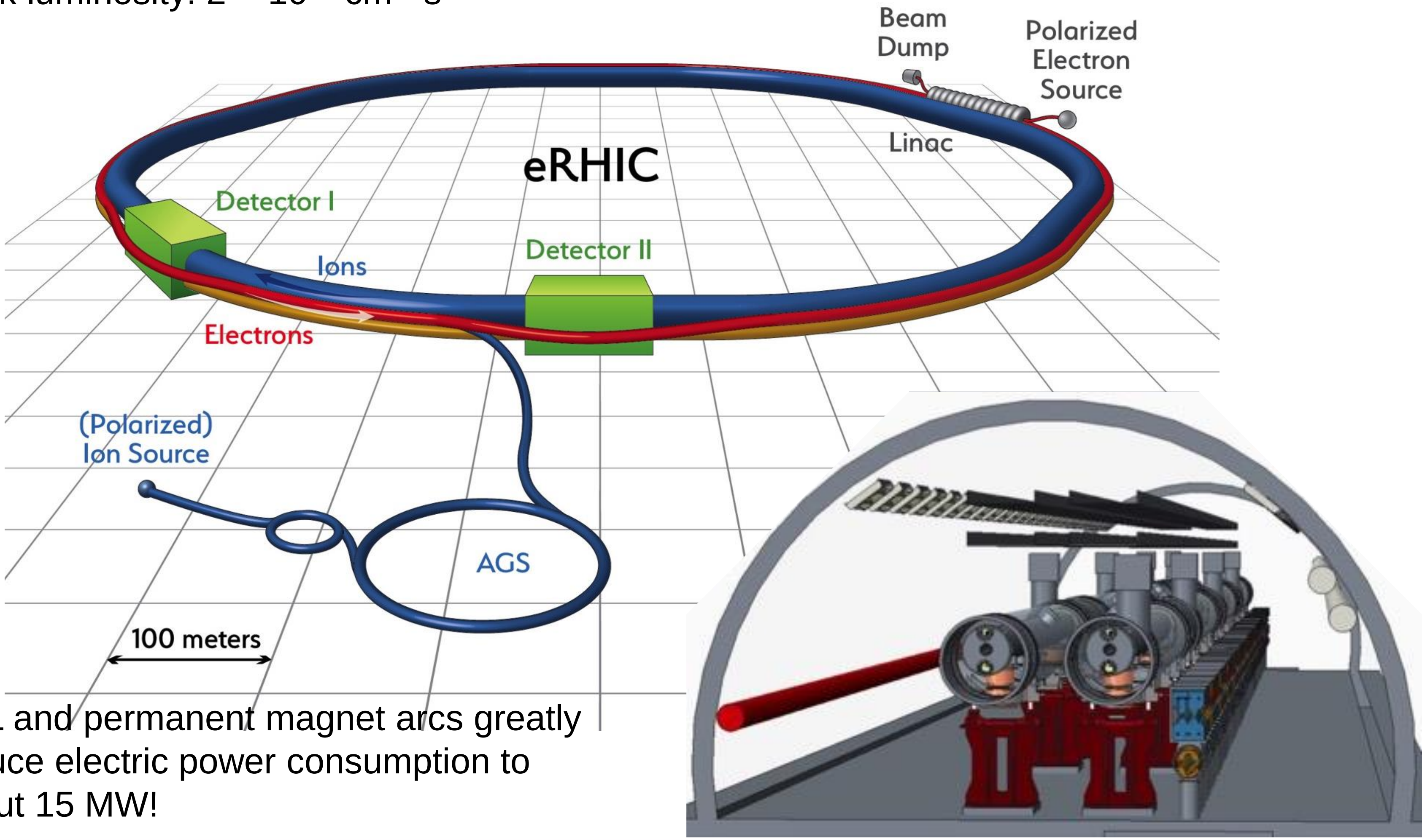
- Two concepts based on RHIC:
  - » Linac-Ring collider requiring more R&D than -
  - » Ring-Ring collider mainly based on existing technology.

JLEIC:

- Ring-Ring collider using CEBAF and two figure-8 storage rings.

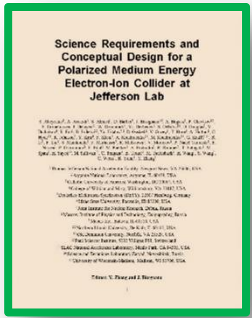
Ultimate eRHIC Design

- Peak luminosity: 2×10^{34} cm^{-2} s^{-1}



- ERL and permanent magnet arcs greatly reduce electric power consumption to about 15 MW!

JLEIC Baseline


Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab


MEIC Design Summary

January 20, 2015

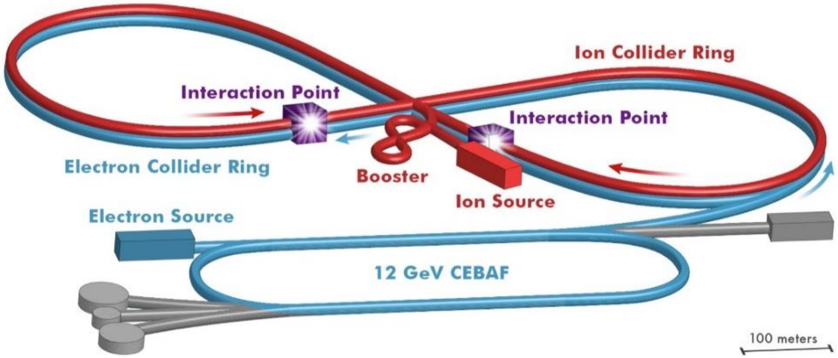
Author List

arXiv:1504.07961

arXiv:1209.0757

2012

energy range:
e⁻: 3-10 GeV
p : 20-100 GeV



Cooling strategy:
- **DC cooler** in booster
- **Bunched beam cooler** in Ion collider ring

Anticipated Potential Challenges for This NAS Study

Possible tendency to focus on factors other than science opportunities (budgets, projected costs, parochial interests of one community or another, etc.)

Difficulty in clearly articulating the relative merit and impact of different science opportunities in the “grand scheme”.

Possible tendency to become too focused on the details of specific machine concepts and their capabilities.

Simply maintaining focus on the job at hand in the daily din….

Outlook

- The nuclear science community has articulated a persistent strong emphasis, for a decade and a half, on the need for and electron ion collider to discover the dynamical basis of hadron structure in terms of the fundamental quark and gluon fields
- Significant effort has been invested in documenting the science case for an EIC over that period
- Significant effort has been invested in pre-conceptual accelerator R&D to make progress in areas key to the feasibility of a future machine
- The 2015 Long Range Plan identified the construction of a high luminosity, polarized electron-ion collider as the highest priority for new construction following the completion of FRIB (currently planned for FY2021)
- Realization of an EIC will also be a focus within SC generally for advancements in accelerator science and technology, and detector research and development.
- An independent assessment of the merit and "urgency" of the science an EIC could provide is the next crucial step in determining the future possibility of this machine