Electron-Ion Collider Status

On behalf of EIC project team:

Andrei Seryi, Jefferson Lab

EIC Associate Director for Accelerator Systems and International Partnership

Institute for Advanced Study, HEP 2021

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Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

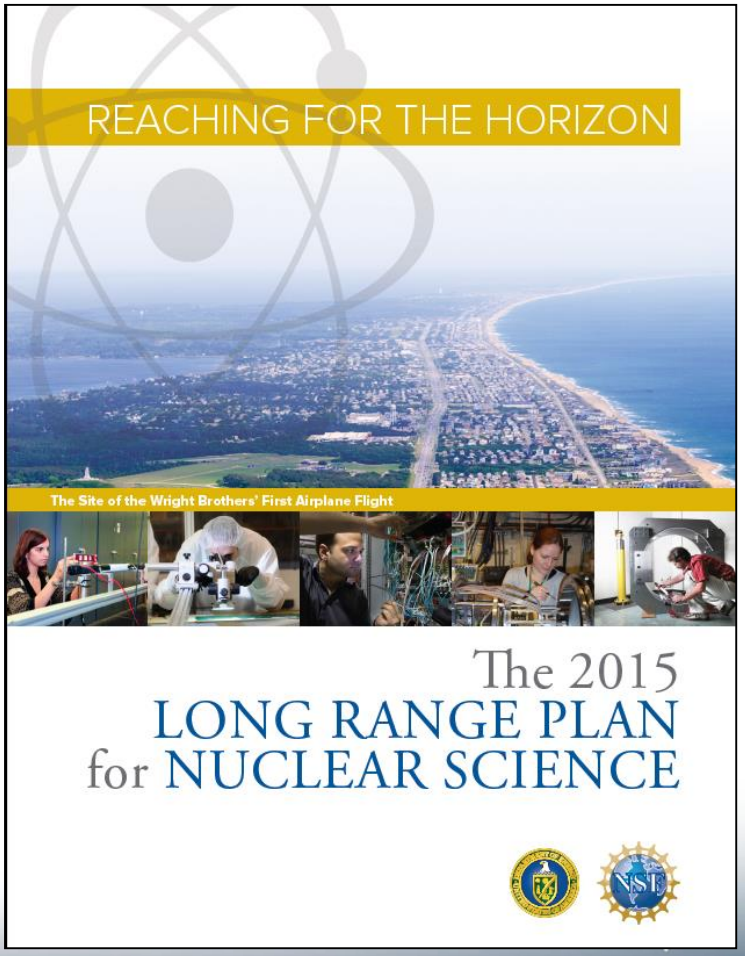
- Science case & path to project approval
- Project – brief overview
- Design overview
  - Technical scope
  - Energy, Luminosity, Polarization, 2 IRs
- Collaboration opportunities
- Summary

Acknowledgement: this talk includes materials from presentations of Tim Hallman (Associate Director of the DOE Office of Science for Nuclear Physics), Jim Yeck (EIC Project Director), Ferdinand Willeke (EIC Deputy Project Director and Technical Director), Elke Aschenauer and Rolf Ent (Co-Associate Directors for the Experimental Program) and many other members of EIC project team

EIC in the 2015 Long Range Plan for Nuclear Science

Recommendations:

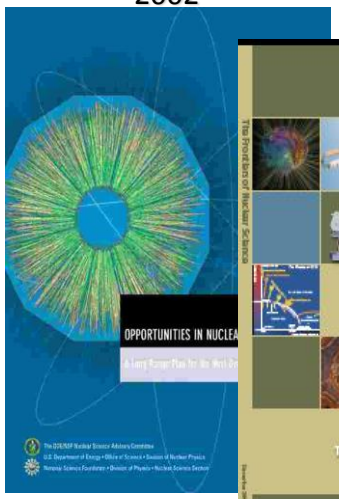
1. Capitalize on investments made to maintain U.S. leadership in nuclear science.
2. Develop and deploy a U.S.-led ton-scale neutrino-less double beta decay experiment.
3. Construct a high-energy high-luminosity polarized electron-ion collider (EIC) as the highest priority for new construction following the completion of FRIB.
4. Increase investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.



Developing the EIC Science Case

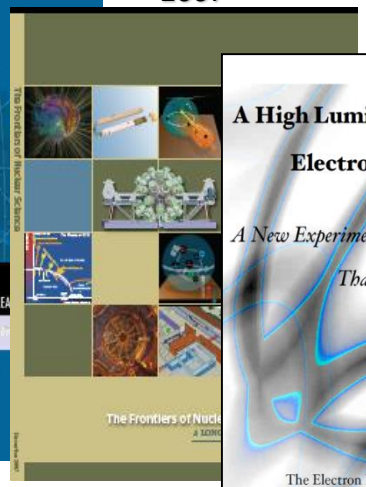
A strong community emphasis on the urgent need for a machine to illuminate the dynamical basis of hadron structure in terms of the fundamental quark and gluon fields has been a persistent message for almost two decades

2002



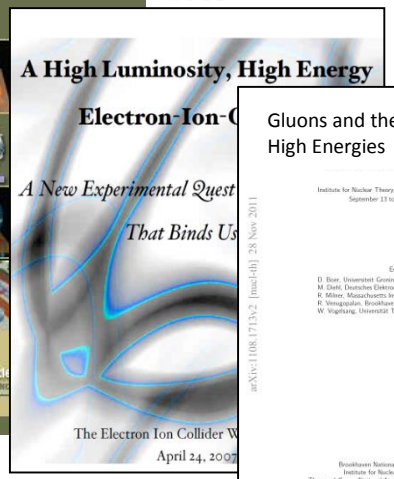
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



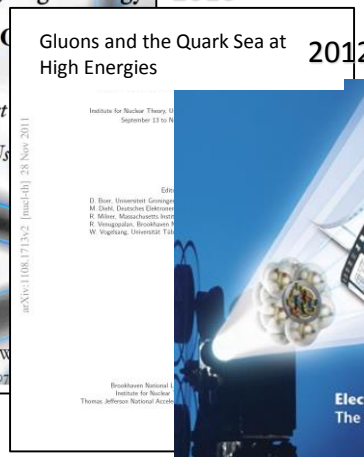
"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

2009



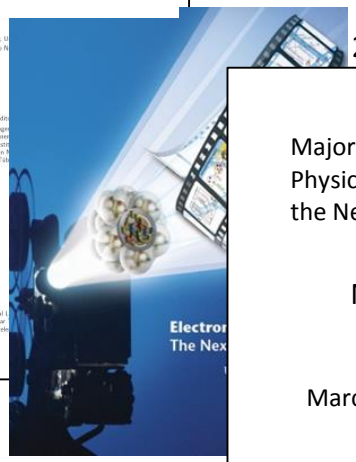
"..a new dedicated facility will be essential for answering some of the most central questions."

2010

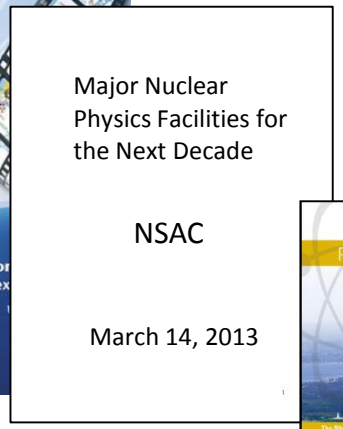


"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider."

2012



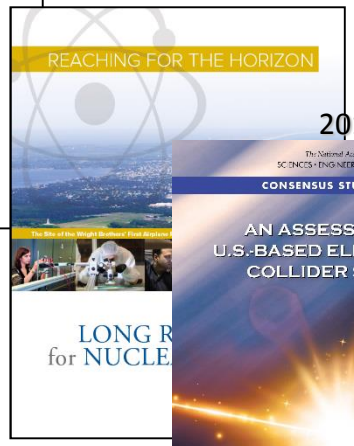
2013



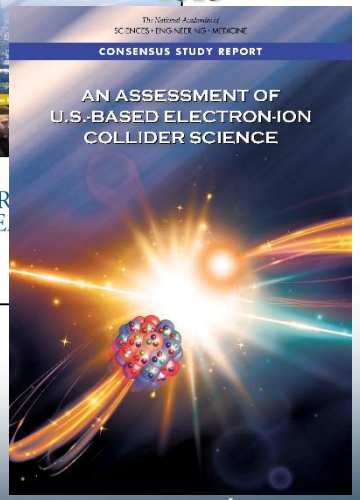
Electron-Ion Collider *absolutely central* to the nuclear science program of the next decade.

"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

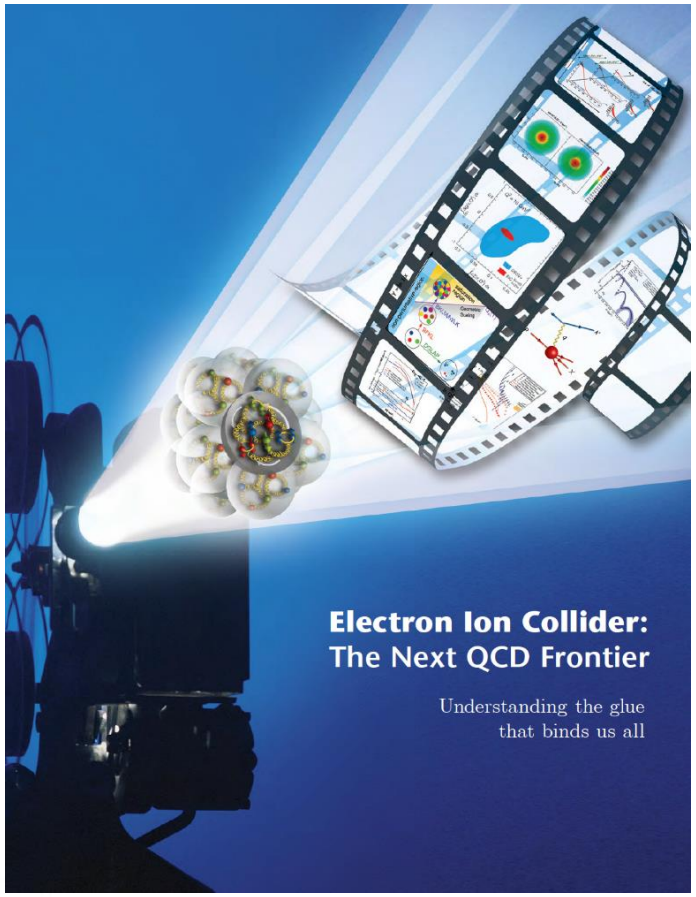
2015

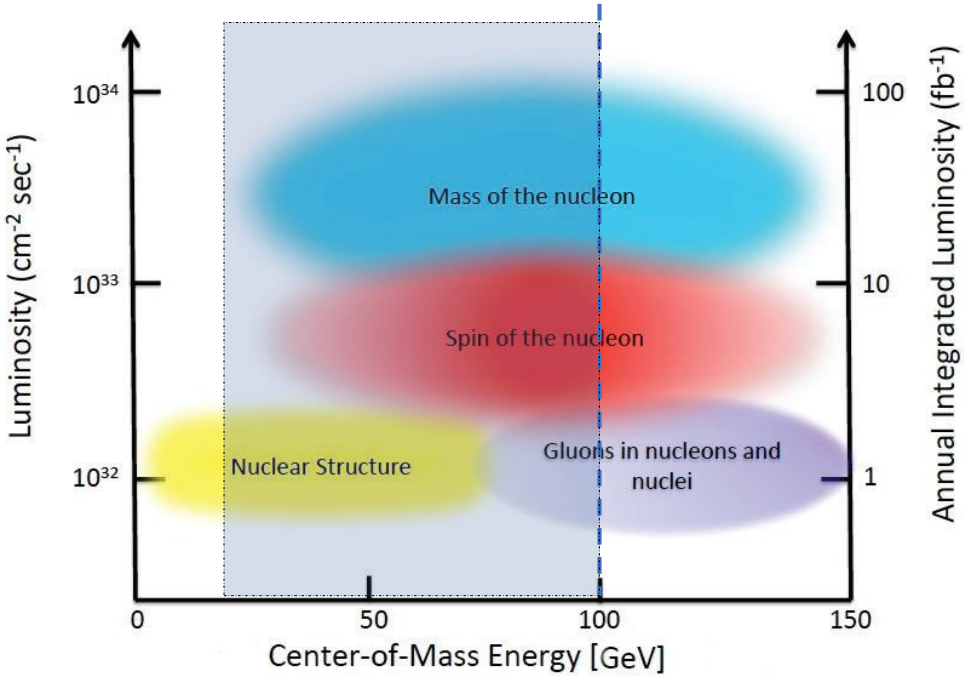


2018



NSAC 2015 LRP Performance Parameters



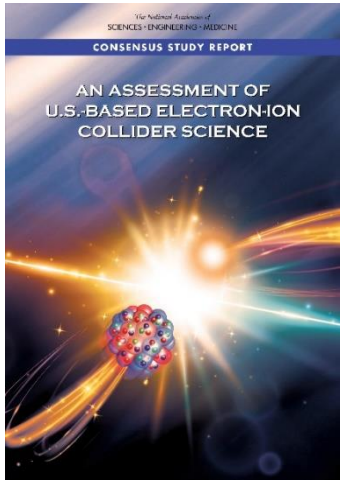


Community and NSAC defined the parameters of machine needed to address the science.

NSAC Performance Parameters:
A - Polarized e, p, light nuclei
B - Ion beam from deuterons to the heaviest table nuclei
C - Center of Mass energy 20-100 GeV
D - Capable of future Center of Mass upgrade to 140 GeV
E - High collision luminosity ~10^{33}-10^{34} cm^{-2} S^{-1}
F - More than one Interaction Region

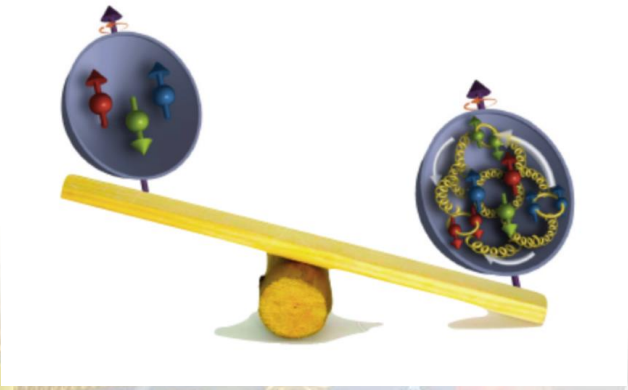
Independent Assessment of the EIC Science Goals

National Academy of Science Report: AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE



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

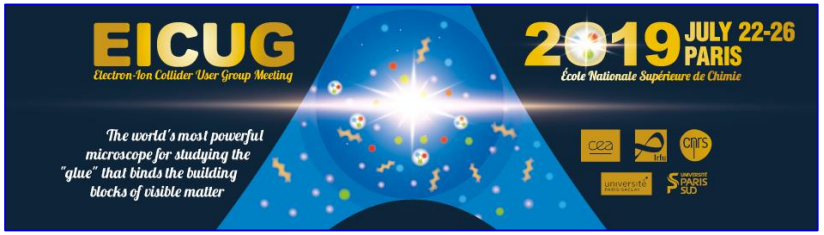
- **How does the mass of the nucleon arise?**
- **How does the spin of the nucleon arise?**
- **What are the emergent properties of dense systems of gluons?"**



The EIC would be a unique facility & maintain leadership in nuclear science

The EIC would maintain leadership in the accelerator science and technology of colliders

Important Ingredient to Success: EIC International Users Community



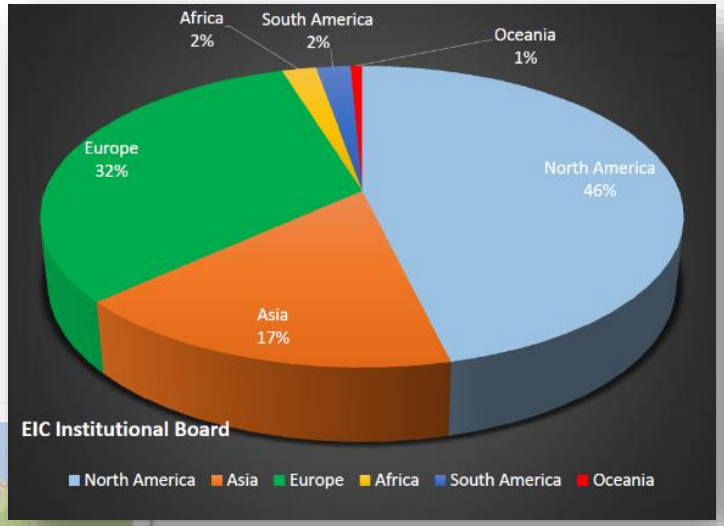
July 22, 2019 Paris, France: EICUG annual meetings alternate between U.S. and Europe

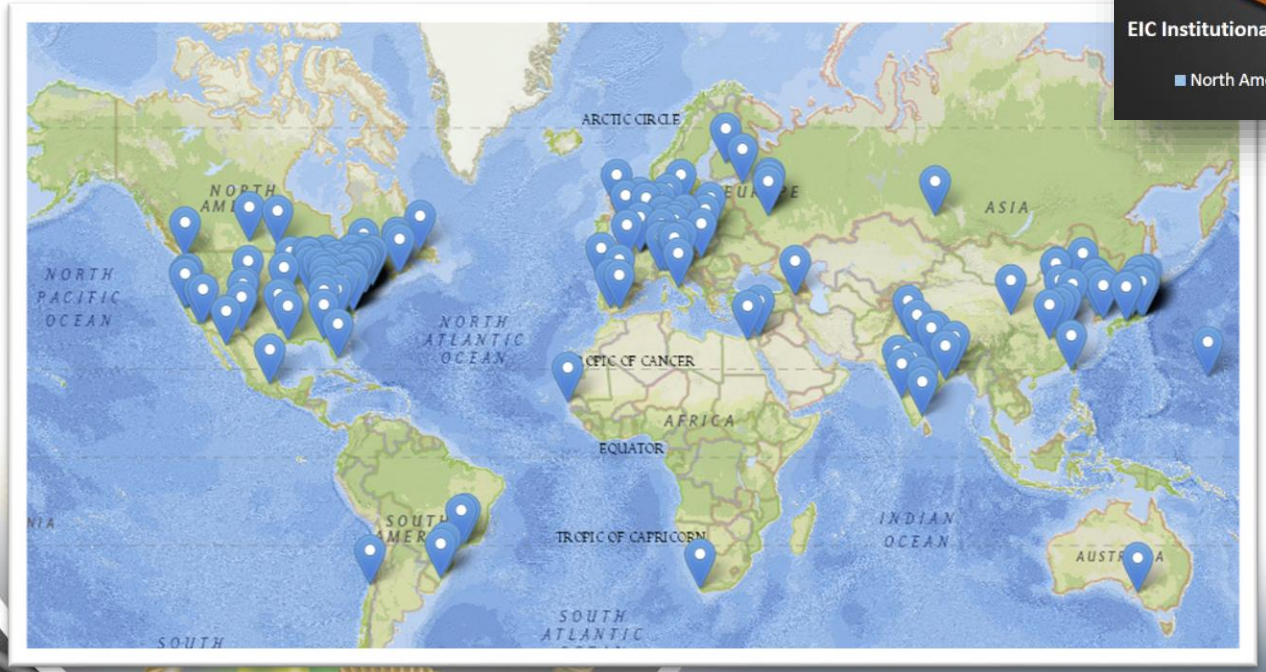
EIC User Community

EIC Users Group Formed in 2016
EICUG.ORG

Status January 2021:

- Collaborators 1243
- Institutions 250
- Countries 34



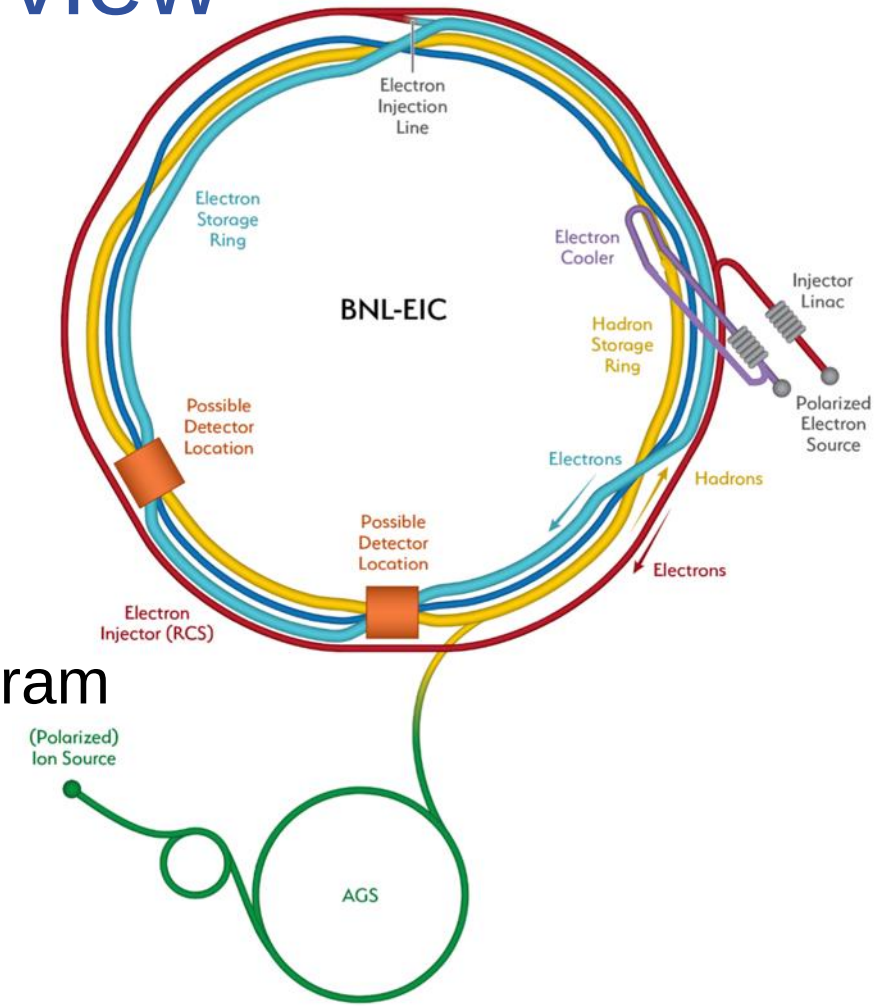


Annual EICUG Meetings

2016	UC Berkeley
2016	Argonne
2017	Trieste, Italy
2018	Washington, DC
2019	Paris, France
2020	Miami
2021	TBD
2022	Warsaw, Poland

Project – brief overview

- Project requirements
- BNL-TJNAF Partnership
- Project Organization
- Project Scope
- Project Partnership plans
- Plans for the Experimental Program
- Schedule
- Funding
- Project Milestones

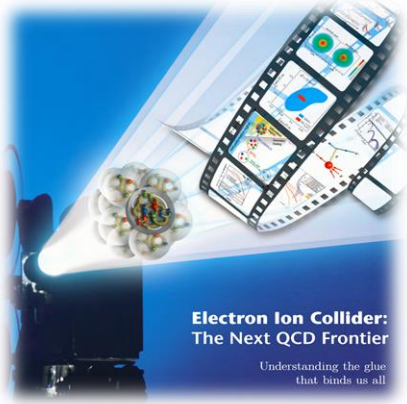


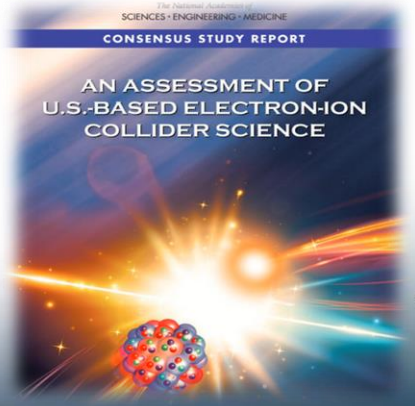
Project Requirements

Project Design Goals

- High Luminosity: $L = 10^{33} – 10^{34} cm^{-2} sec^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

Conceptual design scope and expected performance meets or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)





BNL TJNAF Partnership

- BNL-TJNAF Partnering Agreement Approved- May 7, 2020
- The EIC Project Leadership Team captures project delivery experience from BNL and TJNAF
- EIC Project Executive Management Team (EMT) Established:
  Elke Aschenauer, Rolf Ent, Diane Hatton, Allison Lung, Andrei Seryi, Ferdinand Willeke, and Jim Yeck
- Abhay Deshpande, EIC Science Director, participates in the EMT meeting as an ex-officio member, providing an additional connection to the User community.

BNL Visit to TJNAF – Feb 28, 2020

ELECTRON ION COLLIDER PROJECT

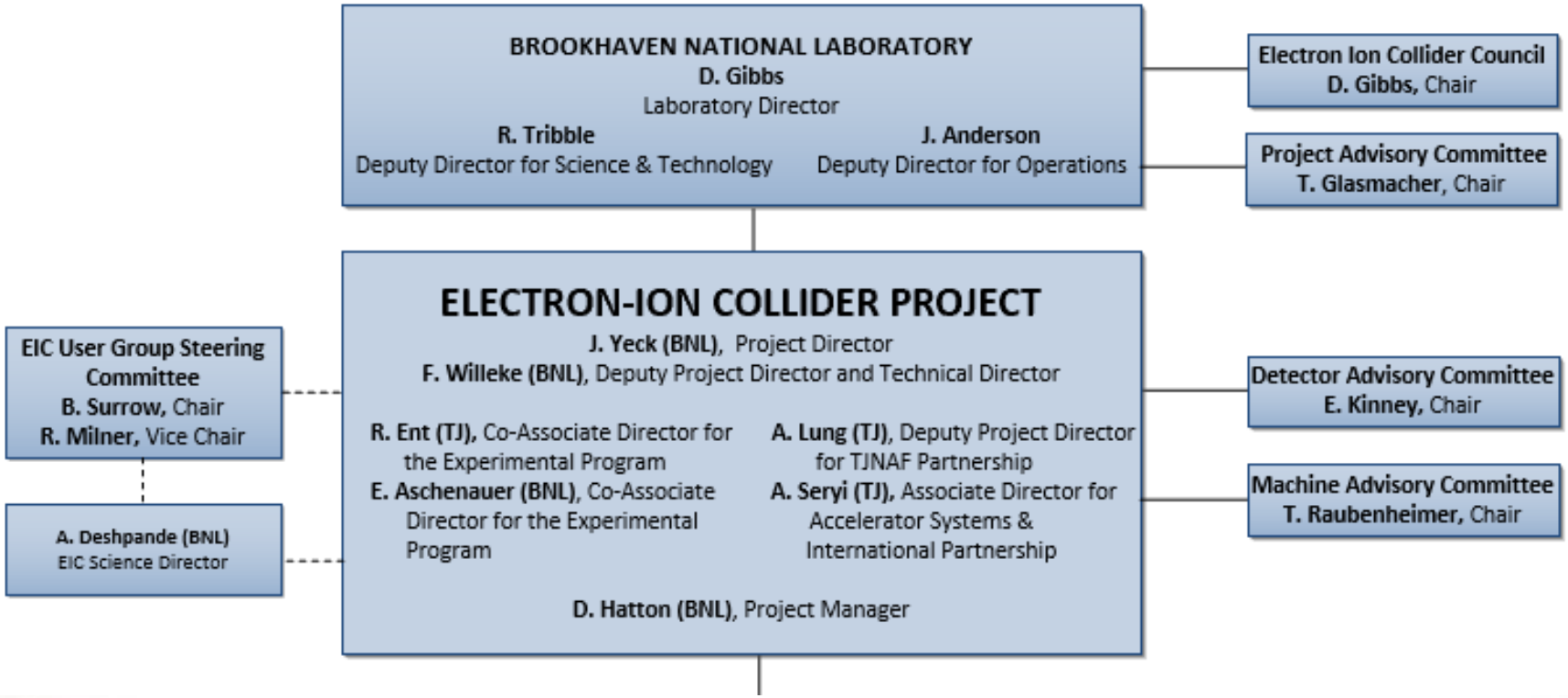
J. Yeck (BNL), Project Director
F. Willeke (BNL), Deputy Project Director and Technical Director

R. Ent (TJ), Co-Associate Director for the Experimental Program
E. Aschenauer (BNL), Co-Associate Director for the Experimental Program

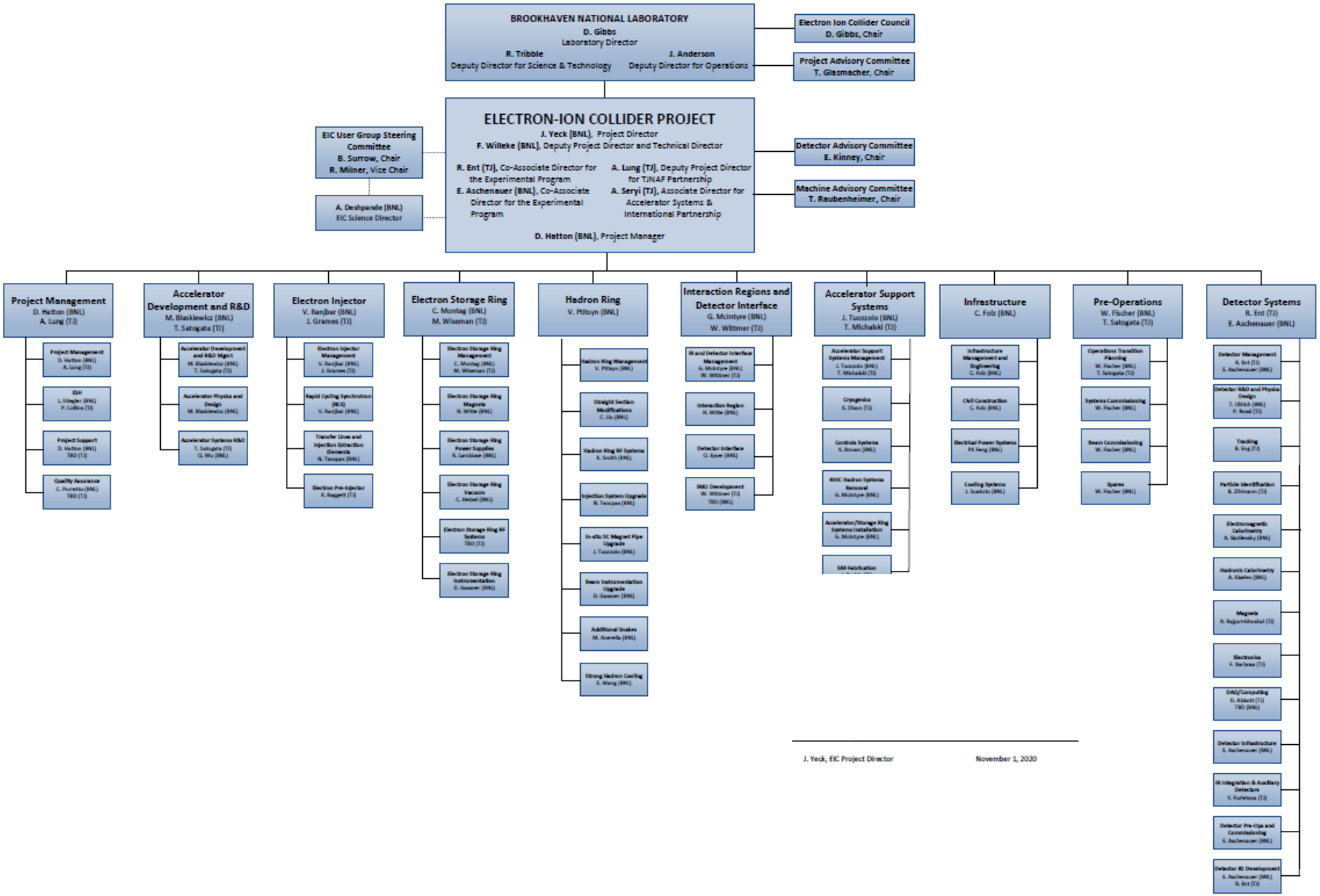
A. Lung (TJ), Deputy Project Director for TJNAF Partnership
A. Seryi (TJ), Associate Director for Accelerator Systems & International Partnership

D. Hatton (BNL), Project Manager

Project Leadership, Committees, and Users



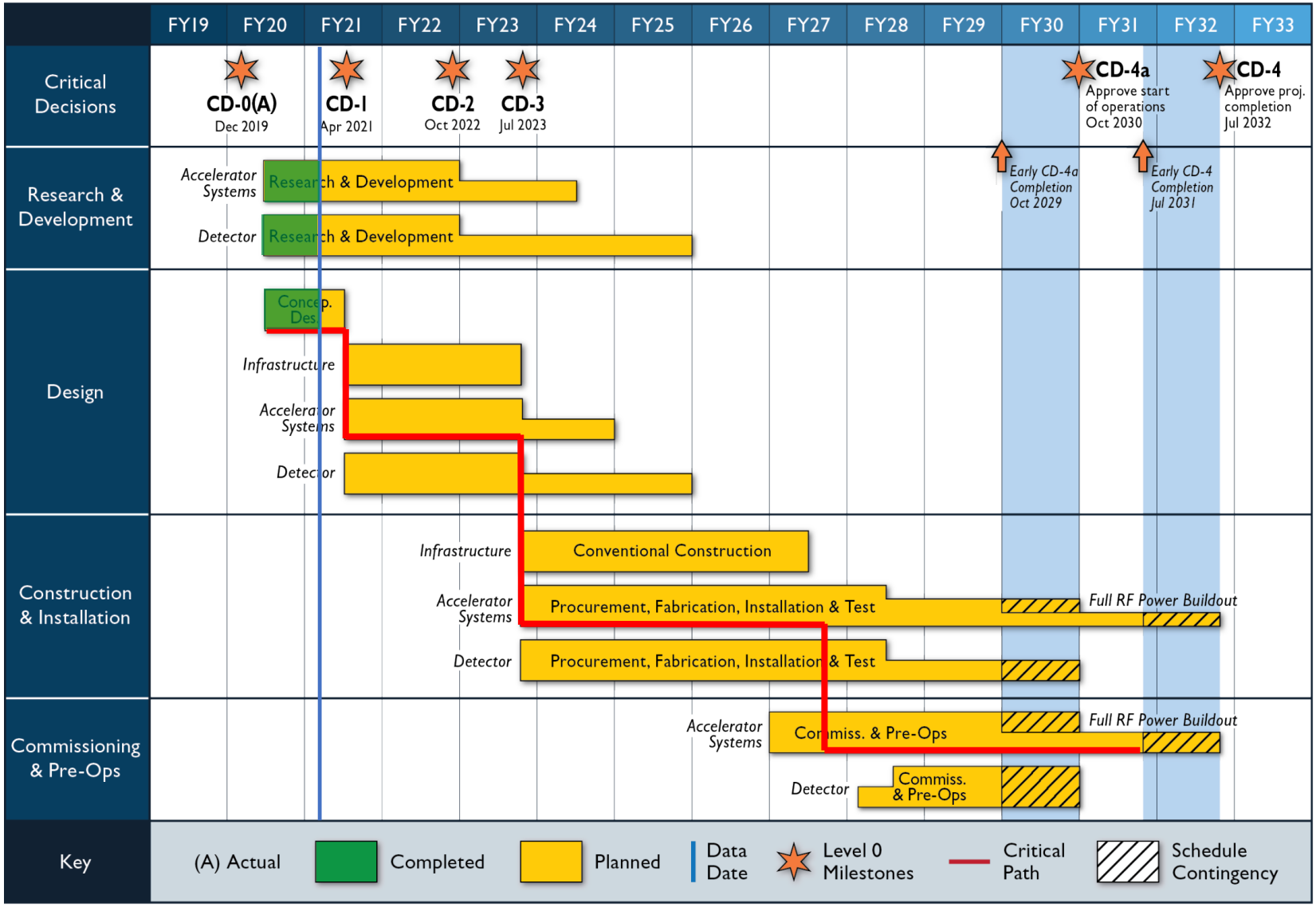
EIC Project Organization



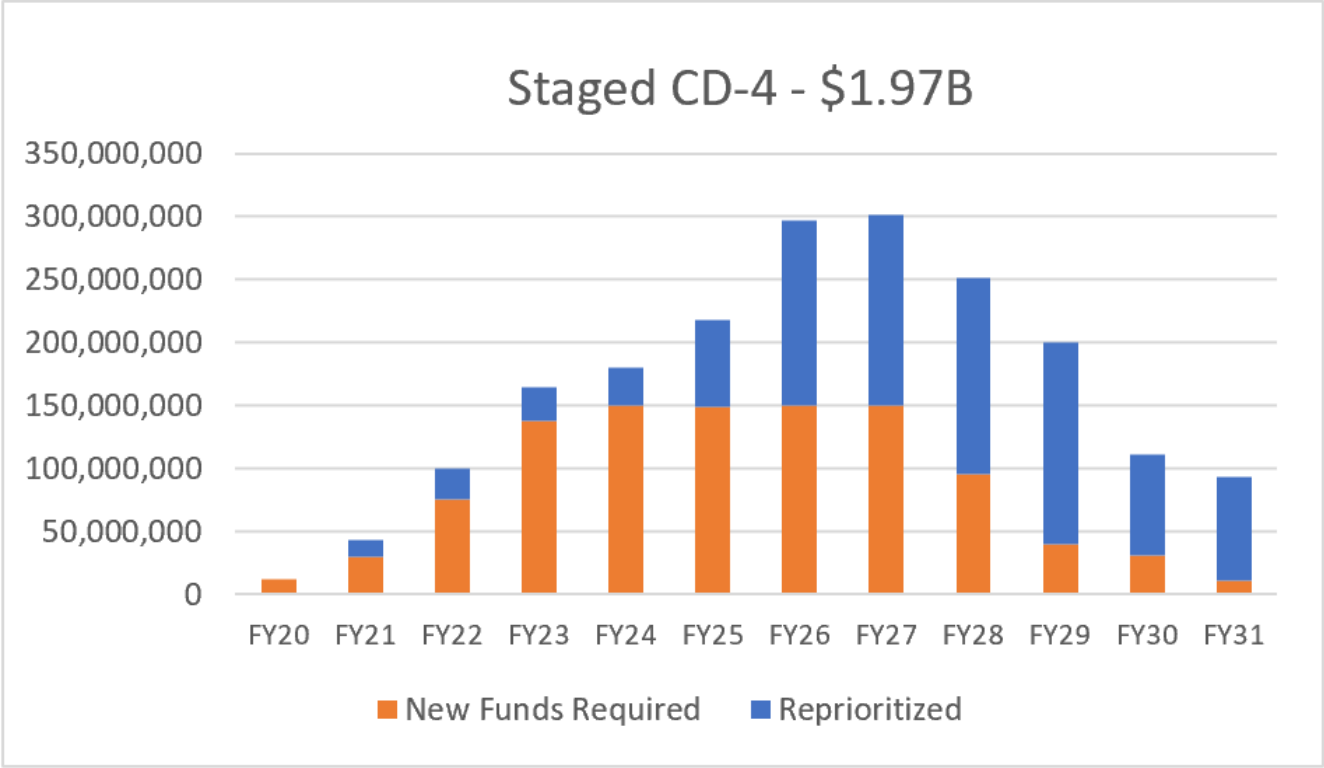
EIC Partnership Plans

- Actively promoting a culture of interdisciplinary and multi-institutional collaboration for both the accelerator and experimental program
- International and domestic partnership is being pursued and bi-lateral meetings with potential partners are well underway to discuss opportunities in the accelerator and experimental areas
- Accelerator Partnership Activities (Assumption of ~5-10% In-kind)
  - Workshop October 7-9 Hosted by Cockcroft Institute, UK – *Promoting Collaboration on the Electron-Ion Collider*
  - In-kind contributions to the accelerator design and hardware are being pursued
- Detector Partnership Activities (Assumption of ~30% In-kind)
  - Expressions of Interest (EoI) for potential cooperation on EIC experimental equipment submitted following a call in May: https://www.bnl.gov/eic/EOI.php
  - Call for proposals for detector(s) planned for March 2021
- DOE Office of Nuclear Physics organizes regular meetings with international funding agencies (next meeting late February).

Schedule


FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28
FY29
FY30
FY31
FY32
FY33
Critical Decisions
CD-0(A)
Dec 2019
CD-1
Apr 2021
CD-2
Oct 2022
CD-3
Jul 2023
CD-4a
Approve start of operations
Oct 2030
CD-4
Approve proj. completion
Jul 2032
Research & Development
Accelerator Systems
Research & Development
Detector
Research & Development
Early CD-4a Completion Oct 2029
Early CD-4 Completion Jul 2031
Design
Conceptual Design
Infrastructure
Accelerator Systems
Detector
Construction & Installation
Infrastructure
Conventional Construction
Accelerator Systems
Procurement, Fabrication, Installation & Test
Full RF Power Buildout
Detector
Procurement, Fabrication, Installation & Test
Commissioning & Pre-Ops
Accelerator Systems
Commiss. & Pre-Ops
Full RF Power Buildout
Detector
Commiss. & Pre-Ops
Key
(A) Actual
Completed
Planned
Data Date
Level 0 Milestones
Critical Path
Schedule Contingency

Reference Funding Profile



- Reprioritized and New Funding
- FY2021 Budget of $30M supports schedule for CD-1
- Funding Profile Set prior to CD-2
- $100M Investment by New York State for Conventional Construction

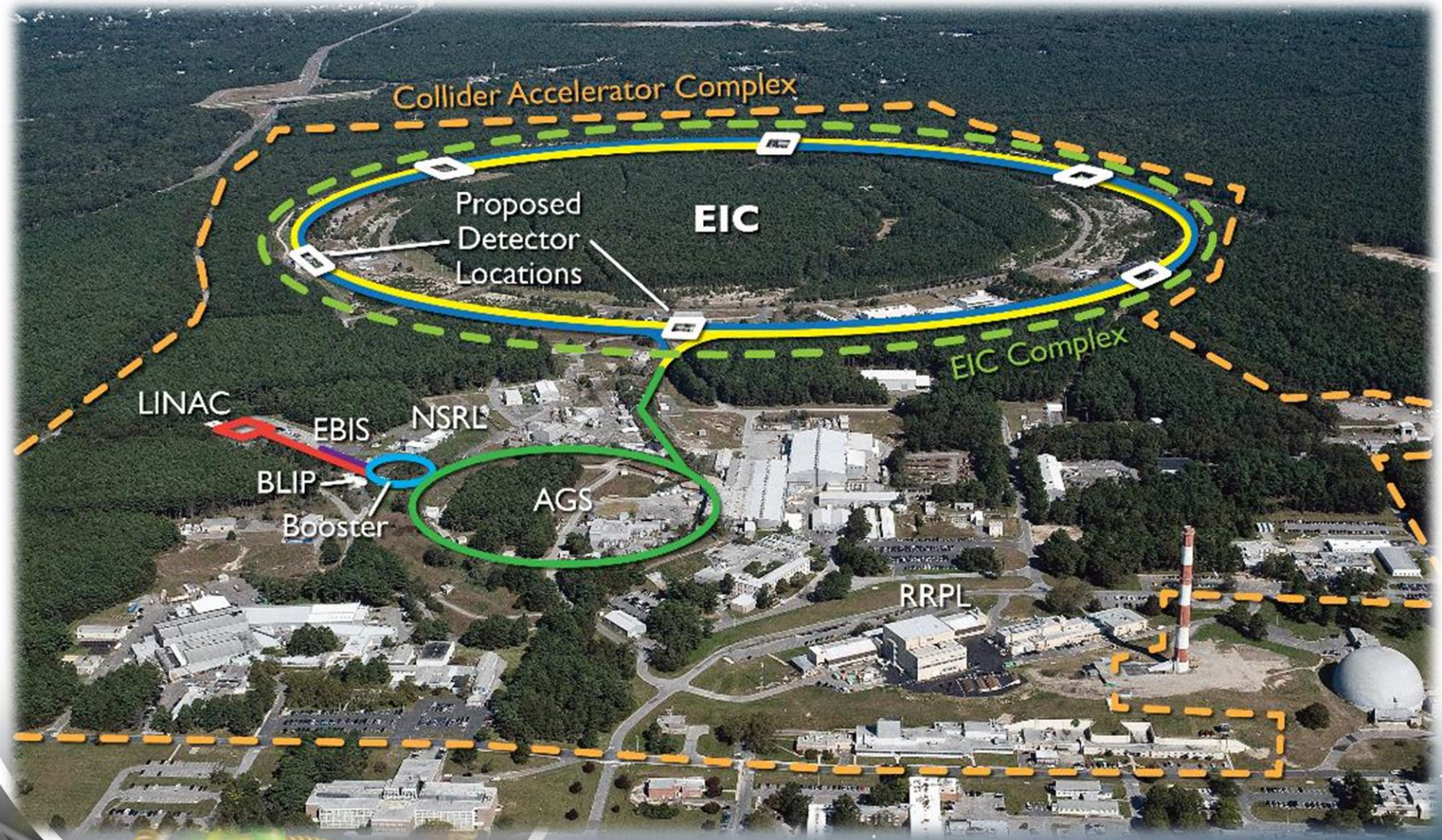
EIC Project - Recent Milestones

Event	Date
DOE Mission Need Statement Approved	January 22, 2019
DOE Independent Cost Review	July 2019
DOE Electron Ion Collider Site Assessment	October 2019
Critical Decision – 0 (CD-0) Approved	December 19, 2019
DOE Site Selection Announced	January 9, 2020
BNL TJNAF Partnership Agreement	May 7, 2020
DOE Office of Science Status Review	September 9-11, 2020
Independent EIC Conceptual Design Review	November 16-18, 2020
BNL Director's Review	December 8-10, 2020
DOE OPA CD-1 Review	***January 26-29, 2021***
CD-1 Approval Target Date	*April 2021*

Post CD-1 Project Milestones

Accelerator Technical Reviews	Spring/Summer 2021
Call for Detector Proposals	March 2021
Start Preliminary Design	April 2021
Detector Proposals Submitted	December 2021
Selection of Project Detector	March 2022
In-kind Deliverables - Agreements	Summer/Fall 2022
Goal for CD-2 Approval	Q1FY2023
Goal for CD-3 Approval	Q4FY2023

EIC Design Overview



EIC designed to meet NSAC and NAS Requirements

• Center of Mass Energies	20 GeV – 140 GeV
• Maximum Luminosity	10^{34} $cm^{-2}s^{-1}$
• Hadron Beam Polarization	>70%
• Electron Beam Polarization	>70%
• Ion Species Range	p to Uranium
• Number of interaction regions	up to two

NSAC - Department of Energy Nuclear Science Advisory Committee
NAS - National Academies of Sciences, Engineering, and Medicine

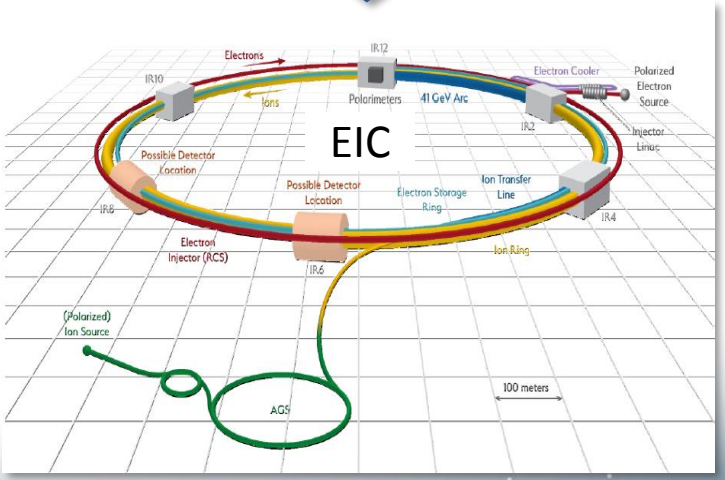
Electron-Ion Collider Concept

Design based on **existing** RHIC,
RHIC is well maintained, operating at its peak

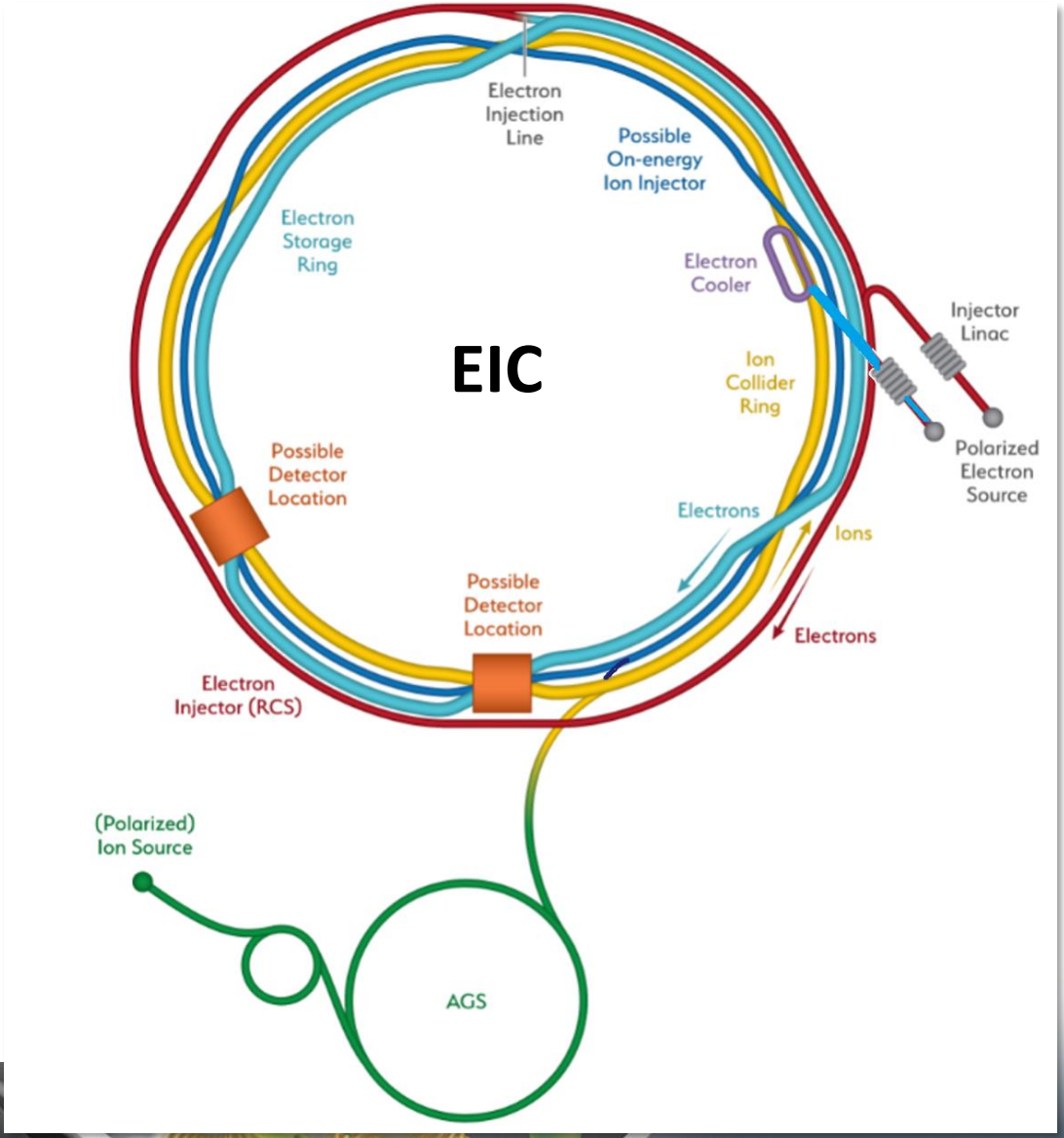
- **Hadron storage ring 40-275 GeV** (existing)
  - Many bunches
  - Bright beam emittance
  - Need strong cooling **or** frequent injections

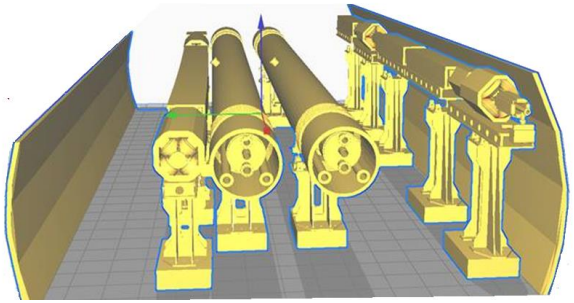
- **Electron storage ring (2.5–18 GeV** (new))
  - Many bunches,
  - Large beam current (2.5 A) ➔ 10 MW S.R. power
- **Electron rapid cycling synchrotron** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity

- **High luminosity interaction region(s)** (new)
  - L = $10^{34}cm^{-2}s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation



From RHIC to the EIC





The strong hadron cooling facility completes the facility

- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex

EIC covers full center of mass energy range of 20 GeV – 140 GeV

Protons up to 275 GeV:

- Existing RHIC with superconducting magnets allow up to **E_p = 275 GeV** and down to **E_p = 41 GeV**
- RHIC beam parameters are close to what is required for EIC

Electrons up to 18 GeV:

Electron storage ring with up to **18 GeV** installed RHIC tunnel, readily achievable with

- large circumference of 3870 m and
- available superconducting RF technology ➔ U_{rf} = 62 MV

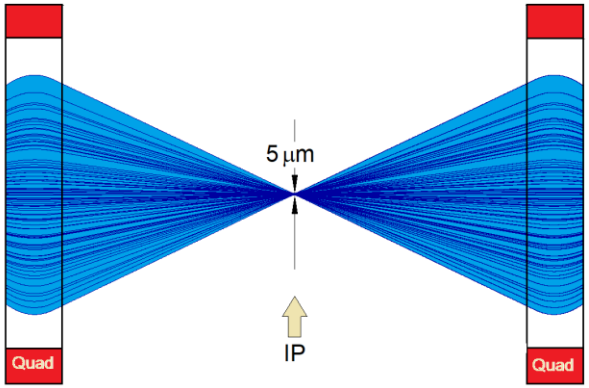
low electron energy of **2.5 GeV** is easily obtainable

EIC achieves high luminosity $L = 10^{34}\ cm^{-2}s^{-1}$

- **Large bunch charges** $N_e \leq 1.7 \cdot 10^{11}$, $N_p \leq 0.69 \cdot 10^{11}$

- **Many bunches,** n_b=1160
  - crossing angle collision geometry
  - large total beam currents
  - limited by installed RF power of 10 MW

Strong focusing β_y =5 cm



- **Small beam size** at collision point achieved by
  - small emittance, requiring either:
    - strong hadron cooling to prevent emittance growth **or**
    - frequent hadron injection
  - and strong focusing at interaction point (small β_y)
  - flat beams $\sigma_x/\sigma_y \approx 10$

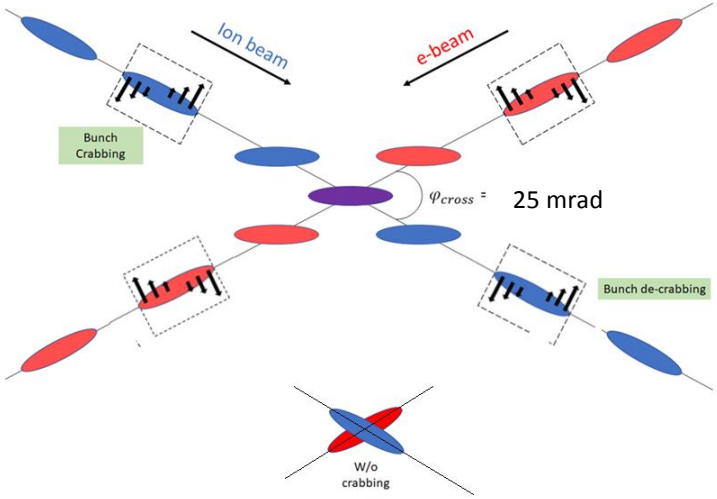
- **Strong, but previously demonstrated beam-beam interaction**

$\Delta\nu_p$ = 0.01 demonstrated in RHIC

$\Delta\nu_e$ = 0.1 demonstrated in HERA, B-factories

EIC High Luminosity with a Crossing Angle

- **Modest crossing angle of 25 mrad**
  - Avoid parasitic collisions due to short bunch spacing
  - For machine elements, to improve detection
  - Reduce detector background

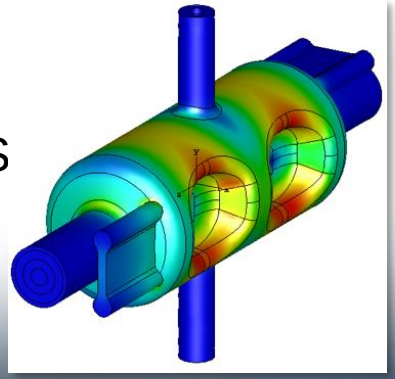


- **However**, crossing angle causes
  - Low luminosity
  - Beam dynamics issues

- **avoided by Crab Crossing**

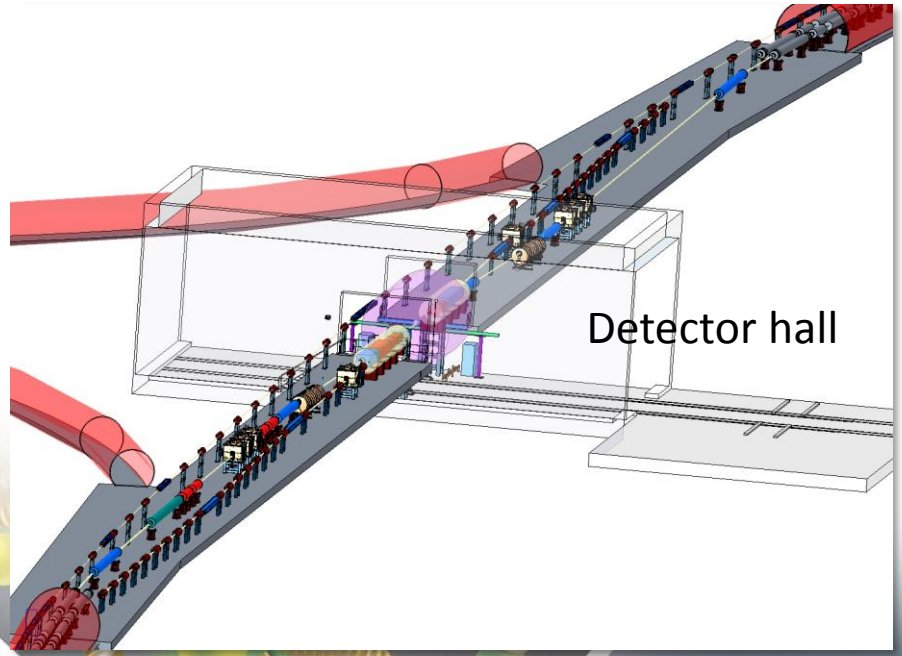
Then :
  - Effective head-on collision restored
  - Beam dynamic issues resolved

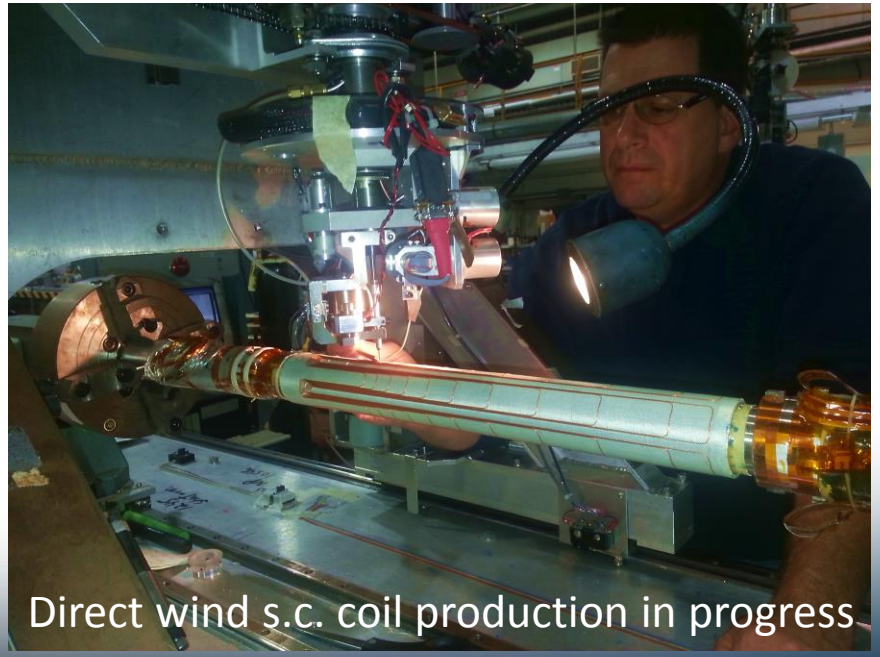
- RF resonator (crab-cavity) prototypes built and tested with proton beam in the CERN-SPS



EIC Interaction Region

- Beam focused to $\beta_y \leq 5$ cm @ $\sigma_y = 5\ \mu$m, gives $L=10^{34} cm^{-2} s^{-1}$
- Manageable IR chromaticity and sufficient dynamic aperture
- Full acceptance for the colliding beam detector
- Accommodates crab cavities and spin rotators
- Synchrotron radiation and impedance manageable
- EIC final focus magnets based on conventional NbTi superconducting magnets using collaring and direct wind - technology



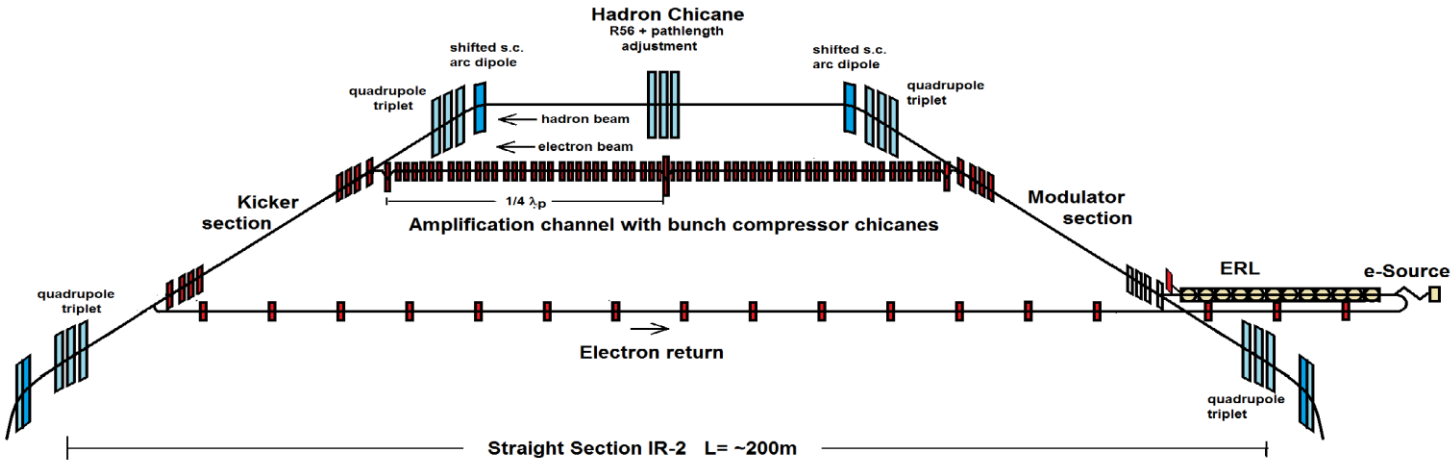


Maintaining high luminosity during a fill

- **Issue:** Dense hadron beam leads to emittance growth due to IBS – causes luminosity decay, would imply reduced average luminosity
- **eA collisions:** existing stochastic cooling system preserves emittance – e-ion luminosity maintained, thus for Ions, straightforward path forward
- **ep collisions**: need to actively prevent p emittance growth with cooling scheme
- **EIC Strong Hadron Cooling**: extension of established stochastic cooling to higher bandwidth: replacing cables @ amplifiers with electron beam and beam dynamical effects: **Coherent Electron Cooling (CeC)**
- **Establishing CeC will provide**:
  - **Long un-interrupted luminosity runs**
  - **Significant advance in accelerator science**
- Active R&D on demonstrating CeC
- Has also considered an alternative of frequent on-energy injections using existing Blue Ring that restores average luminosity up to ~ the peak luminosity
- Several alternative options are also being studied – an electron storage ring (single or dual energy) for incoherent electron cooling, use of induction accelerators to produce high power electron beam for cooling, etc.

EIC Strong Hadron Cooling

Coherent Electron Cooling with μ-bunching amplification

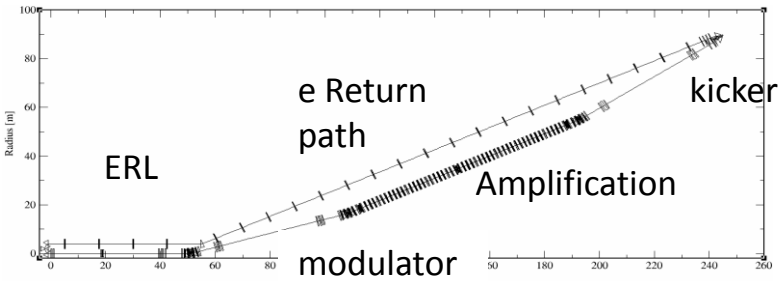


- Design Cooling Rate R_{cool}= 1-2 h^{-1}
- Electron beam current I_e=100 mA (1nC/bunch), electron emittance ε_{xyN}= 2.5/0.5μm

- **EIC Strong Hadron Cooling**: extension of established stochastic cooling to higher bandwidth: replacing cables @ amplifiers with electron beam and beam dynamical effects: **Coherent Electron Cooling (CeC)**
- **Establishing CeC will provide**:
  - **Long un-interrupted luminosity runs**
  - **Significant advance in accelerator science**

Progress on Strong Hadron Cooling

Optics and Geometry



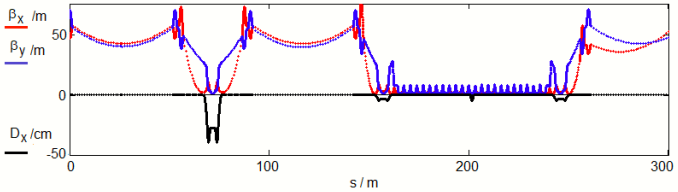
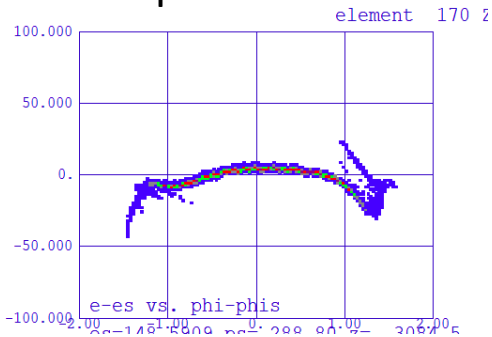
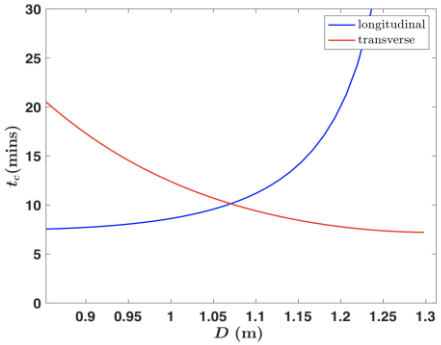


Figure 2: Electron beam optics in the cooling section

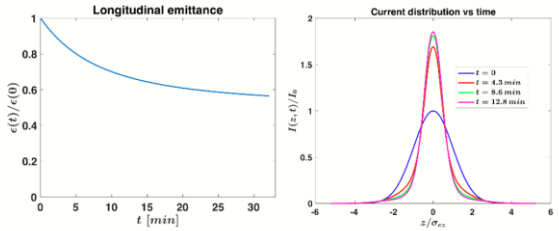
ERL optimization:
Less components,
better performance!!



Optimization of transverse
vs longitudinal cooling

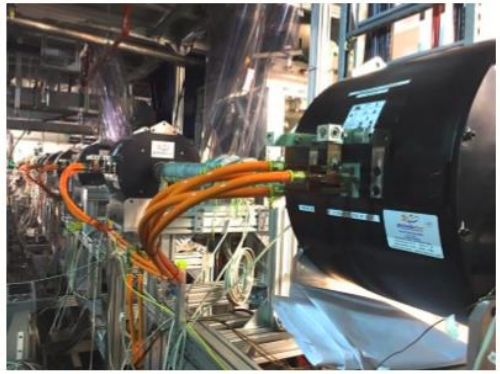


Cooling Simulation
1h cooling time !!

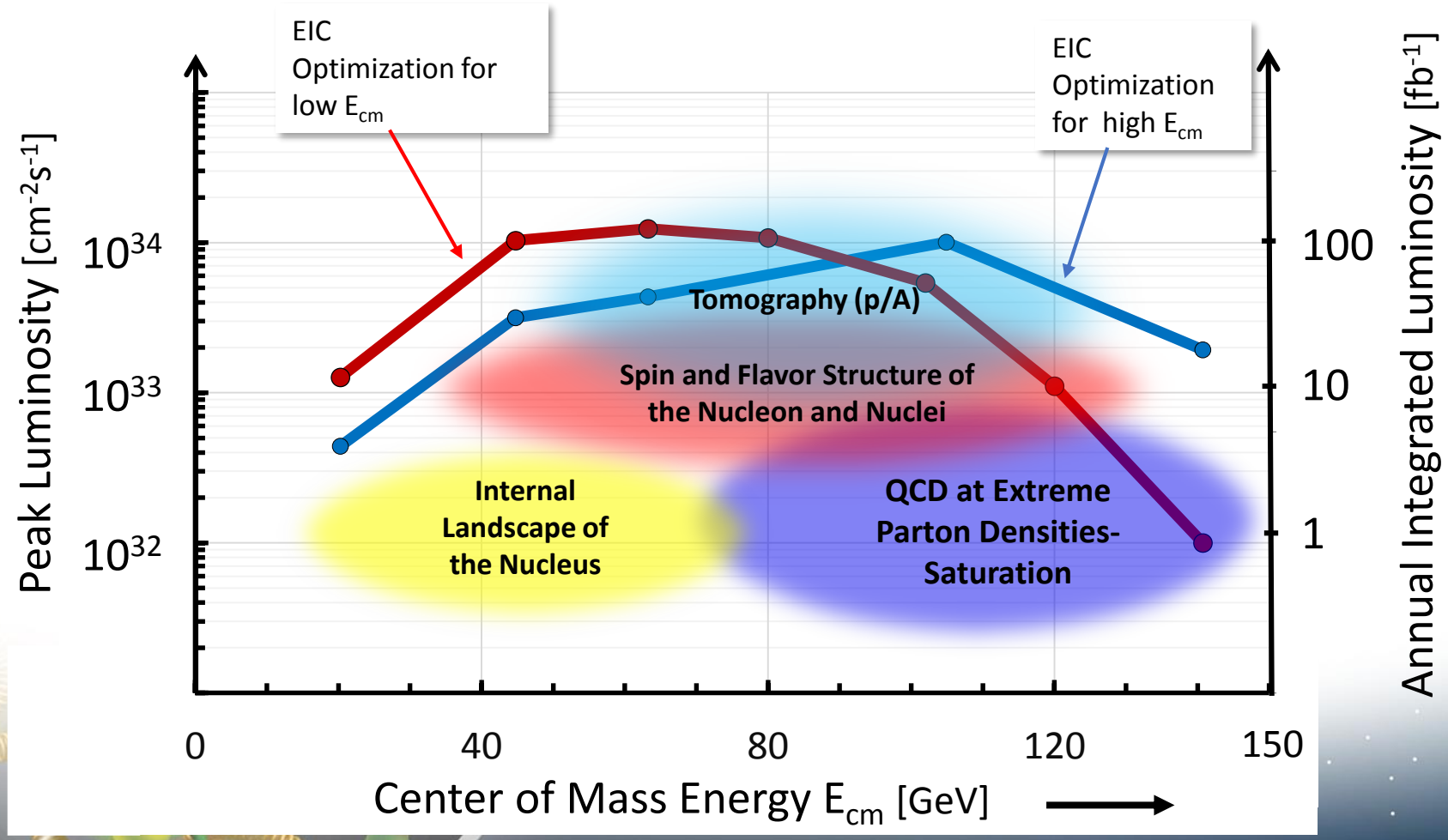


Evolution of the longitudinal emittance of the proton beam (left plot) and the longitudinal distribution function at several moments of time.

- CeC test set up in RHIC: Plasma cascade amplification section with strong solenoids



Luminosity versus E_{CM} center of mass energy

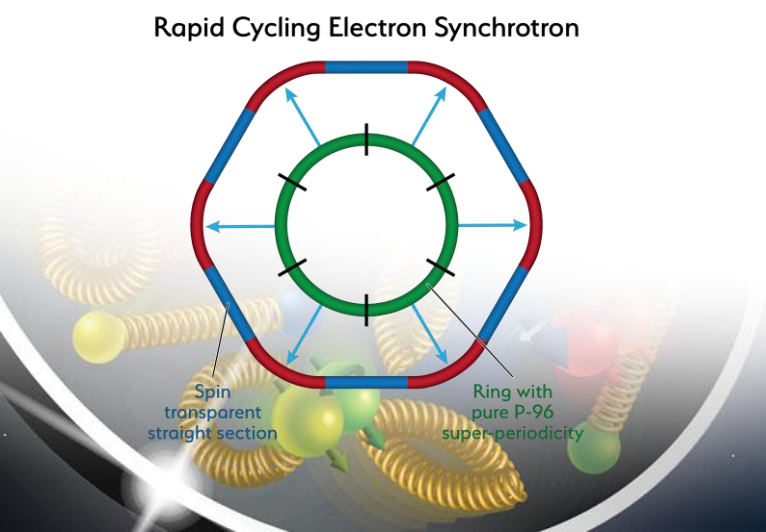


18 GeV Rapid Cycling Synchrotron enables high electron polarization in the electron storage ring

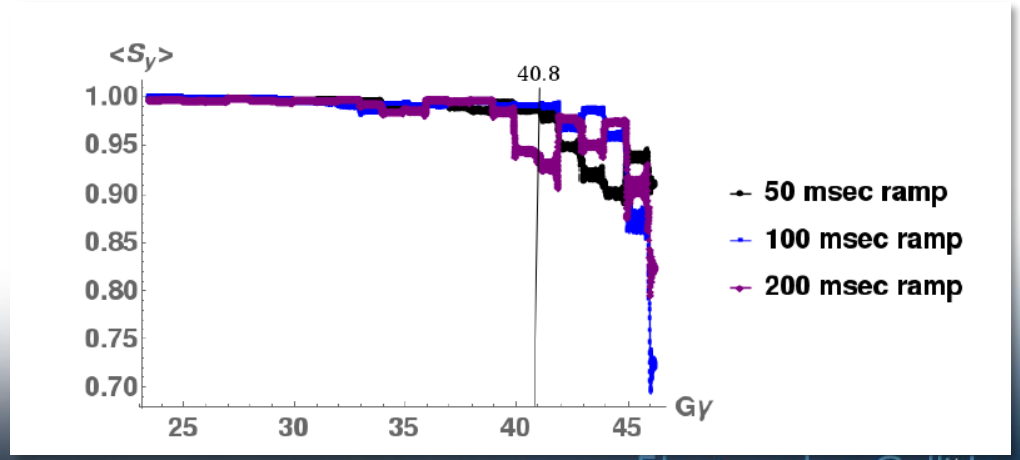
- 85% polarized electrons from a polarized source and a 400 MeV s-band linac get injected into the fast cycling synchrotron in the RHIC tunnel
- AGS experience confirms depolarization suppressed by lattice periodicity
- Ingenious optical design with high quasi-periodicity arcs and unity transformations in the straights suppresses all systematic depolarizing resonances up to E >18 GeV
- Good orbit control $y_{cl.o.} < 0.5$ mm; good reproducibility suppresses depolarization by imperfection resonances

➔ No depolarizing resonances during acceleration 0.4-18 GeV
no loss of polarization on the entire ramp up to 18 GeV (100 ms ramp time, 2 Hz)

RCS Design



RCS Polarization Performance confirmed by extensive simulations



High average polarization at electron storage ring of 80% by

- Frequent injection of bunches on energy with high initial polarization of 85%
- Initial polarization decays towards P_∞ < ~50% (equilibrium of self-polarization and stochastic excitation)
- At 18 GeV, every bunch is refreshed within minutes with RCS cycling rate of 2Hz
- Need both polarization directions present at the same time

B P

Refilled every 1.2 minutes

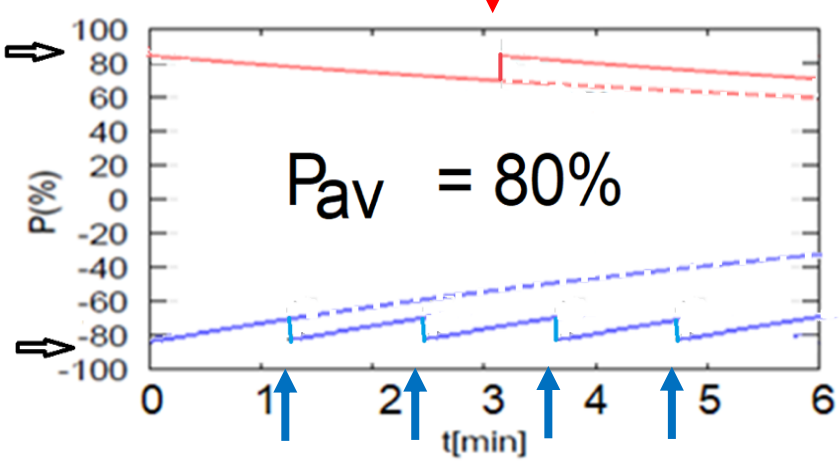
B P

Refilled every 3.2 minutes

Re-injection

P(0) = 85%

P(0) = -85%



P_{av} = 80%

P_∞= 30% (conservative)

Re-injections

EIC Hadron Polarization

- Existing p Polarization in RHIC achieved with “Siberian snakes”
- Near term improvements will increase proton polarization in RHIC from 60% to 80%
- ^{3}He polarization of >80% measured in source
- 80% polarized ^{3}He in EIC will be achieved with six “snakes”,
- Acceleration of polarized Deuterons in EIC 100% spin transparent
- Need tune jumps in the hadron booster synchrotron

Electron beam ion source EBIS with polarized ^{3}He extension

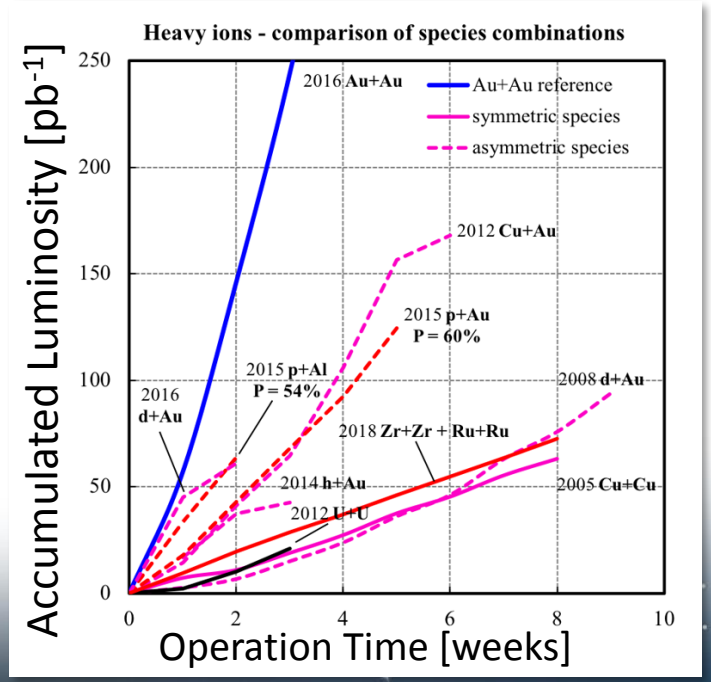
The existing RHIC ion sources & ion acceleration chain provide already **today** all ions needed for EIC

- Ions from He to U have been already generated in the Electron-Beam-Ion-Source ion source (EBIS), accelerated and collided in RHIC
- EBIS can generate any ion beam from ^{3}He to U for the BNL EIC
- Existing EBIS provides the entire range of ion species from He to U in sufficient **quality** and **quantity** for the EIC

Enormous versatility! is a unique capability!

Ion Pairs in the RHIC Complex	
Zr-Zr, Ru-Ru	(2018)
Au-Au	(2016)
d-Au	(2016)
p-Al	(2015)
h-Au	(2015)
p-Au	(2015)
Cu-Au	(2012)
U-U	(2012)
Cu-Cu	(2012)
D-Au	(2008)
Cu-Cu	(2005)

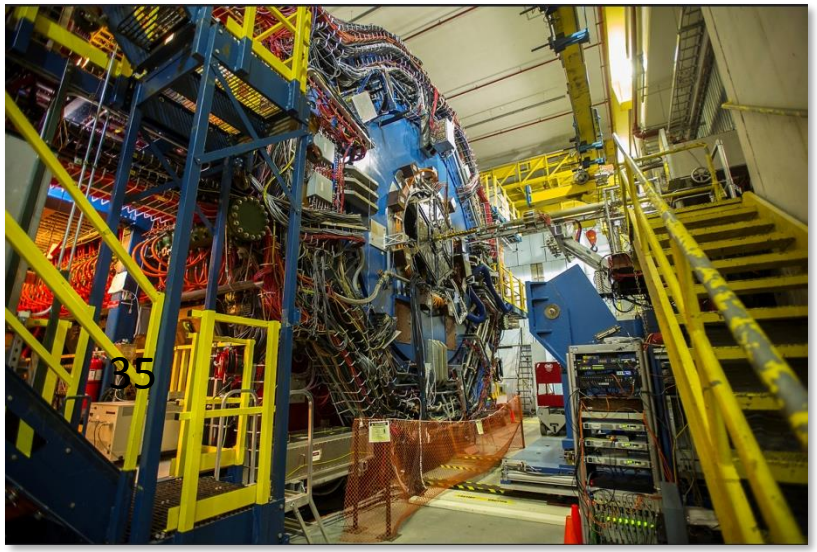
Ion-Ion Luminosity Runs in RHIC 2005-2018



The EIC will benefit from two large existing detector halls in IR 6 and IR 8

- Both halls are **large** and **fully equipped** with infrastructure such as power, water, overhead crane, ….

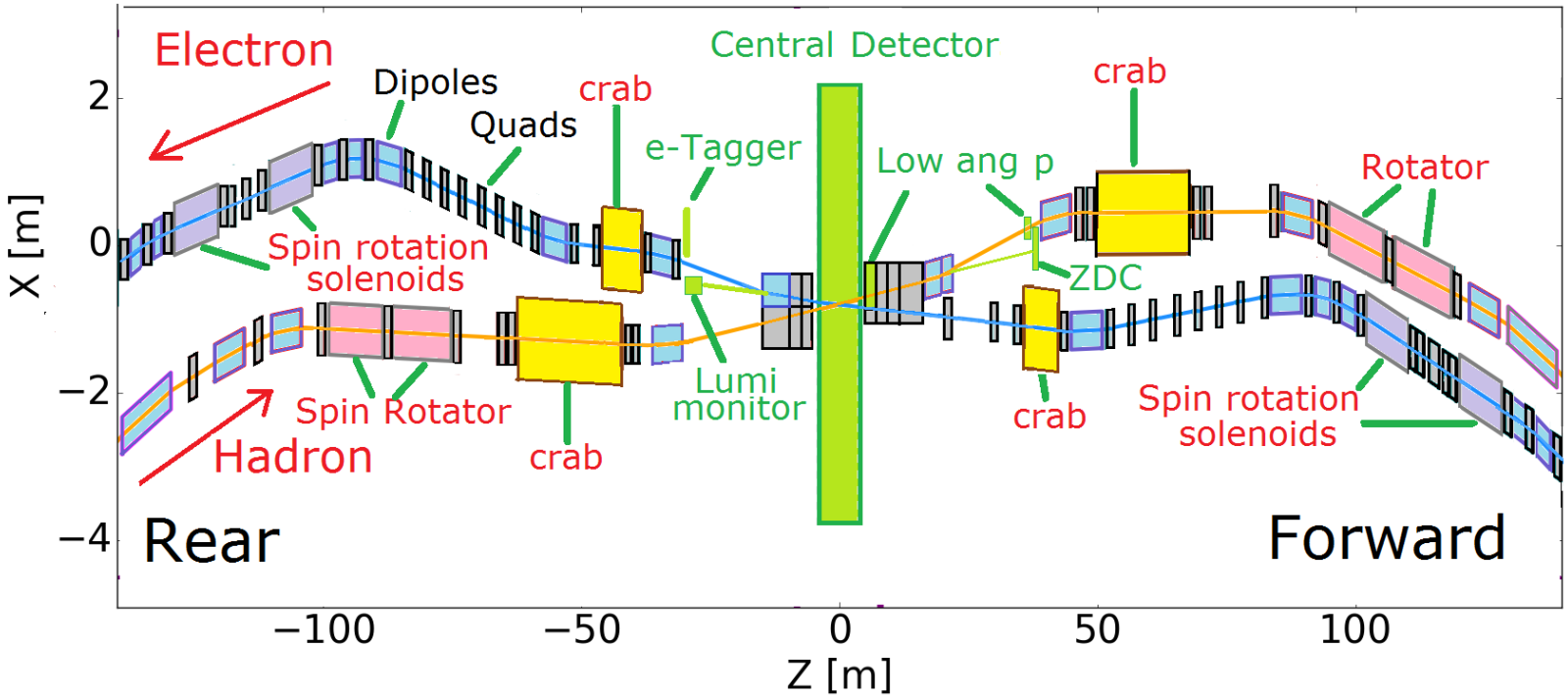
IR 8 detector hall with PHENIX detector (transitioning to sPHENIX)



IR 6 detector hall with STAR detector

- Both IRs can be implemented simultaneously in the EIC lattice and be accommodated within beam dynamics envelope
- 2 IR's: laid out <u>identically</u> or <u>optimized for maximum luminosity at different</u> E_{CM}

Interaction Region Design

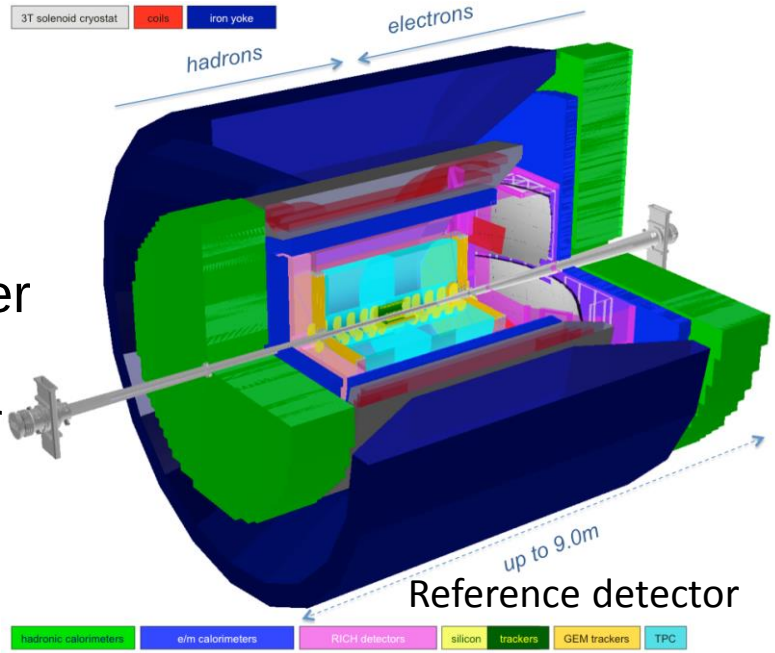


- Interaction Region, the accelerator around the colliding beam detector is the most complex and most constrained section of a collider
- 2nd IR and 2nd detector is not in the project scope but we unanimously agree that the EIC should have 2 detectors (and 2 IR s)
- The layout of a second IR is being studied under the assumption that more luminosity can be achieved at lower center of mass energy (60GeV) if more bunches are used in collisions

Experimental Program Preparation

EIC User Community Yellow Report – December 2019 Kick Off

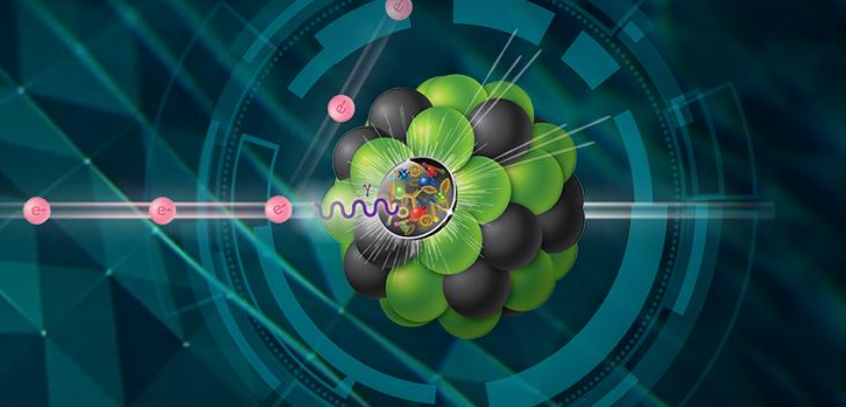
- 4 workshops to prepare physics studies & detector concepts in preparation for realization of the EIC
- Final workshop in November 2020. Draft Yellow Report is available



Reference detector

BNL and TJNAF Jointly Leading Process for Defining Detector(s)	
Call for Expressions of Interest (EOI) for "Potential Cooperation on the EIC Experimental Program"	May 2020
EOI Responses	November 2020
Assessment of EOI Responses	On-going
Call for Detector Proposals	March 2021
BNL/TJNAF Program Advisory Committee Established	Summer 2021
Detector Proposals Submitted	December 2021
Decision on Detector(s)	Early 2022

Call for Expressions of Interest for Potential Cooperation on the EIC Experimental Program



Dear prospective Electron-Ion Collider users,

Brookhaven National Laboratory (BNL), in association with Thomas Jefferson National Accelerator Facility (TJNAF), would like to invite interested groups to submit an Expression of Interest (EOI) for their potential cooperation on the experimental equipment in support of a broad and successful science program at the Electron-Ion Collider (EIC).

We encourage interested groups to work together within their country, their geographical region, or as a general consortium, to submit such EOIs.

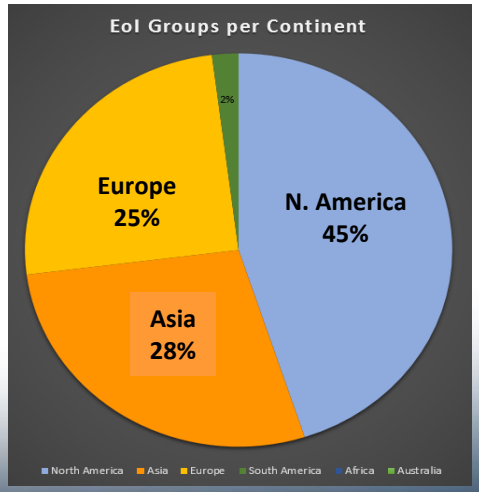
This call focuses on all detector components to facilitate the diverse EIC science program, including those integrated in the interaction region.

Please visit https://www.bnl.gov/eic/EOI.php to see further details about this call and how to submit an Expression of Interest.

Best regards,
Elke Aschenauer and Rolf Ent for the EIC Project Team

- Call was issued May 2020
- Deadline: November 1st 2020
- Call advertised worldwide
  https://www.bnl.gov/eic/EOI.php

Received 47 EoIs, available at:
https://indico.bnl.gov/event/8552/



EIC Accelerator Collaboration Opportunities

- EIC is international from its conception
- Collaboration on EIC design and construction – mutually beneficial, providing a gateway to EIC science, advancing accelerator science and technology

- Possible contributions to the EIC accelerator could include the full range of accelerator design & hardware
  - E.g. IR magnet design and construction, luminosity monitoring, RF R&D and construction, normal conducting magnets, critical vacuum components, feedback systems, polarimetry, contributions to the 2nd IR, beam-dynamics calculations, etc.

Partnership development

- Building up and expanding collaboration on EIC accelerator
- Two approaches: bi-lateral dialogue & workshops:
  - Bi-lateral discussions
    - Between EIC project and a specific lab
    - Allow for focused discussion on specific scope
  - Dedicated partnership workshops
    - Wide attendance, 2-3 days workshops
    - Hosted by one of key international partners
    - Aimed at both domestic and international partners, and for discussion of contribution of any scale

Organizing Committee:

Jim Clarke (Cockcroft Institute and ASTeC, UK)
Peter McIntosh (Cockcroft Institute, UK)
Peter Williams (Cockcroft Institute, UK)
Graeme Burt (Cockcroft Institute, UK)
Peter Ratoff (Cockcroft Institute, UK) (Co-Chair)
Andrei Seryi (JLab) (Co-Chair)
Ferdinand Willeke (BNL)
Bernd Surrow (EIC User Group)

Technical & Administrative Support

Liz Kennedy (Cockcroft Institute)
Andy Collins (STFC Daresbury Laboratory)
Stuart Eyres (STFC Daresbury Laboratory)
Laura Bennett (STFC Daresbury Laboratory)

https://www.cockcroft.ac.uk/events/eic20/
https://indico.cern.ch/event/949203/

October 7-9, 2020 EIC partnership workshop

- 365 invited participants
- 26 countries
- 6 continents

- A truly global event!
- 76 scheduled talks
- 33 hours of presentations spread across 16 sessions in a period of 50 hours

From Peter Ratoff's summary, Cockcroft Institute Director, Workshop co-Chair:

- Evidence of very strong interest in collaboration from many North American and overseas laboratories
- The hosts labs (BNL/JLAB) naturally took the lead with 19 presentations
- 11 other North/South American labs made contributions:
  - ANL (4 talks), LBNL (3), FNAL (2), SLAC (2), U. Guanajuanto Mexico (2), ORNL, TRIUMF, Cornell U.,
  - U. Kansas, NIU, LNLS (Brazil)
- 6 Asia/Oceania labs made contributions:
  - KEK (7 talks), JPARC, Spring-8, PAL (S. Korea), SLRI (Thailand), ANSTO (Australia)
- 12 Europe/Africa labs made contributions:
  - Cockcroft (4 talks), PAS Poland (3), CERN (2), INFN Frascati (2), iThemba RSA (2), John Adams (2),
  - DESY, CEA Saclay, IJC Paris, U. Rome "La Sapienza", T.U. Dortmund, AGH-UST Poland
- In addition, we had 3 talks about accelerator schools in USA, Europe and Japan
- And 2 talks from accelerator industry in USA (Euclid TechLabs LLC & RadiaSoft LLC)

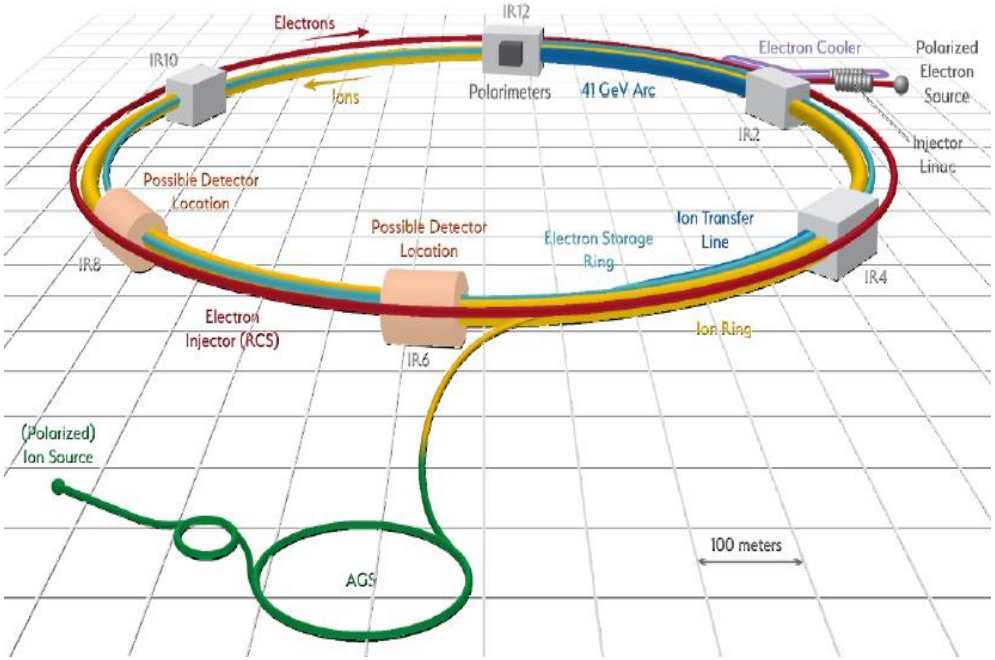
EIC Accelerator Collaboration – path forward

- The EIC team making efforts to stay as close as possible to technically driven schedule
- With anticipated CD1 in 2021, CD2 in 2022 the time to engage is now
- Mechanisms for collaboration developing

  1) Partnership workshops allow to see the broad picture and indicate the areas where project needs and the interests and expertise match

  2) Meetings between the institutional team and EIC project team allow for focused discussion on specific collaboration scope

EIC – the big picture



EIC scope includes the machine upgrade to RHIC asset and two interactions regions with one of the interaction regions outfitted with a major detector.

The EIC will be located at BNL and will be realized with TJNAF as a major partner. The realization of the EIC will be accomplished over the next decade at an estimated cost between $1.6 and $2.6 billion.

Utilize existing operational hadron collider; add electron storage ring, cooling in existing RHIC tunnel and electron injector.

The EIC's high luminosity and highly polarized beams will push the frontiers of accelerator science and technology and provide unprecedented insights into the building blocks and forces that hold atomic nuclei together.

Working towards CD-1 in Q3 FY 2021

Message from Tim Hallman - Associate Director of the DOE Office of Science for Nuclear Physics:

The EIC will be a game-changing resource for the international nuclear physics community. *DOE looks forward to engaging with the international community and the international funding agencies about potential collaborations and contributions to the EIC effort, in nuclear, accelerator and computer science.*

Summary

- The EIC will be a discovery machine, providing answers to long-elusive mysteries of matter related to our understanding the origin of mass, structure, and binding of atomic nuclei that make up the entire visible universe
- EIC project is underway aiming to start physics in about a decade
- The EIC project will work closely with domestic and international partners to deliver the EIC construction project and then begin EIC operations
- **Collaboration in EIC design, construction and scientific exploration is welcome!**