Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

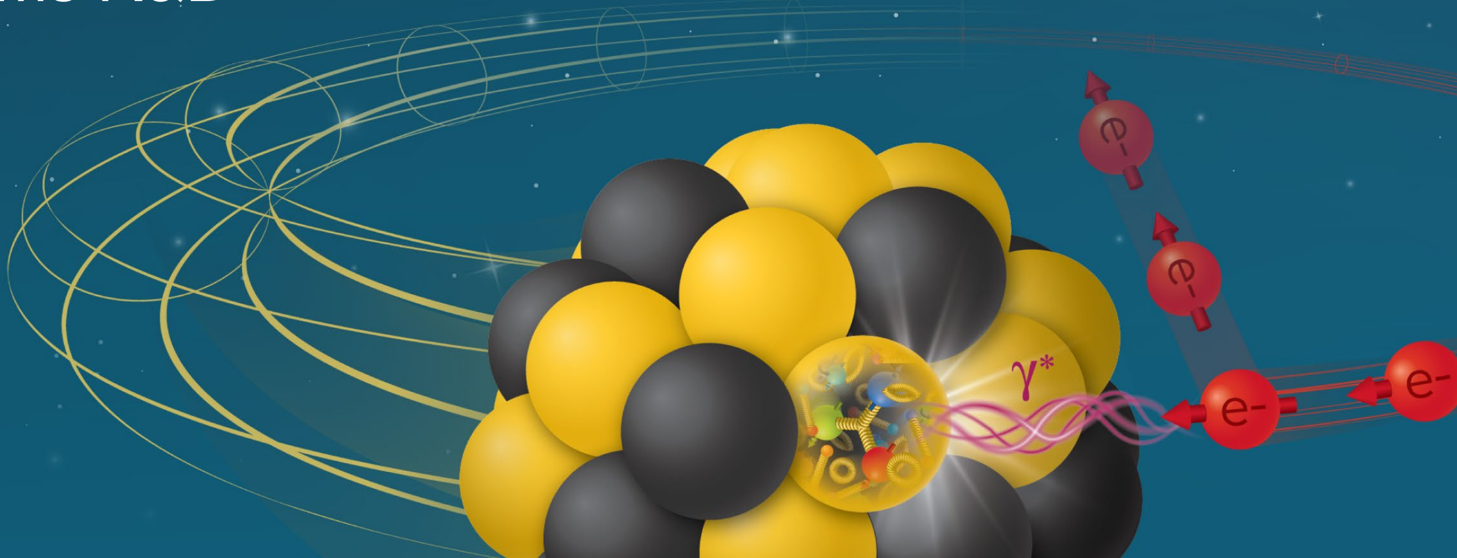
Report from the Accelerator Working Group

Qiong Wu

Manager, EIC Accelerator Systems R&D

July 24, 2024

Electron-Ion Collider

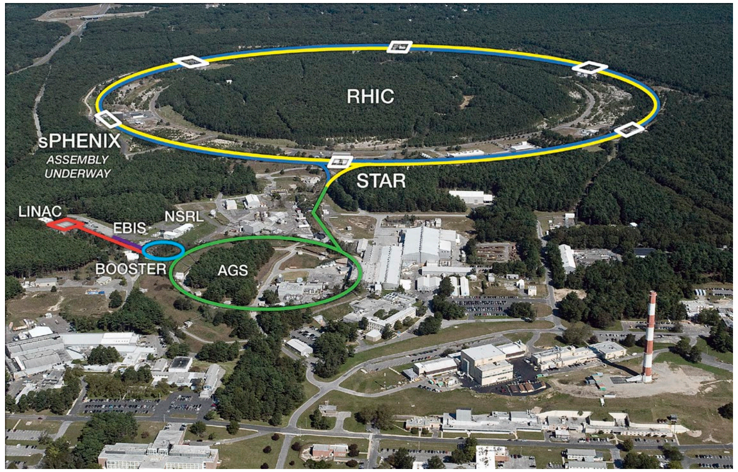


Outline

- Introduction
- Accelerator Technical Updates
- Accelerator Project Updates
- Summary

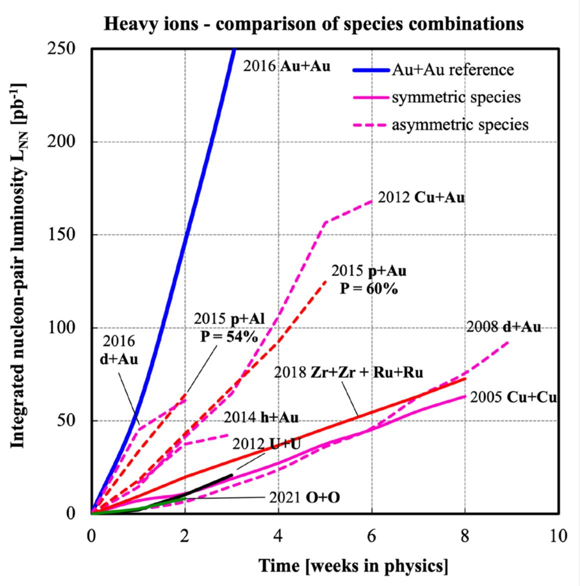
Introduction

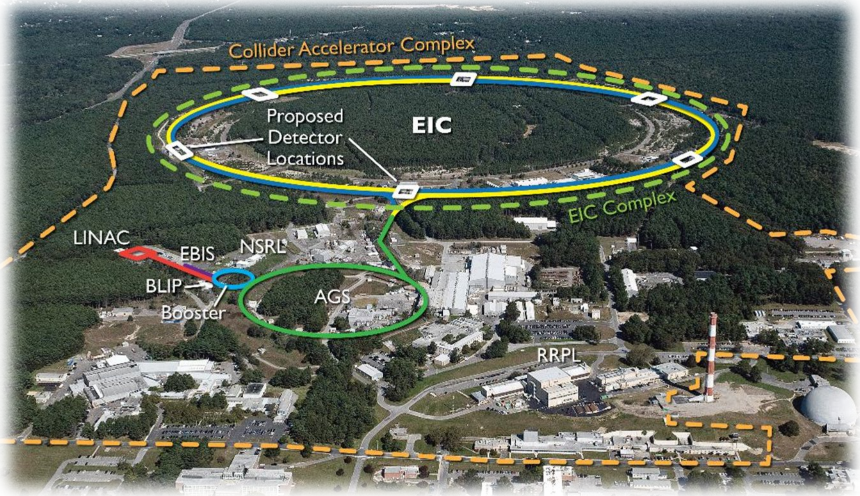
Starting Point



Relativistic Heavy Ion Collider (RHIC)

- is the first machine in the world capable of colliding heavy ions.
- primarily uses ions of gold but can operate and detect collision with a wide range of ion species from helium to uranium.
- is the world's only machine capable of colliding high-energy beams of polarized protons.





We are progressing towards constructing a groundbreaking machine for the international nuclear physics community: the Electron-Ion Collider (EIC)

The Electron Ion Collider Platform

Ultimate EIC Performance Parameters:

- High Luminosity: L= 10^{33} – 10^{34}cm-2sec-1, 10 – 100 fb-1/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: Ecm = 28 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Forward Acceptance and Good Background Conditions
- Possibility to Implement a Second Interaction Region (IR)

Accelerator Status in a glance:

✓ Polarized ion/proton source

✓ Ion injection and initial acceleration systems – Linac (200 MeV), Booster (1.5 GeV), AGS (25 GeV)

UPGRADE Hadron Storage Ring (40-275 GeV) – HSR

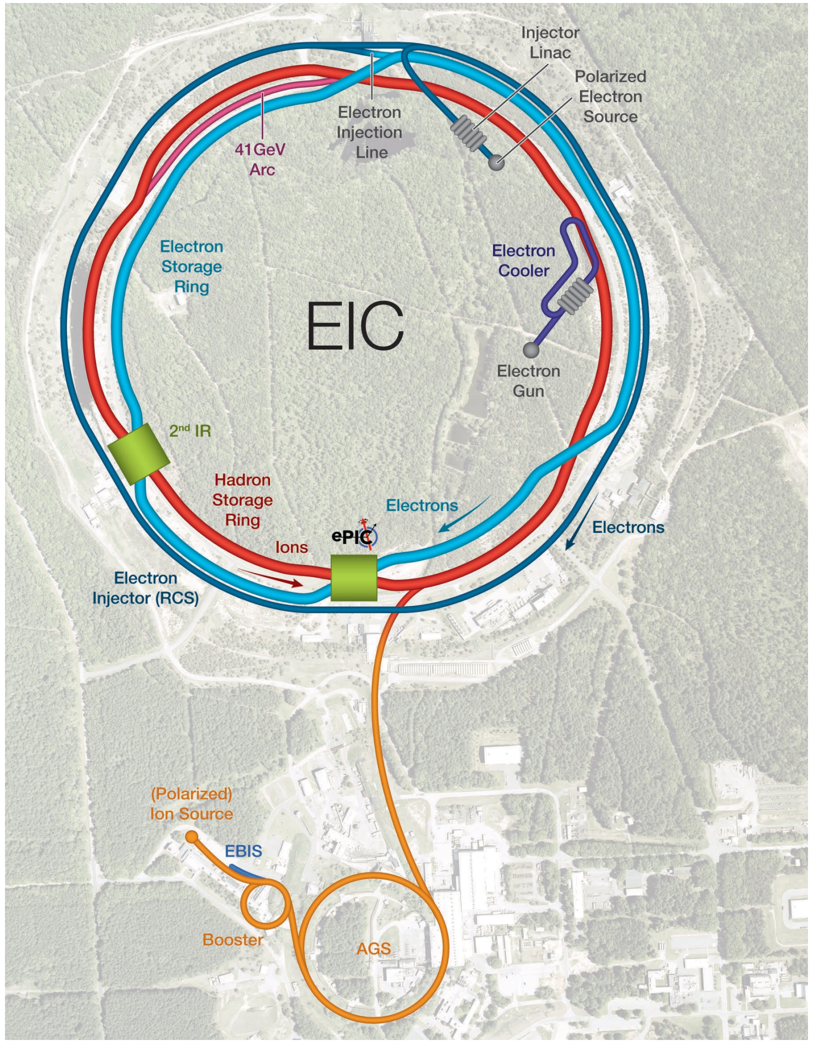
NEW Electron Pre-Injector (3 GeV) – EPI

NEW Electron Rapid Cycling Synchrotron (3 GeV – top energy) – RCS

NEW Electron Storage Ring (5 GeV – 18 GeV) – ESR

NEW High Luminosity Interaction Region(s) – IR

NEW Strong Hadron Cooler System – SHC



Project Planning Update

The focus of EIC project planning efforts is to **deliver the DOE approved mission need** based on a realistic assessment of **technical readiness, cost, schedule, and risk**. This continues to be the focus of the EIC project planning efforts.

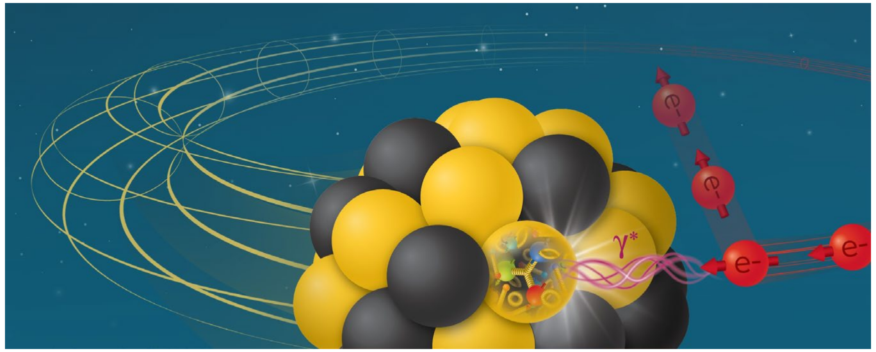
There are two primary project planning goals/constraints:

1. Annual EIC project funding requirements should not exceed $300M per year,
2. Total Project Cost less than $3B, and,
3. Deliver science within ten years after RHIC shuts down.

The **annual funding limitation** may require the **phased delivery of the accelerator**, which is more than 85% of the DOE funded project scope. It is possible to **start the science program in less than ten years with electron-ion collisions with the first phase of the accelerator**. The second and final phase of the project would complete the scope required to achieve the DOE approved mission need and the **two phases will overlap**.

A Project Strategy Workshop is planned for August 21, 2024, to discuss plans for early science and the completion of the full scope needed to satisfy the DOE approved mission need.

Path to Supporting Science Discoveries



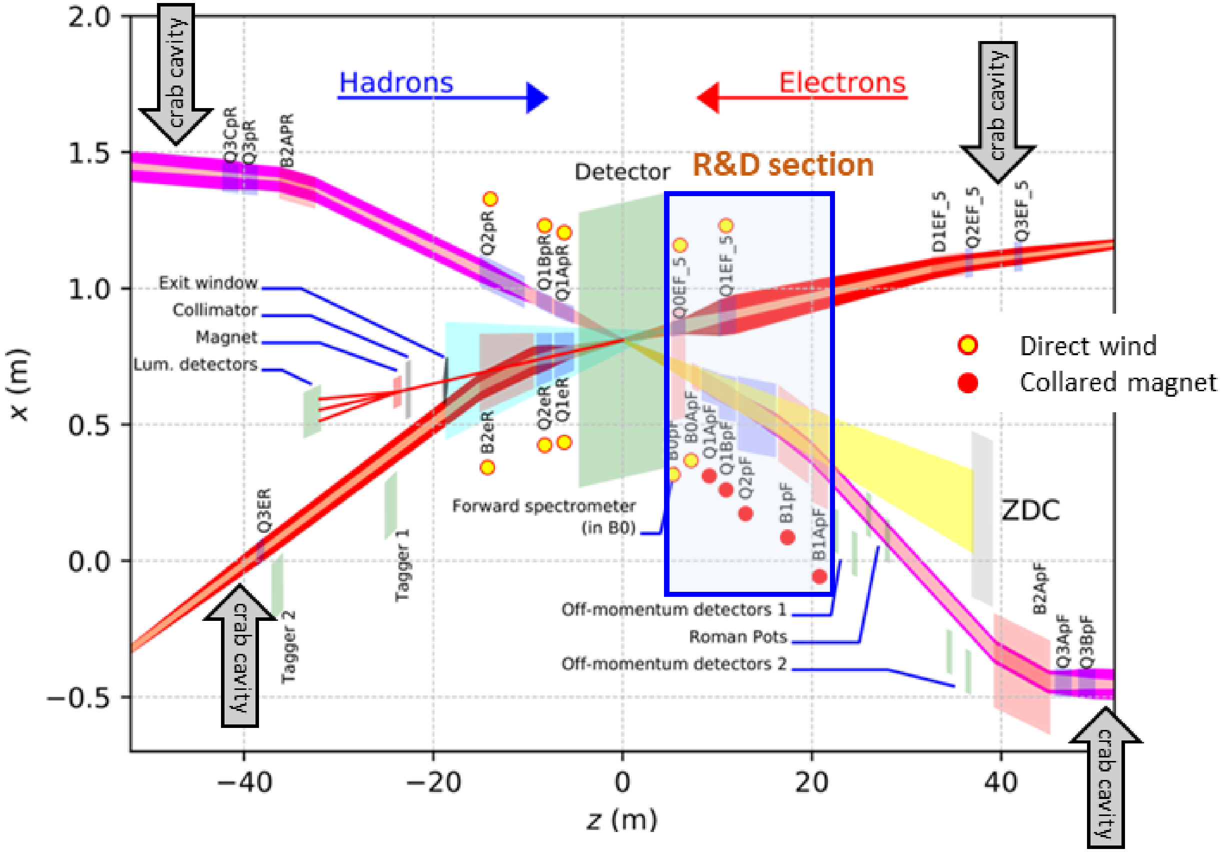
Final Performance Phase: Achieve parameters listed in the Conceptual Design Report

Early Science Phase:

- 5 GeV or 10 GeV polarized electron
- 7 nC per electron bunch
- 100 – 250 GeV polarized proton
- >100 GeV/u various ion
- No Strong Hadron Cooling at full energy
- Pre-Cooling at injection energy

Accelerator Technical Updates

The Interaction Region



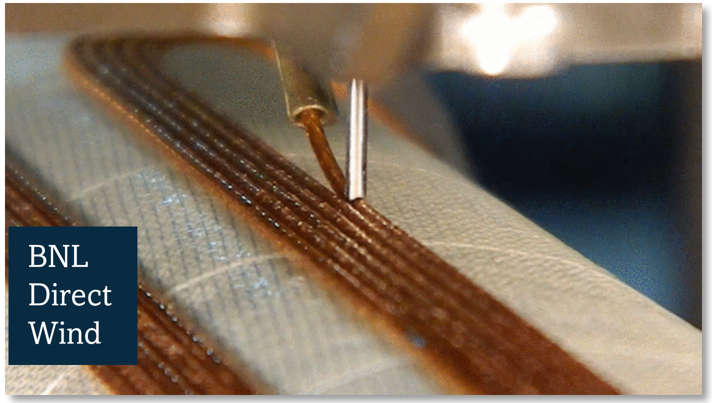
At the interaction point:

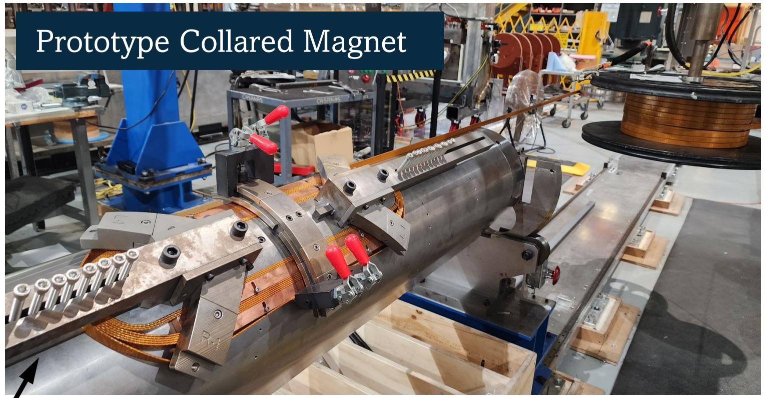
- Two colliding beams confront each other at 25 mrad crossing angle
- The bunched beams are tilted to fully regain the head-on collision
- The two species are manipulated to a perfect matching cross section to maintain stability after the collision
- Magnet aperture must accommodate particles with a transverse momentum of up to 1.3 GeV/c

Challenges in the Interaction Region

Superconducting Magnets

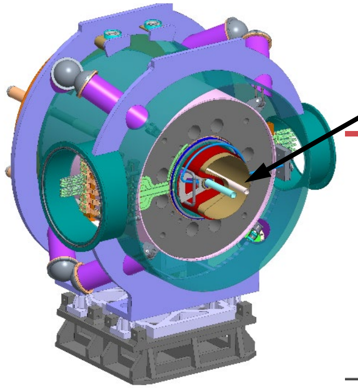
- 17 superconducting magnets with large apertures on the hadron forward side and high field/gradient requirements
- All hadron forward collared magnets are extremely challenging, due to the required aperture, field/gradient, and limited spacing – Prototype B1pF
- Some direct wind magnet designs are very challenging, due to the aperture and field requirements. Several employ a novel winding scheme (tapered CCT) – Prototype Q1ABpF


BNL Direct Wind

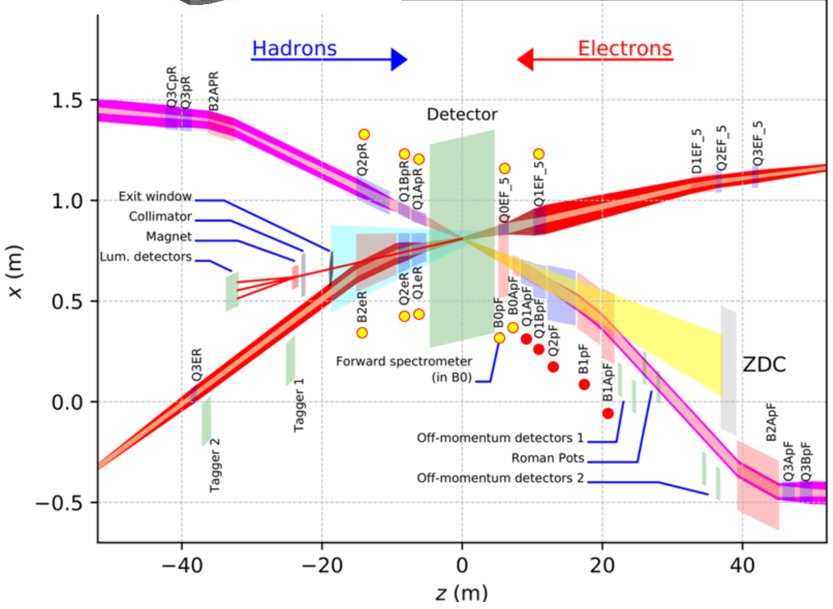

Prototype Collared Magnet


Prototype Direct Wind Magnet

Name	Inner Radius [m]	Length [m]	Mag Field [T]	Field Grad [T/m]
B1pF	0.135	3	-3.4	-72.6
Q1ApF	0.056	1.46	0	-72.6
Q1BpF	0.078	1.61	0	-66.2


Hadron beam pipe is inside the warm detector volume (IP end)

B0pF – Q0eF



- Prototyping two magnets with top challenge and finalizing all IR magnet physics designs
- Collaboration with FNAL (quench study + persistent current), LBNL (matching dipole + cable), CEA Saclay (under negotiation)

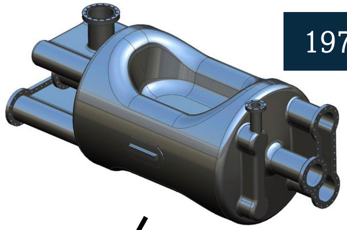
Challenges in the Interaction Region

Crab Cavity

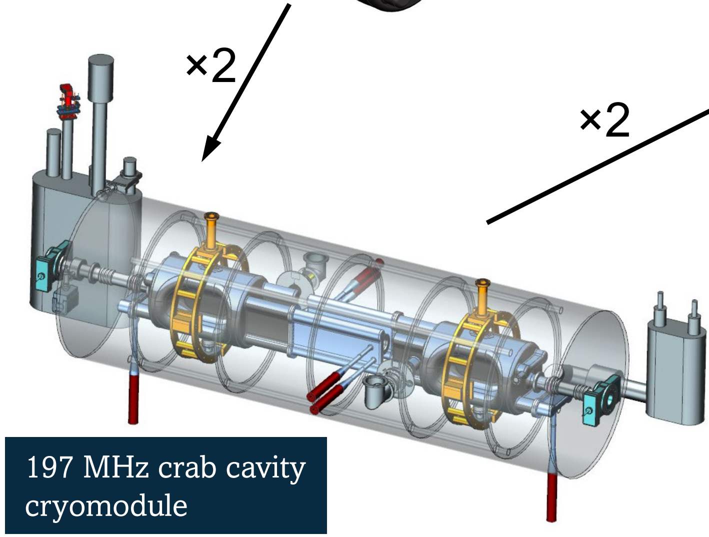
- Very rare type of cavity designed to apply a time dependent momentum kick to each bunch to compensate the geometric luminosity loss due to the crossing angle.
- Ideally, two sets of identical crabbing system installed symmetrically across the IP with 90 degrees phase advance, creating bunch tilting at IP with half of the crossing angle.
- The realistic challenges includes the sinusoidal nonlinear dependence, the non-ideal phase advances and phase/amplitude in RF control

- Full crab cavity system for hadron/proton:
  - 197 MHz crab cavity x4
  - 394 MHz crab cavity x2
- Full crab cavity system for electron:
  - 394 MHz crab cavity x1

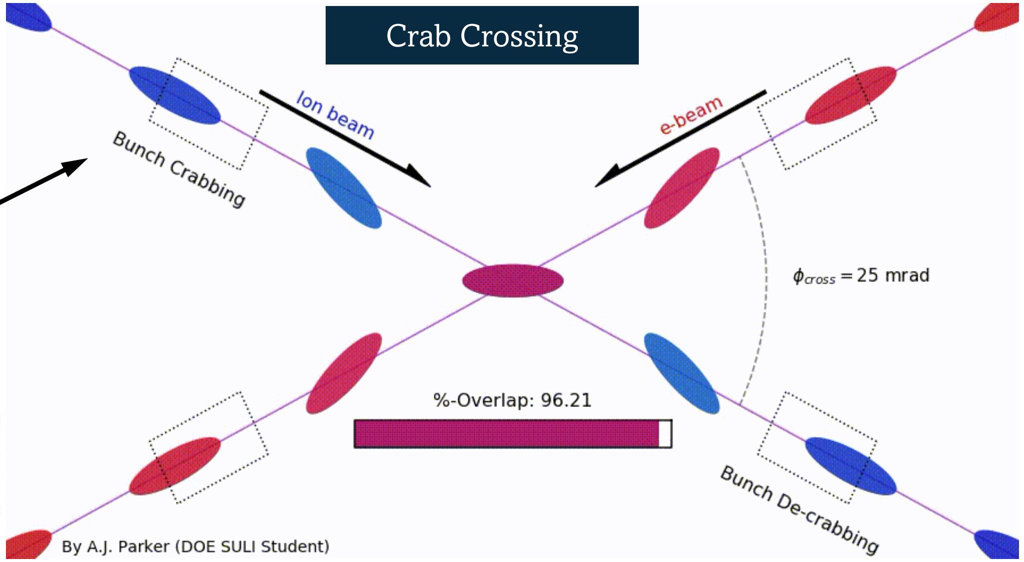
Property	Value
Operating frequency [MHz]	197
Cryomodule length [m]	5.8
Cryomodule profile radius [m]	1.89
Voltage per cavity [MV]	8.5/11



197 MHz crab cavity



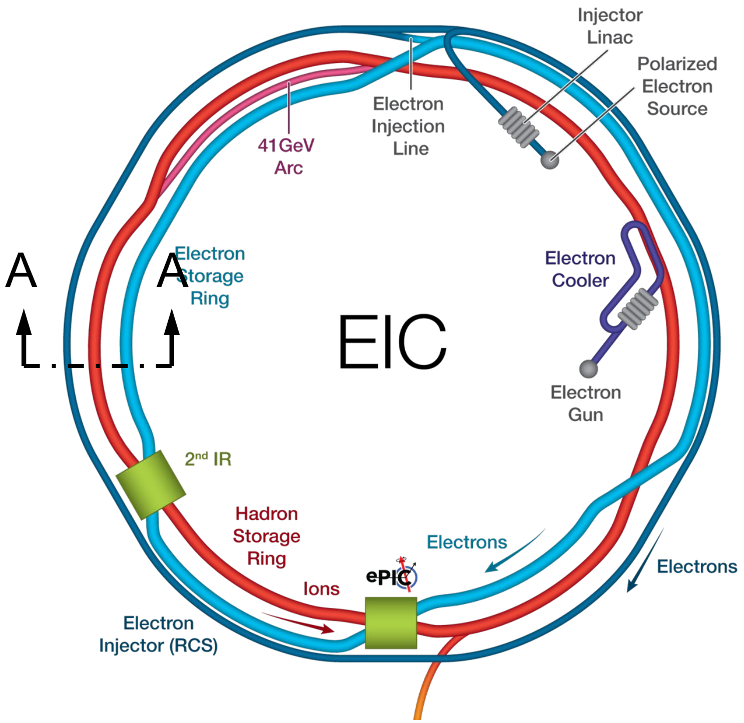
197 MHz crab cavity cryomodule



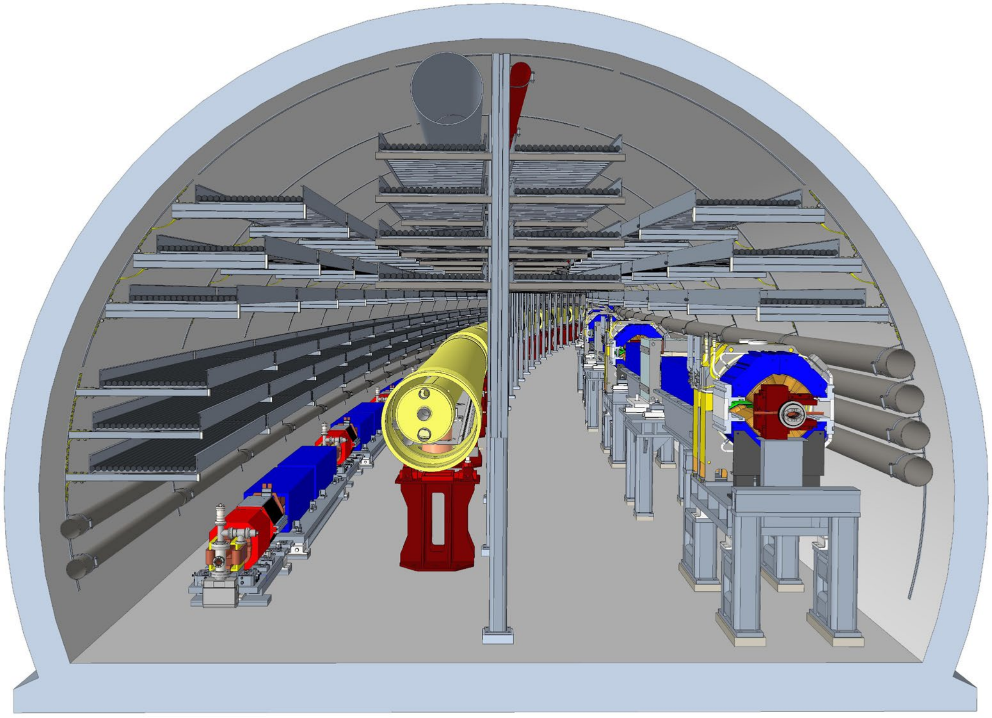
Crab Crossing

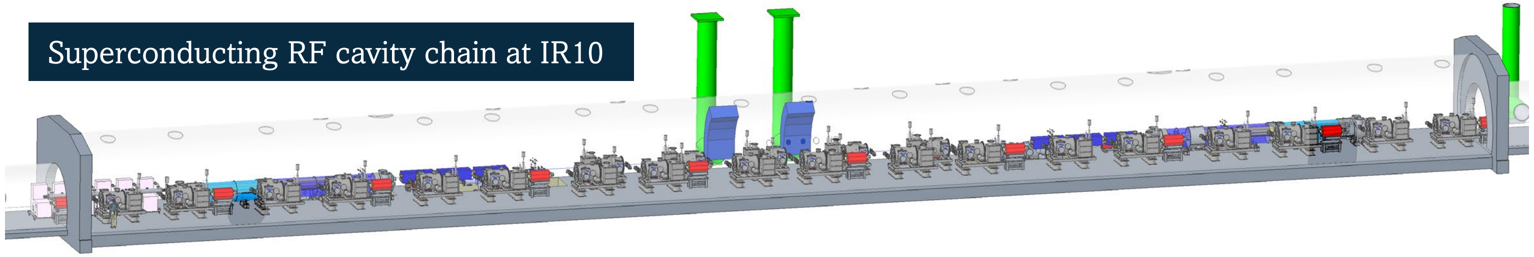
By A.J. Parker (DOE SULI Student)

Storage Rings

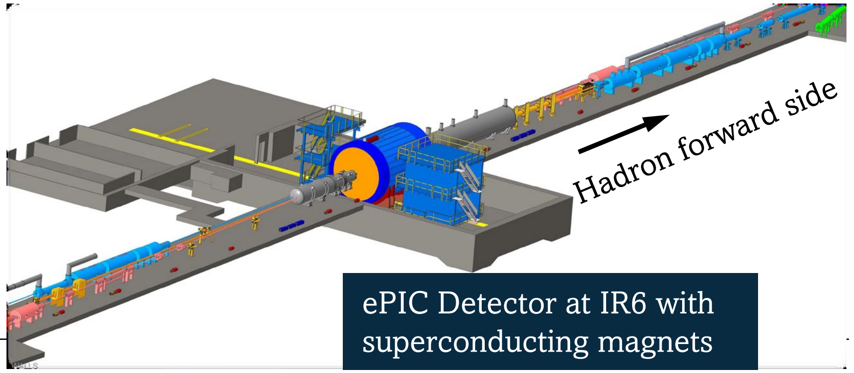


Section A – A





Superconducting RF cavity chain at IR10

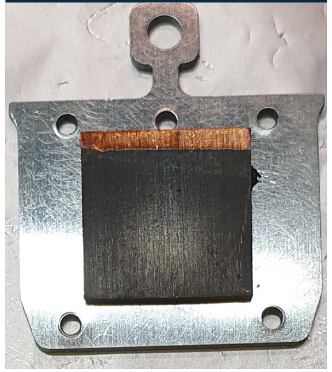


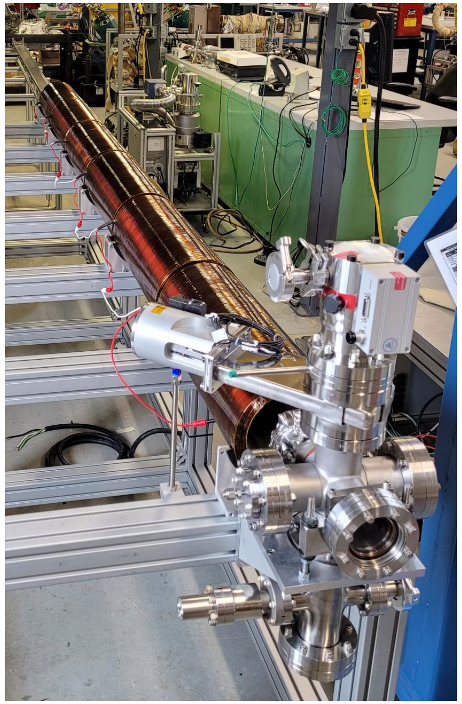
ePIC Detector at IR6 with superconducting magnets

Challenges in the Storage Rings

Beam Screen:
- Existing stainless steel beam pipe can not tolerate the increased the design current of EIC compared to RHIC due to resistive wall heating and electron cloud build-up
- Insert another layer of beam screen into all superconducting magnets
- Stainless-steel insertion tubes with an interior coating consisting of 75 μm of laminated copper and 150 nm of amorphous carbon

BNL amorphous carbon film sample





PoP horizontal coating system

HSR Bellows /BPM Module

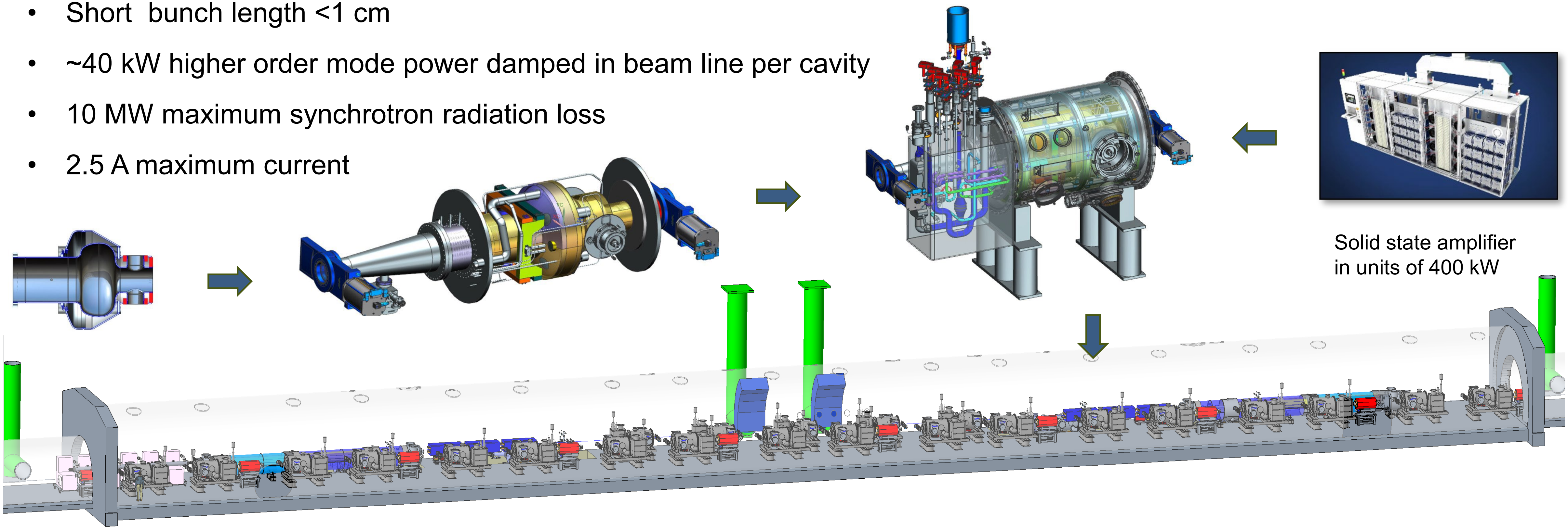
- There are a total of 469 magnets to insert the beam screens, which accumulate to nearly the entire HSR circumference.
- The beam screen is actively cooled
- Impedance and electron cloud are under evaluation
- Installation of the beam screen with precise alignment is required.
- Collaborations with multiple external institutes are actively ongoing, including Collider Accelerator Department and Center for Functional Nanomaterials at BNL, INFN-Frascati, and others like CERN are under discussion.

Challenges in the Storage Rings

Main cavity for the Electron Storage Ring:
- Superconducting cavity operating with extremely high power and heavy absorption of unwanted higher order modes
- Compensating for synchrotron radiation loss and extracted higher order mode RF power

Providing 68 MV using 17 single cell elliptical SRF cavities @ 591 MHz

- Short bunch length <1 cm
- ~40 kW higher order mode power damped in beam line per cavity
- 10 MW maximum synchrotron radiation loss
- 2.5 A maximum current



Solid state amplifier
in units of 400 kW

Challenges in the Storage Rings

Strong Hadron Cooling:

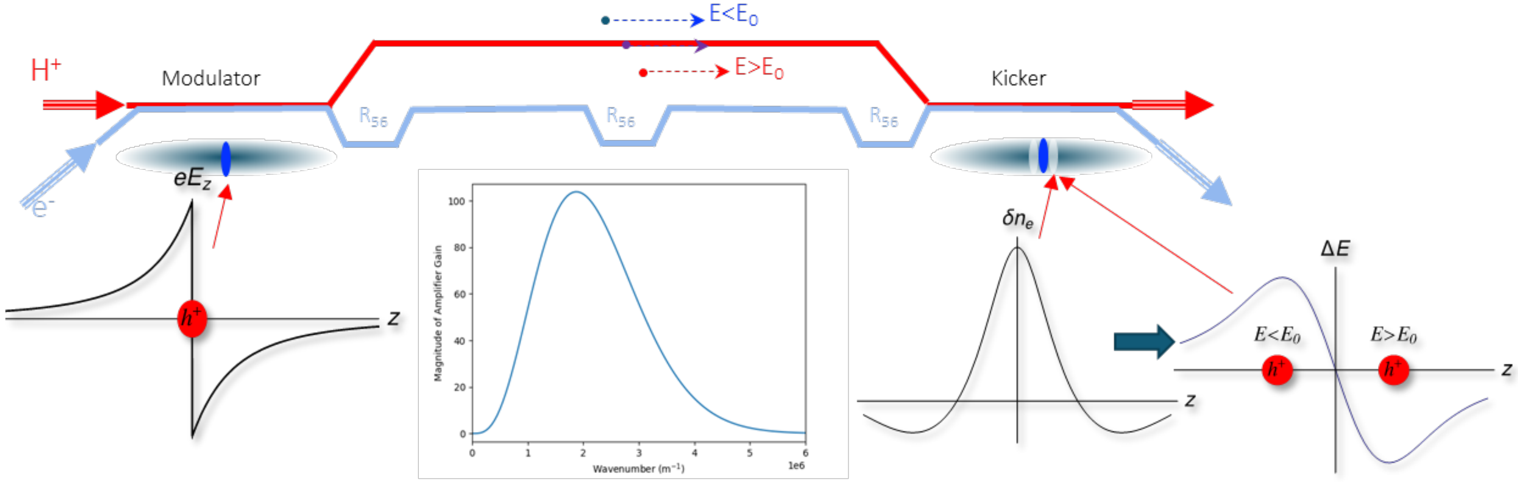
- The luminosity of EIC benefits strongly from cooling the hadron’s transverse and longitudinal beam emittance
- Intra-Beam Scattering longitudinal and transverse (horizontal) growth time is 2-3 hours. Beam-beam growth time (vertical) is > 5 hours. The cooling time shall be equal to or less than the diffusion growth time from all sources.

Required strong hadron cooling for EIC at top hadron energies for high intensity hadron beam

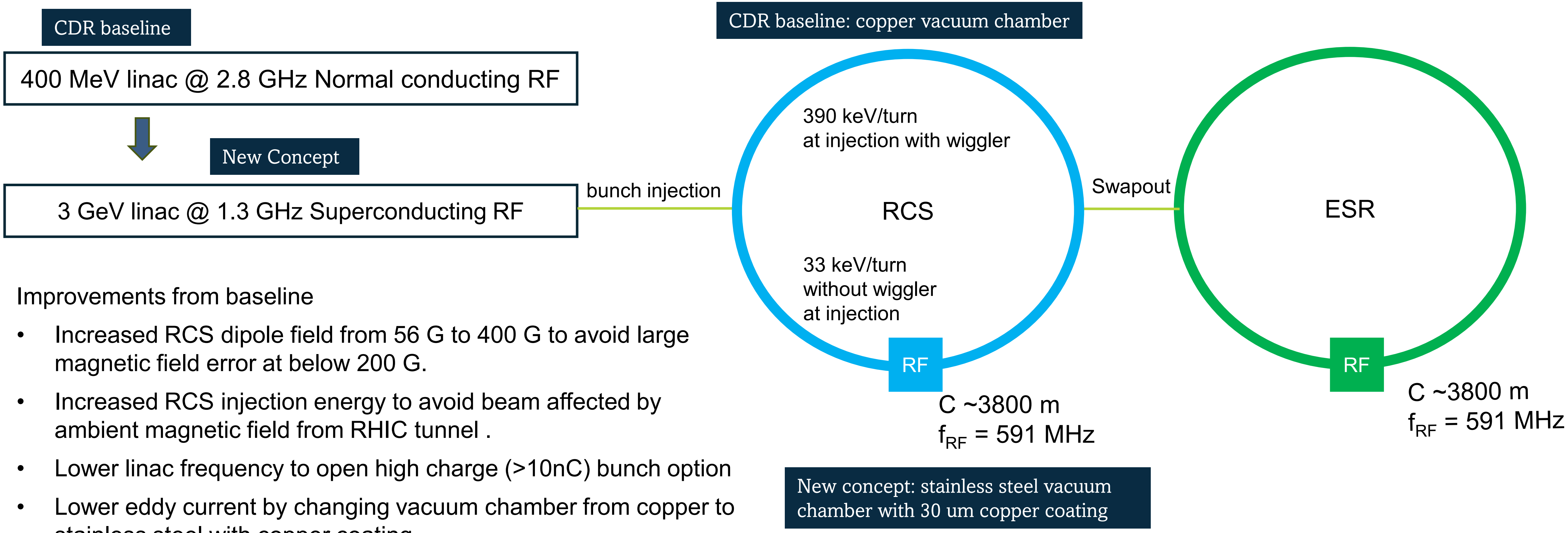
- High current (100 mA)
- Precise alignment between the hadron beam and the cooling electron beam
- Precise control of the electron profile
- Low time dependent fluctuation electron bunches
- Distribute longitudinal cooling to transverse direction

CDR baseline: Micro-Bunched Electron Cooling

- Current approaches were reviewed, no show-stoppers found
- Pre-cooling at injection energy needed, so Strong Hadron Cooling only required to maintain emittances
- Incorporated pre-cooler into IR2 cooler design



Electron injection



CDR baseline

400 MeV linac @ 2.8 GHz Normal conducting RF

New Concept

3 GeV linac @ 1.3 GHz Superconducting RF

C ~3800 m
f_{RF} = 591 MHz

C ~3800 m
f_{RF} = 591 MHz

New concept: stainless steel vacuum chamber with 30 um copper coating

Improvements from baseline

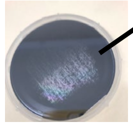
- Increased RCS dipole field from 56 G to 400 G to avoid large magnetic field error at below 200 G.
- Increased RCS injection energy to avoid beam affected by ambient magnetic field from RHIC tunnel .
- Lower linac frequency to open high charge (>10nC) bunch option
- Lower eddy current by changing vacuum chamber from copper to stainless steel with copper coating
- Change accumulation scheme to avoid large bunch charge single bunch injection
- Add spin rotation option at low energy

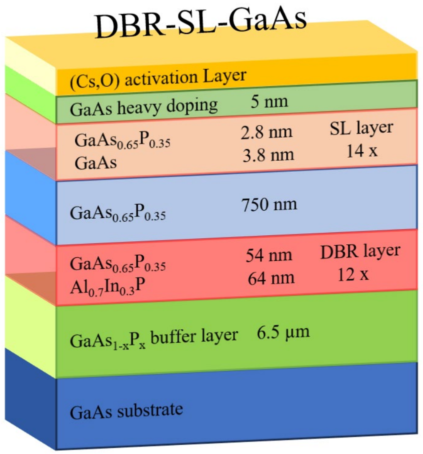
Challenges in the Electron Injection

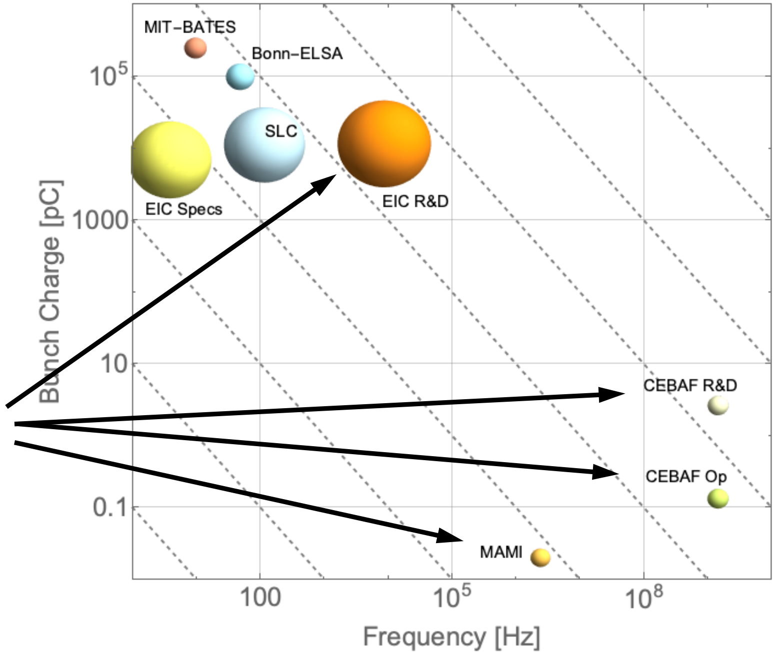
Polarized electron source

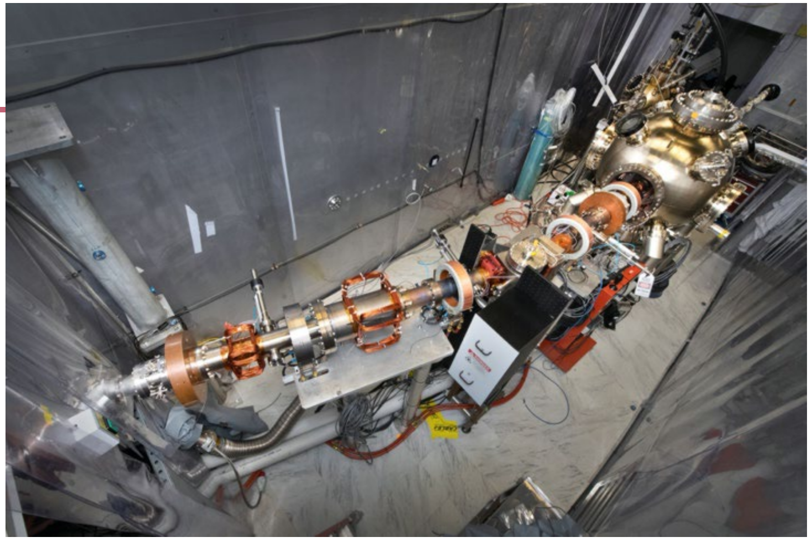
- High charge polarized electron bunch
- Stable operation continuously for more than one week

distributed Bragg reflector (DBR) super lattice (SL) GaAs photocathode

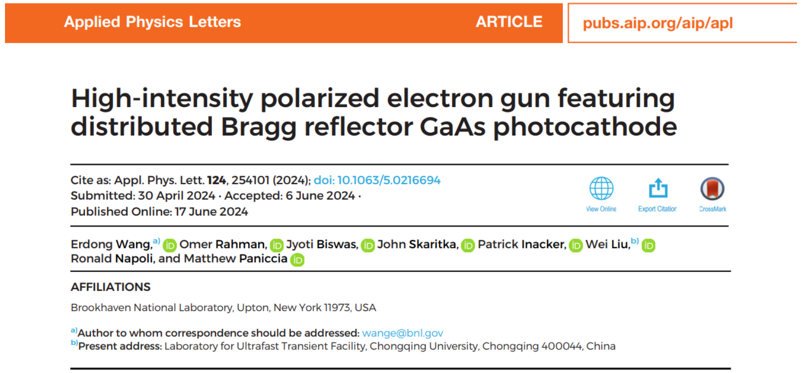








	EIC	R&D achieve in stable operation
Bunch charge [nC]	7	7.5 (max 11.6)
Peak current [A]	3.8	4.8 (No SCL)
Average Current	56 nA	76 uA
Polarization [%]	> 85%	86%



Applied Physics Letters ARTICLE pubs.aip.org/aip/apl

High-intensity polarized electron gun featuring distributed Bragg reflector GaAs photocathode

Cite as: Appl. Phys. Lett. **124**, 254101 (2024); doi: 10.1063/5.0216694
Submitted: 30 April 2024 · Accepted: 6 June 2024 ·
Published Online: 17 June 2024

Erdong Wang,[a] Omer Rahman, Jyoti Biswas, John Skaritka, Patrick Inacker, Wei Liu,[b] Ronald Napoli, and Matthew Paniccia

AFFILIATIONS

Brookhaven National Laboratory, Upton, New York 11973, USA

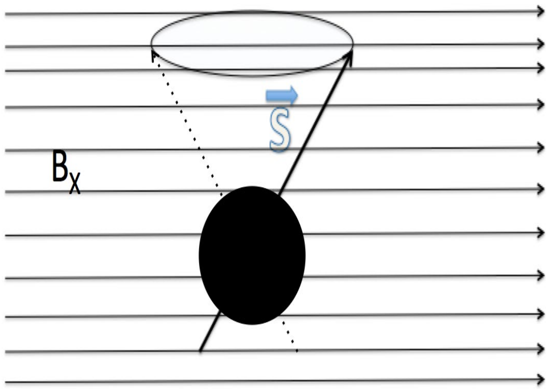
[a] **Author to whom correspondence should be addressed:** wange@bnl.gov
[b] **Present address:** Laboratory for Ultrafast Transient Facility, Chongqing University, Chongqing 400044, China

- Long term stable operation @ 5000 bunches/s with **7.5 nC per bunch.**
- More than **1e9 bunches continuously** generated from a single cathode. **No decay** observed after apply 3kV bias voltage on the anode.
- Maximum operation reached 11.6 nC per bunch.
- Lifetime determined by the outgassing from Faraday Cup.

Challenge in the Electron Injection

Spin resonance free lattice

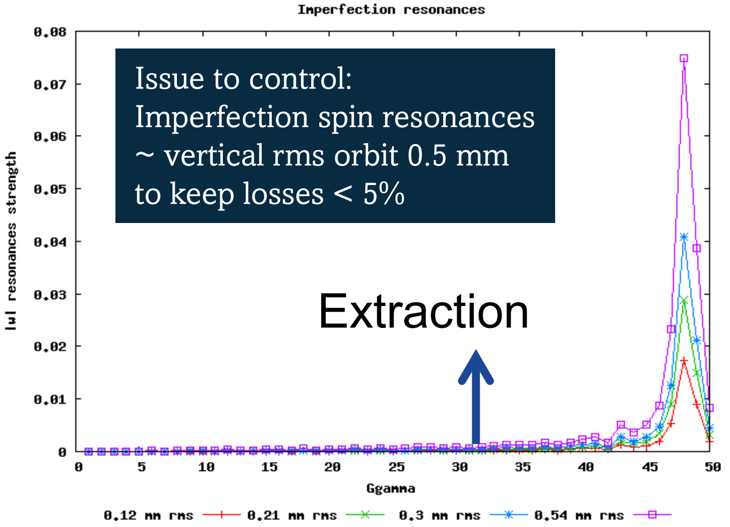
- Transfer polarized electrons from the cathode to top energy without significant polarization loss by avoiding spin resonance conditions.
- Optimize lattice to relax the requirement on magnets and power supplies



- Spin precesses at a rate of Gγ in a planar dipole - dominated ring, where G is the anomalous g-factor.
- Electron circulating in a horizontal plane with dipole fields in the vertical direction, there will be horizontal fields from imperfections and from focusing in the quadrupoles. If these horizontal fields occur with a frequency that matches the spin precessing frequency, they can cause the direction of the spin to change – **Spin Resonance**
- Strong intrinsic and imperfection Spin resonances occur at:
  - $K = nP +/- Q_y$
  - $K = nP +/- [Q_y]$ (integer part of tune)

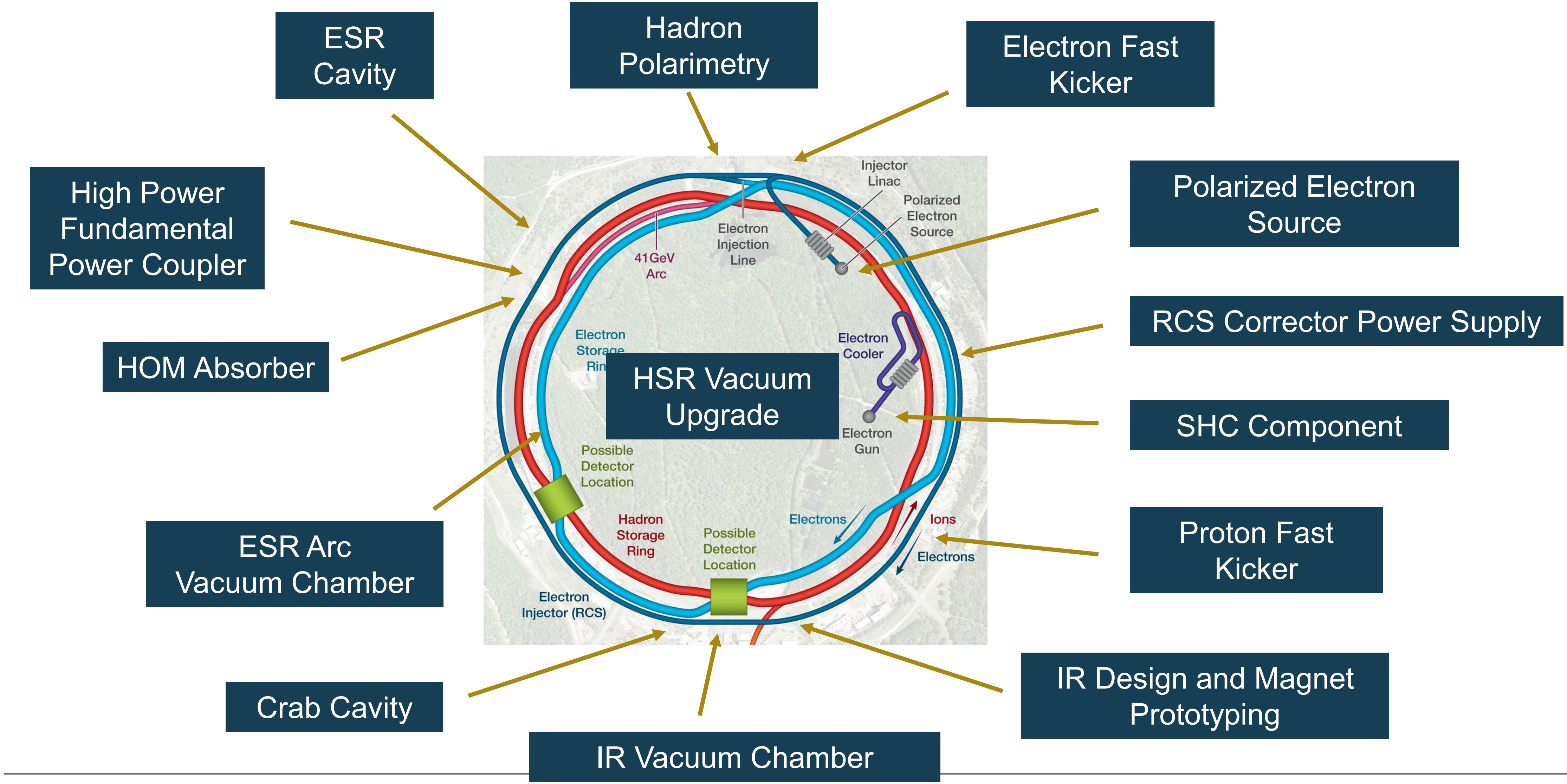
Here **P** is the lattice Periodicity and **n** any integer and **Q_y** the vertical betatron frequency.

If we pick **P** and **Q_y** correctly we can avoid all strong spin resonances in a given energy range



Issue to control:
Imperfection spin resonances
~ vertical rms orbit 0.5 mm
to keep losses < 5%

Other Challenges and World Leading Developments



ESR Cavity

Hadron Polarimetry

Electron Fast Kicker

High Power Fundamental Power Coupler

Polarized Electron Source

RCS Corrector Power Supply

HOM Absorber

HSR Vacuum Upgrade

SHC Component

ESR Arc Vacuum Chamber

Proton Fast Kicker

Crab Cavity

IR Design and Magnet Prototyping

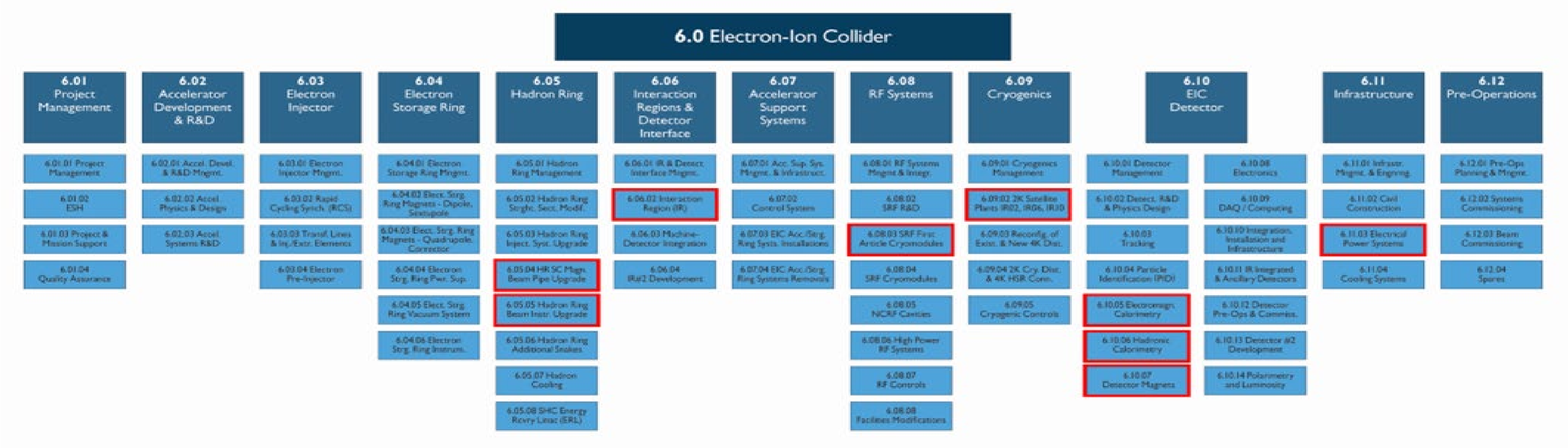
IR Vacuum Chamber

Accelerator Project Updates

CD-3A Long Lead Procurements (LLPs)

Control Account	CAM Authority	CAM
6.05.04 HR SC Magnet Beam Pipe Upgrade	$921,716	Hetzel, C.
6.05.05 Hadron Ring Beam Instrumentation Upgrade	$2,810,585	Gassner, D.
6.06.02.07 Cables	$4,133,118	Witte, H.
6.08.03.02 591 MHz 1-Cell Cryomodule First Article	$3,658,827	Matalevich, J.
6.09.02 2K Satellite Plants IR02, IR06, IR10	$13,872,734	Yang, S.
6.10.05 Electromagnetic Calorimetry	$4,886,870	Bazilevsky, A.
6.10.06 Hadronic Calorimetry	$5,454,560	Kiselev, A.
6.10.07 Detector Magnets	$13,971,290	Rajput-Ghoshal, R.
6.11.03 Electrical Power Systems	$16,948,209	Nehring, T.
Grand Total	**$66,657,910**	

- CD-3A LLPs Approved by ESAAB March 2024 totaling $66.7M with Contingency TPC $90M.
- Cost Contingency for LLPs at 35%
- LLP Scope Baselined as of May 2024.
- LLP list is based on:
  - Design Maturity (FDR/spec dates)
  - Lead time to delivery
  - Reducing Risk



LLP items allocated across project: Accelerator, Detector, Infrastructure

In-Kind Contributions

- The In-kind contribution (IKC) target for the EIC accelerator is about 5% of the total scope approx. 50M$.
- Advanced stage IKCs are now mostly for SRF scope: 394 MHz Crab cavities and accelerating cavities.
- Potential IKCs include magnets, beam screens and beam pipes.
- More Countries may participate in EIC accelerator IKCs in the future.

Advanced Stage Accelerator IKCs

394 MHz Crab Cryomodules	UK + Canada
591 MHz 5-Cell Cryomodules	France
Vacuum SEY measurements	Italy INFN

Accelerator IKCs under discussion

IR Spin Rotator Magnets	Spain
IR region Magnets	Spain
1773 MHz 5-Cell Cavity CM	UK
RF amplifiers	Spain
1.3 GHz electron injector LINAC	France CEA
LLRF	Czech Republic
Beam screen and beam pipes	CERN

Summary

- The EIC accelerator design and fabrication is making steady progress.
- Successful prototypes and ongoing design adjustments have consistently enhanced maturity and reduced risk levels.
- CD3-A long lead procurements scope baselined as of May 2024.
- The path forward for deliver a world leading polarized nuclear physics experimental platform is clear with cost and schedule set at high priorities.
- In-Kind contributions and collaborations are under active discussion.

Acknowledge

- Thank you to all whose collective contributions were represented here.
- Special thanks to Bijan Bhandari, George Dacos, and Karim Hamdi for providing the 3D layouts of various locations within the EIC accelerator
- I would also like to thank Vahid Ranjbar, Erdong Wang, Paolo Berrutti, and Cathleen Lavelle for their contributions to preparing this presentation.
- Am thankful for continuous and extended communications with Sergei Nagaitsev, Elke Aschenauer, and James Yeck.

Thank You