The Electron-Ion Collider – Accelerator Design Overview

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Electron-Ion Collider

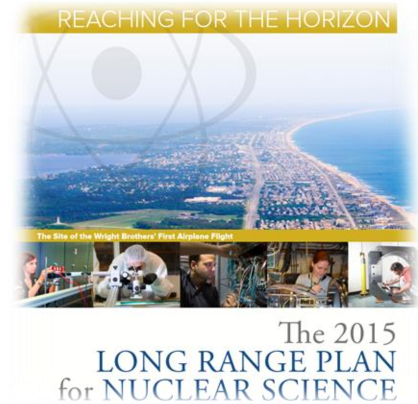
BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

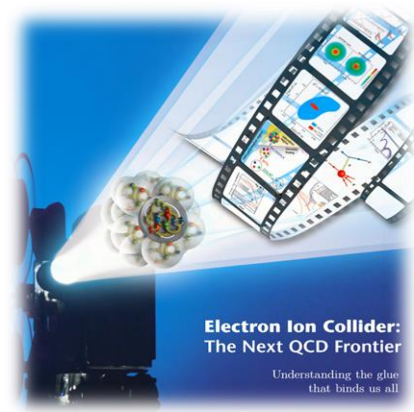
Project Requirements

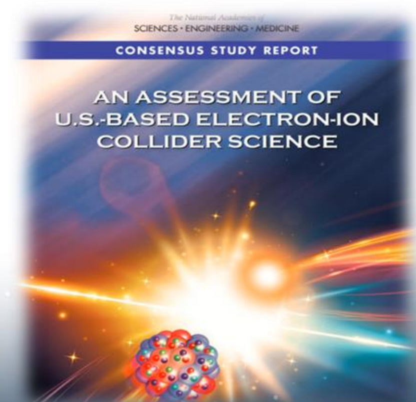
Project Design Goals

- 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)

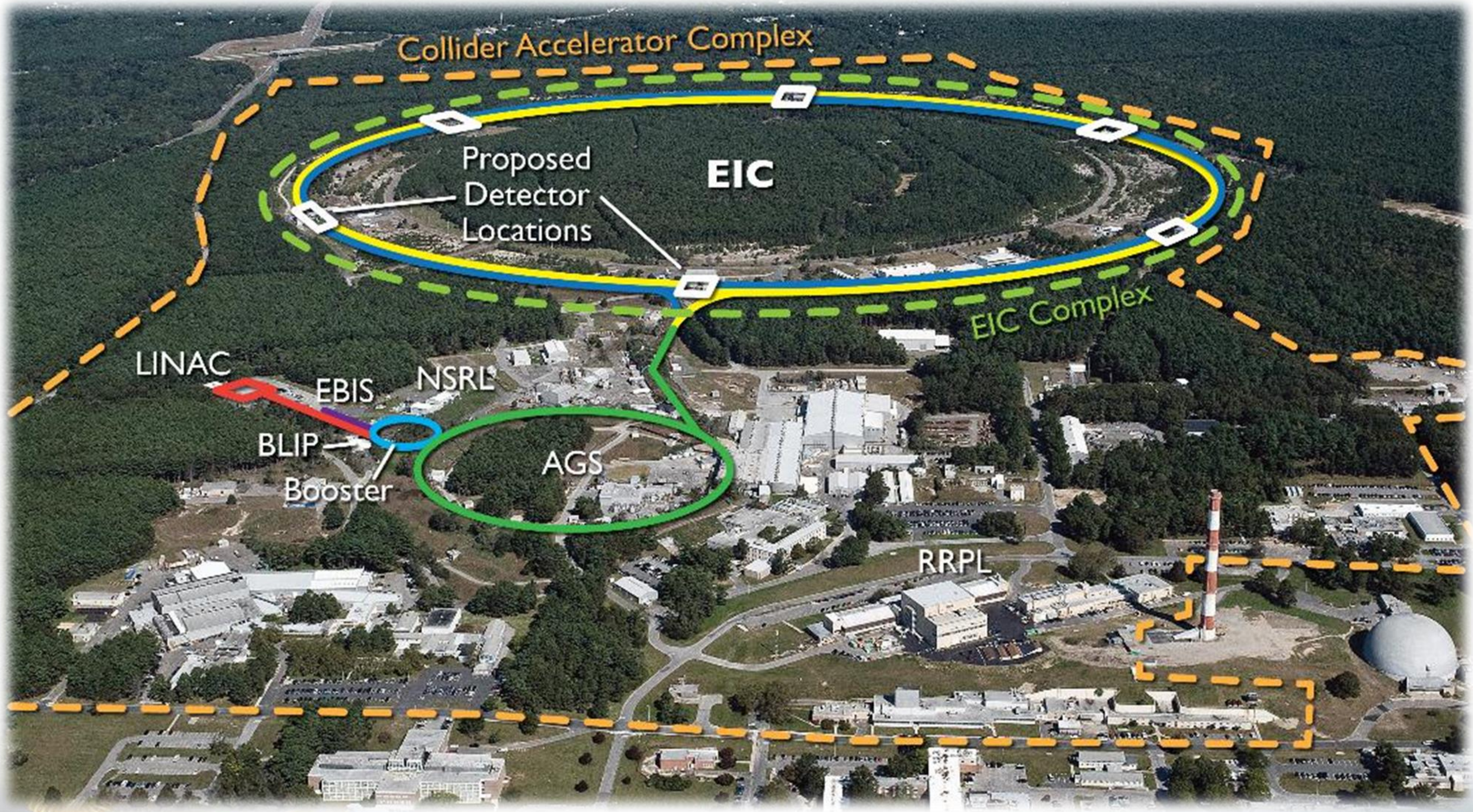
Conceptual design scope and expected performance meets or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)







EIC Design Overview



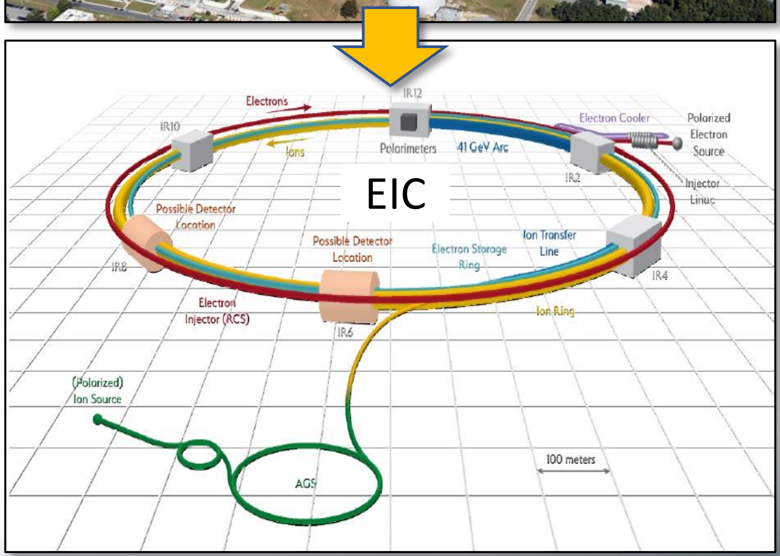
EIC benefits from $B class investments at BNL and the highly successful RHIC program.

EIC CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

EIC Design Concept

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

- **Hadron storage ring 40-275 GeV** (existing)
  - Many bunches (max 1160)
  - Bright beam emittances (for hadrons)
  - Need **strong cooling**
- **Electron storage ring 2.5–18 GeV** (new)
  - Many bunches (max 1160)
  - Large beam current (2.5 A) ➔10 MW SR power
- **Electron rapid cycling synchrotron** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
  - Luminosities up to $10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
  - Superconducting magnets
  - 25 mrad crossing angle with crab cavities
  - Spin rotators (longitudinal spin)
  - Forward hadron instrumentation

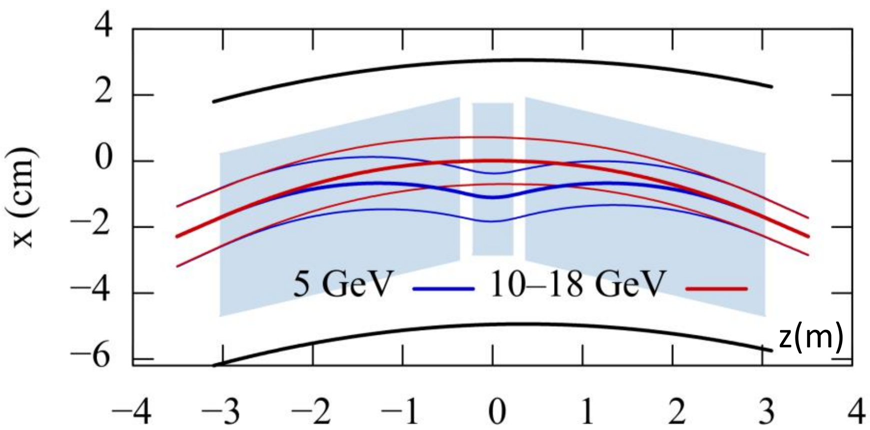


EIC Design Parameters

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

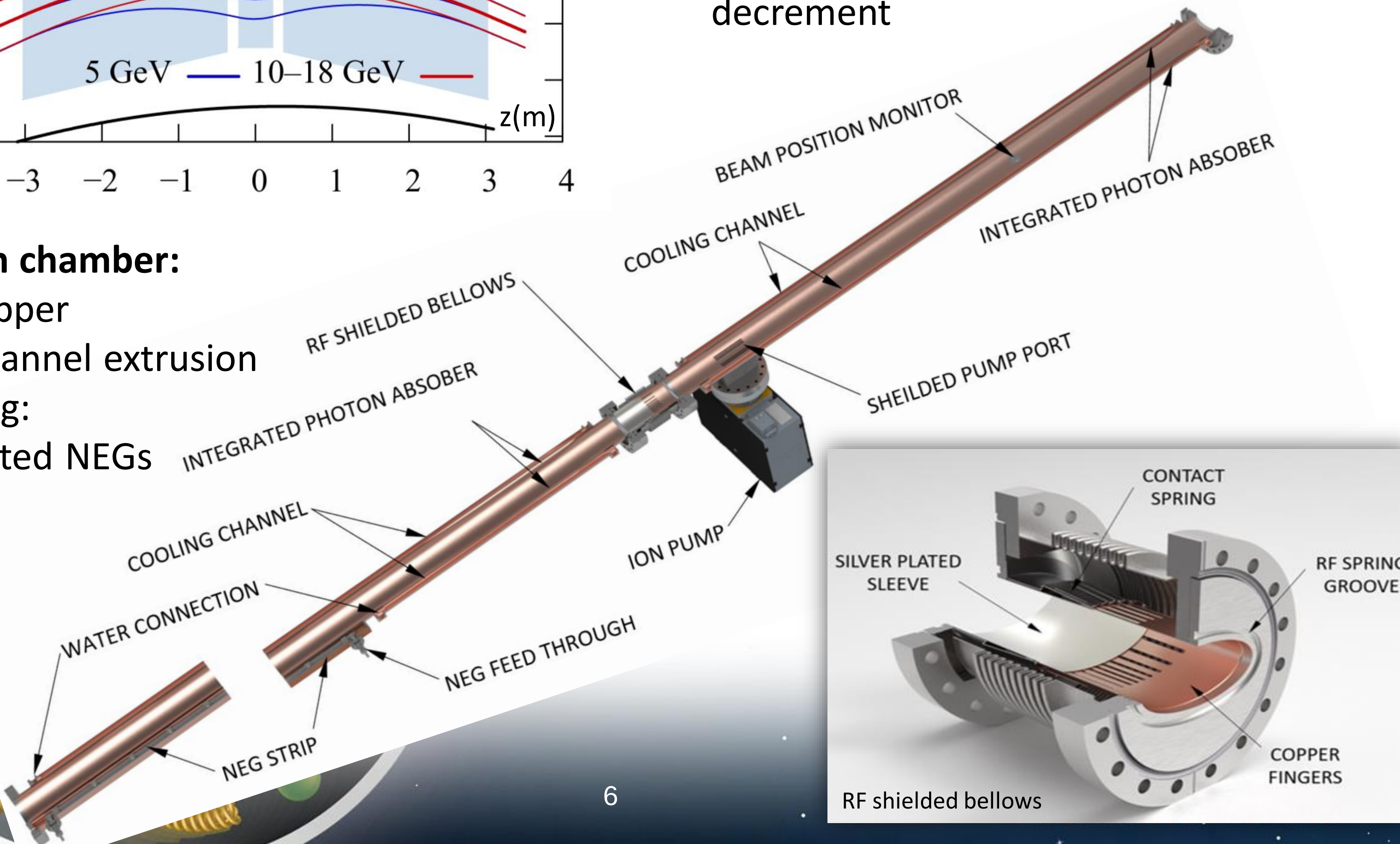
Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1.54		10.00		4.48		3.68		0.44	

Electron Storage Ring



Above 10 GeV, all segments powered uniformly to reduce SR power
At 5 GeV, short center dipole provides a reverse bend to increase damping decrement

Vacuum chamber:
OFE Copper
Multichannel extrusion
Pumping:
distributed NEGs



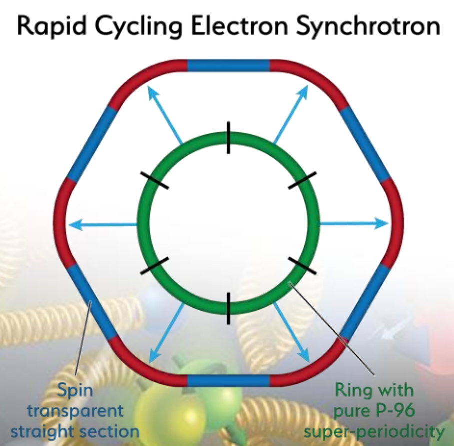
RF shielded bellows

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

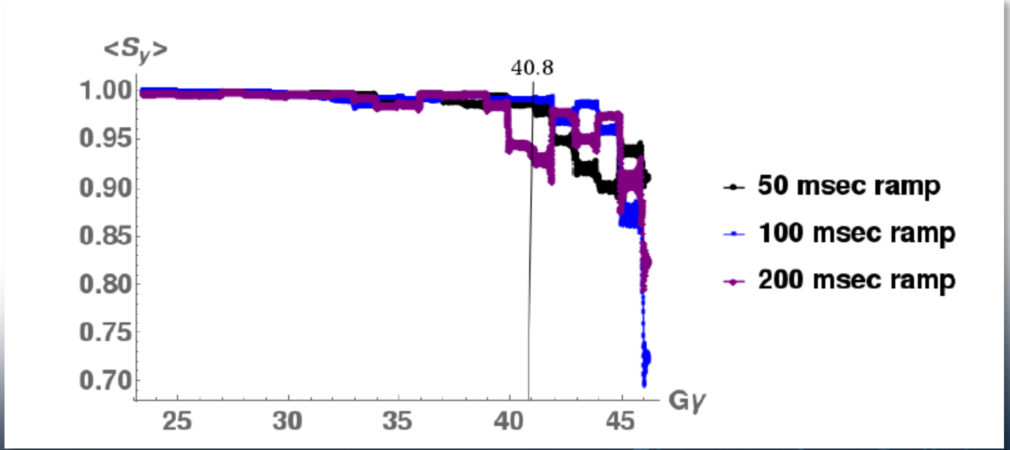
- 85% polarized electrons from a polarized source and a 400 MeV s-band linac get injected into the fast cycling synchrotron in the RHIC tunnel
- AGS experience confirms depolarization suppressed by lattice periodicity
- RCS with high (P=96) quasi-periodicity arcs and unity transformations in the straights 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

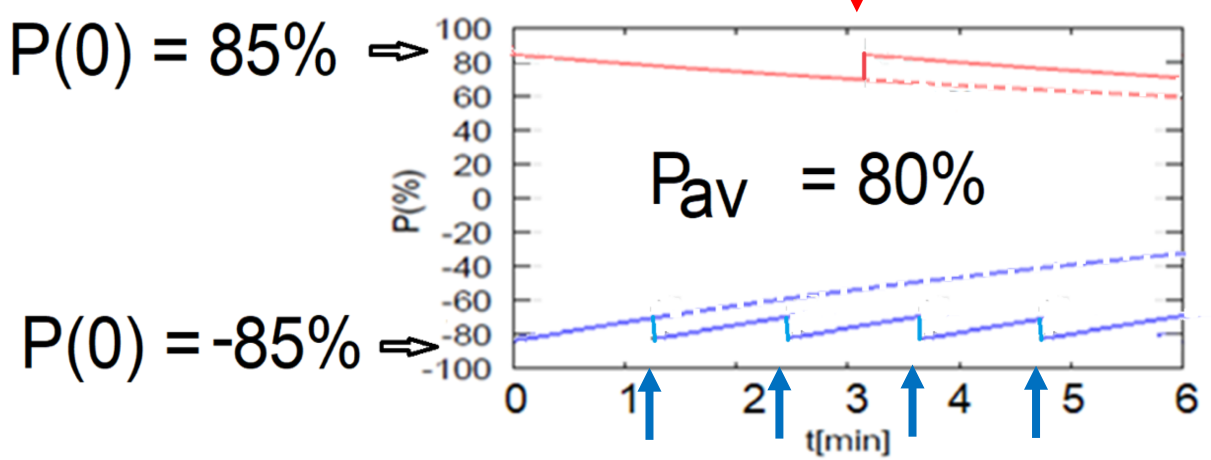
B P

Refilled every
1.2 minutes

B P

Refilled every
3.2 minutes

Re-injection

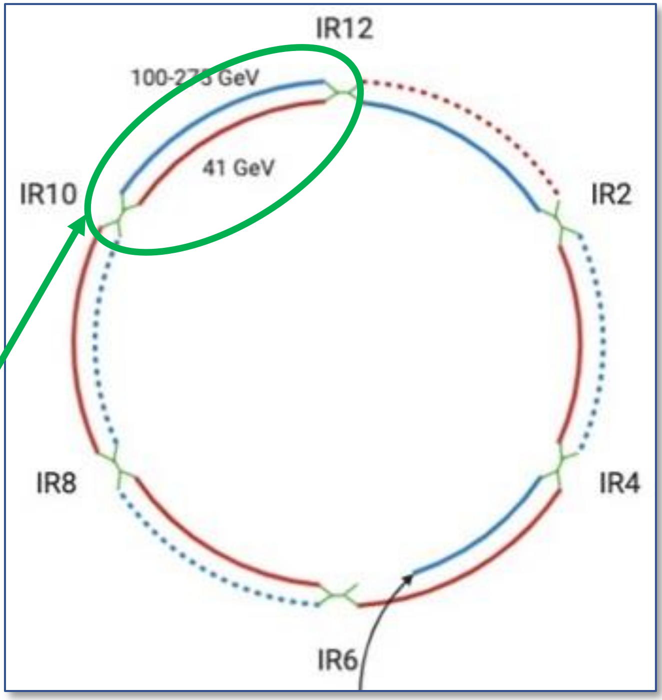


P_∞= 30%
(conservative)

Re-injections

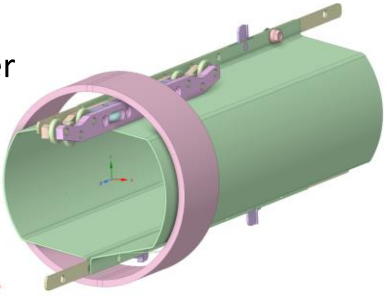
Hadron Storage Ring

- Existing RHIC with superconducting magnets allow up to E_p = 275 GeV and down to E_p = 41 GeV
- HSR pathlength must be reduced for 41 GeV ops to maintain f_{rev} and collisions
  - Accomplished by using one RHIC blue ring arc as a pathlength adjustment bypass
  - Requires reversing one arc of quench protection diodes
  - Other hadron pathlength adjustments feasible with arc radial shifts

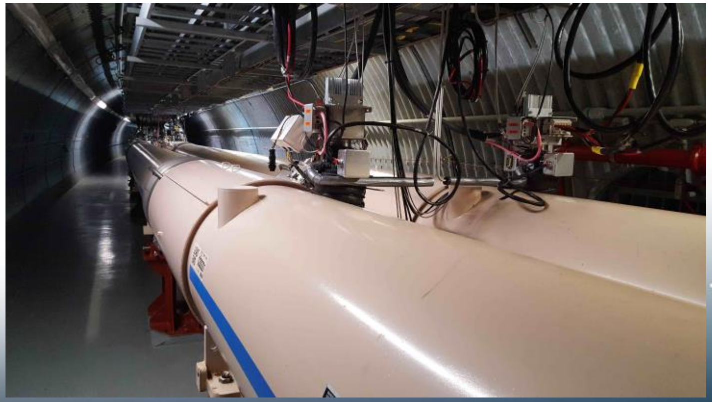


Hadron Ring Vacuum chamber upgrade:

- Two main concerns towards existing RHIC vacuum pipes during EIC operation with higher current and shorter bunch length:
  - Resistive-wall impedance
  - e-cloud buildup
- Solution: **copper-clad stainless-steel screen + a-C thin film**
  - *Cu significantly reduces surface resistivity, esp. at cryo*
  - *a-C reduces secondary electron emission*



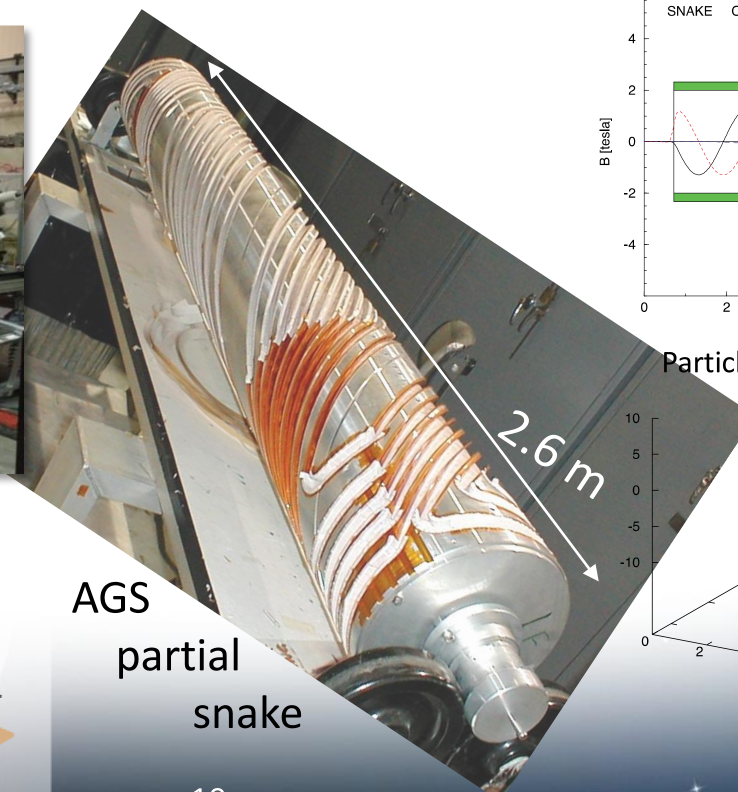
conceptual design



EIC Hadron Polarization

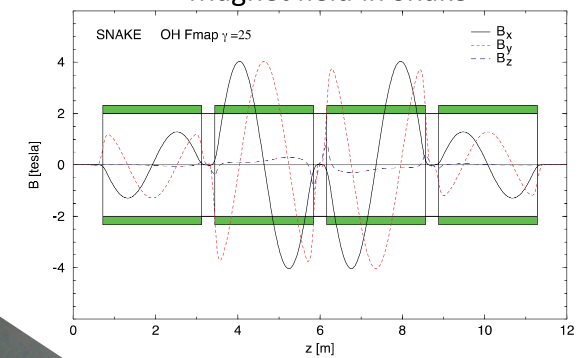
- Existing p Polarization in RHIC achieved with “Siberian snakes”
- RHIC near term improvements: proton polarization 60% → 80%
- ^{3}He polarization of >80% measured in source
- 80% polarized ^{3}He in EIC will be achieved with six “snakes”
- Acceleration of polarized Deuterons in EIC 100% spin transparent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

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

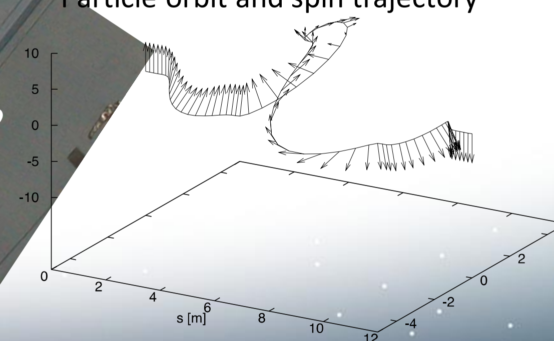


AGS partial snake

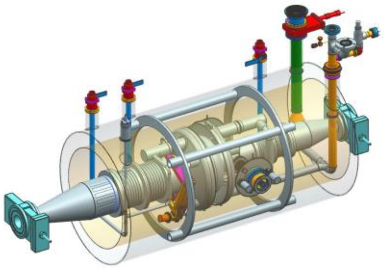
Magnet field in Snake



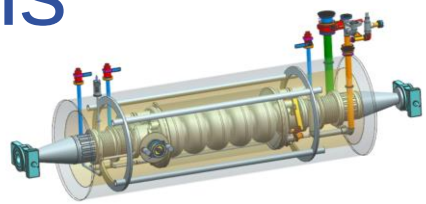
Particle orbit and spin trajectory



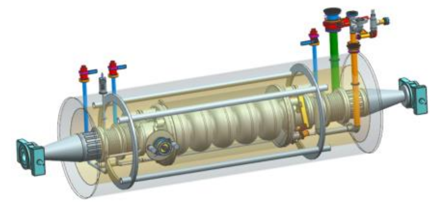
EIC RF systems



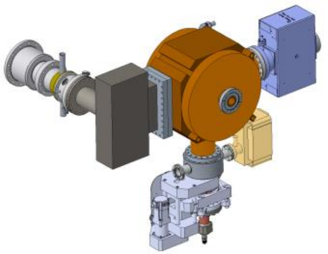
Electron - 591 MHz electron storage cavity



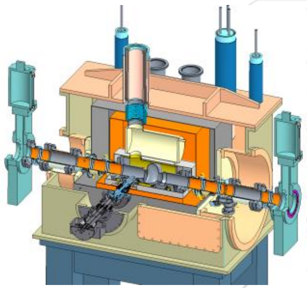
Hadron - 591 MHz bunch compression cavity



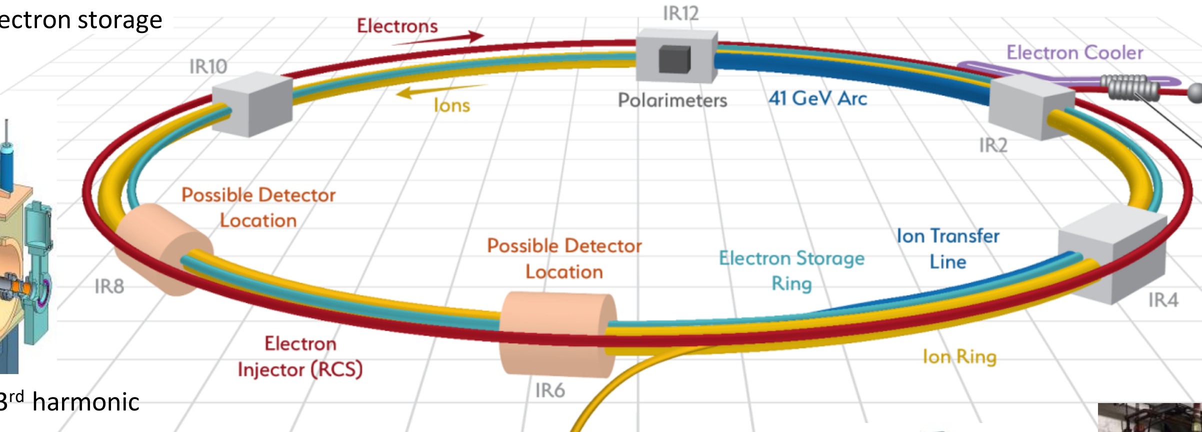
Hadron Cooling - 591 MHz acceleration cavity



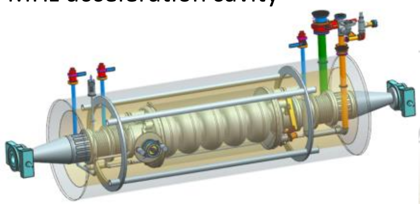
Injector - 571 MHz bunch compression cavity

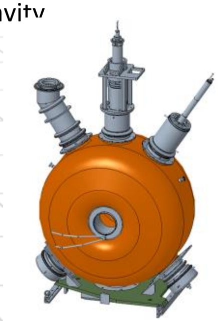


Electron - 1773 MHz 3rd harmonic cavity



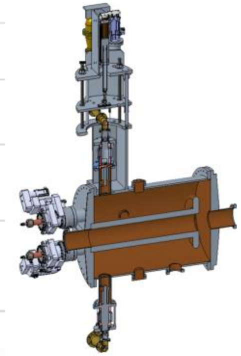
Rapid Cycling Synchrotron - 591 MHz acceleration cavity



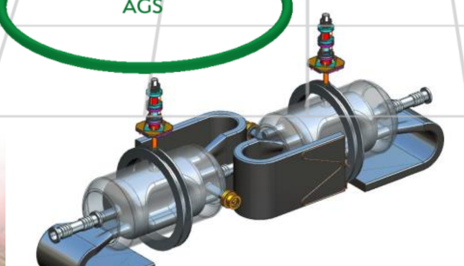


Hadron - 197 MHz bunch compression cavity

Hadron – 24.5 MHz acceleration cavity



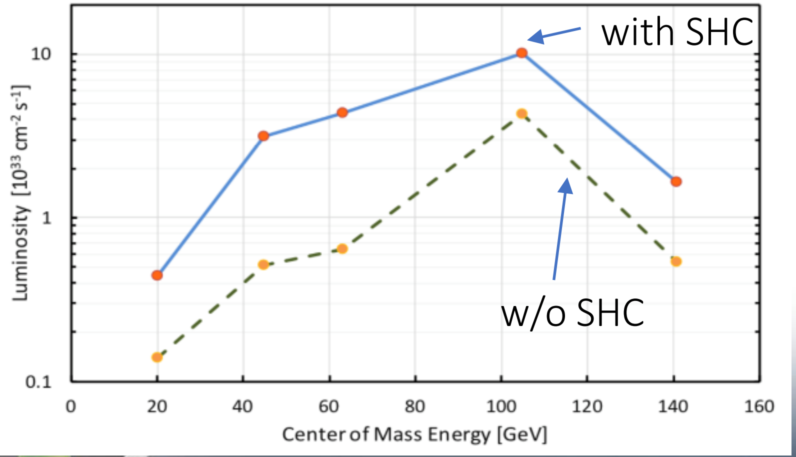
Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity



Both rings –crab cavities

EIC cooling requirements

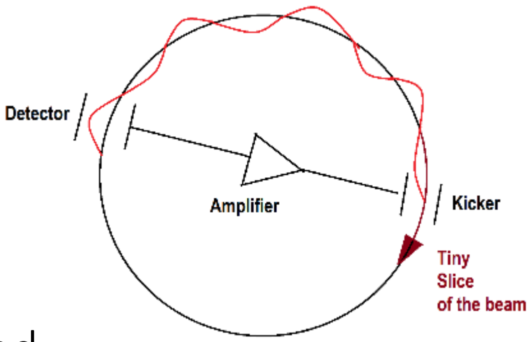
- Luminosity of lepton-hadron colliders in the energy range of the EIC benefits strongly (factor ≈ 3-10) from cooling the hadron's transverse and longitudinal beam emittance.
- Cool the proton beam at 275 GeV and 100 GeV , need for 41 GeV under study.
- IBS longitudinal and transverse(h) growth time is 2-3 hours. The cooling time shall be equal to or less than the diffusion growth time from all sources.
- Must cool the hadron beam normalized rms vertical emittance from 2.5 um(from injector) to 0.5 um in 2 hours.
    - Pre-cooling at injection (24GeV) with electron cooling is desired.
- The cooling section must fit in the available IR 2 space.



Coherent Electron Cooling (CEC)

Like in stochastic cooling, tiny fluctuations in the hadron beam distribution (which are associated with larger emittance) are detected, amplified and fed back to the hadrons thereby reducing the emittance in tiny steps on each turn of the hadron beam

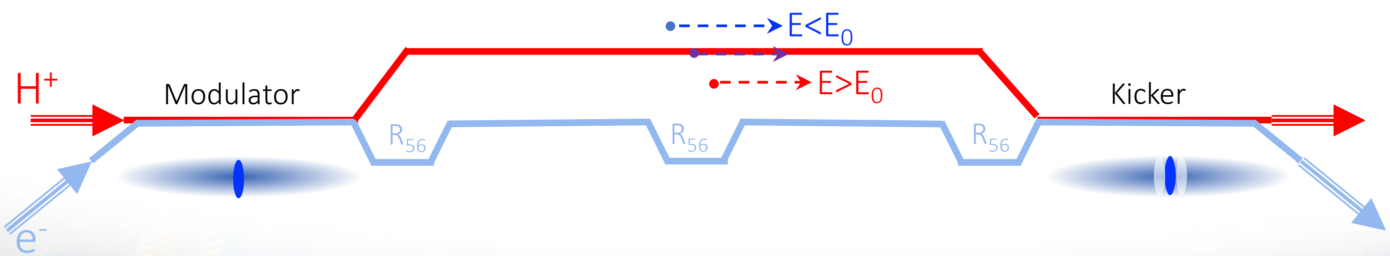
- High bandwidth (small slice size)
- Detector, amplifiers and kickers



For high energy protons, a large bandwidth is required:

➔ Using an electron beam to detect fluctuations, to amplify and to kick.

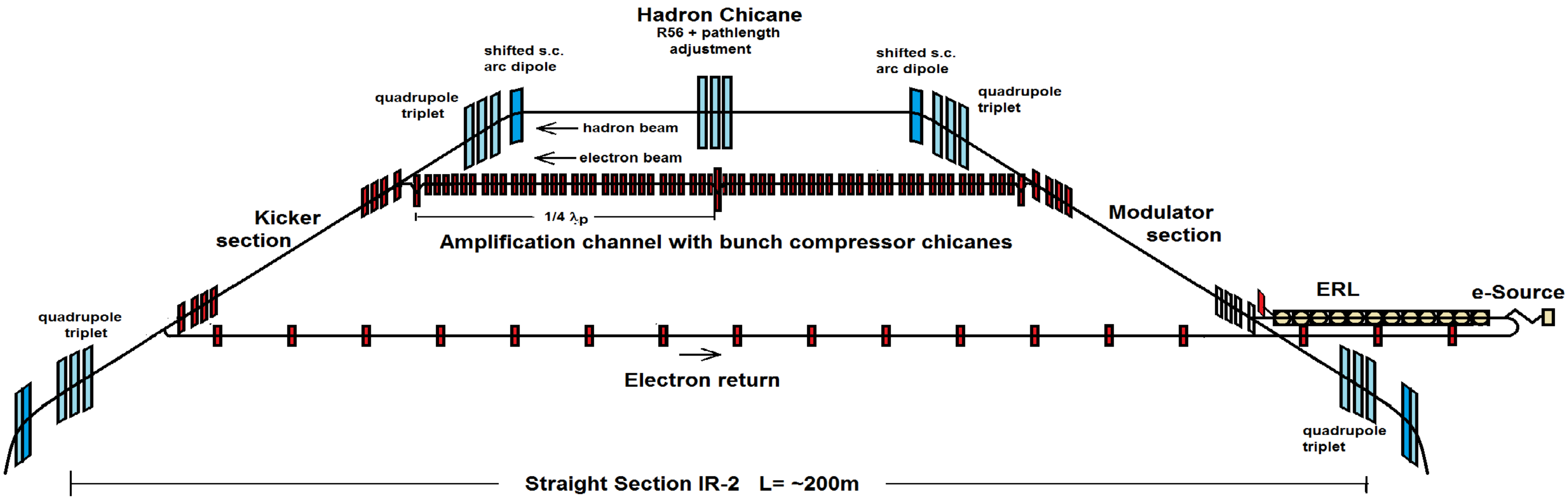
CDR baseline Amplification: micro-bunched amplifier



We acknowledge there are other three amplification schemes

EIC Strong Hadron Cooling

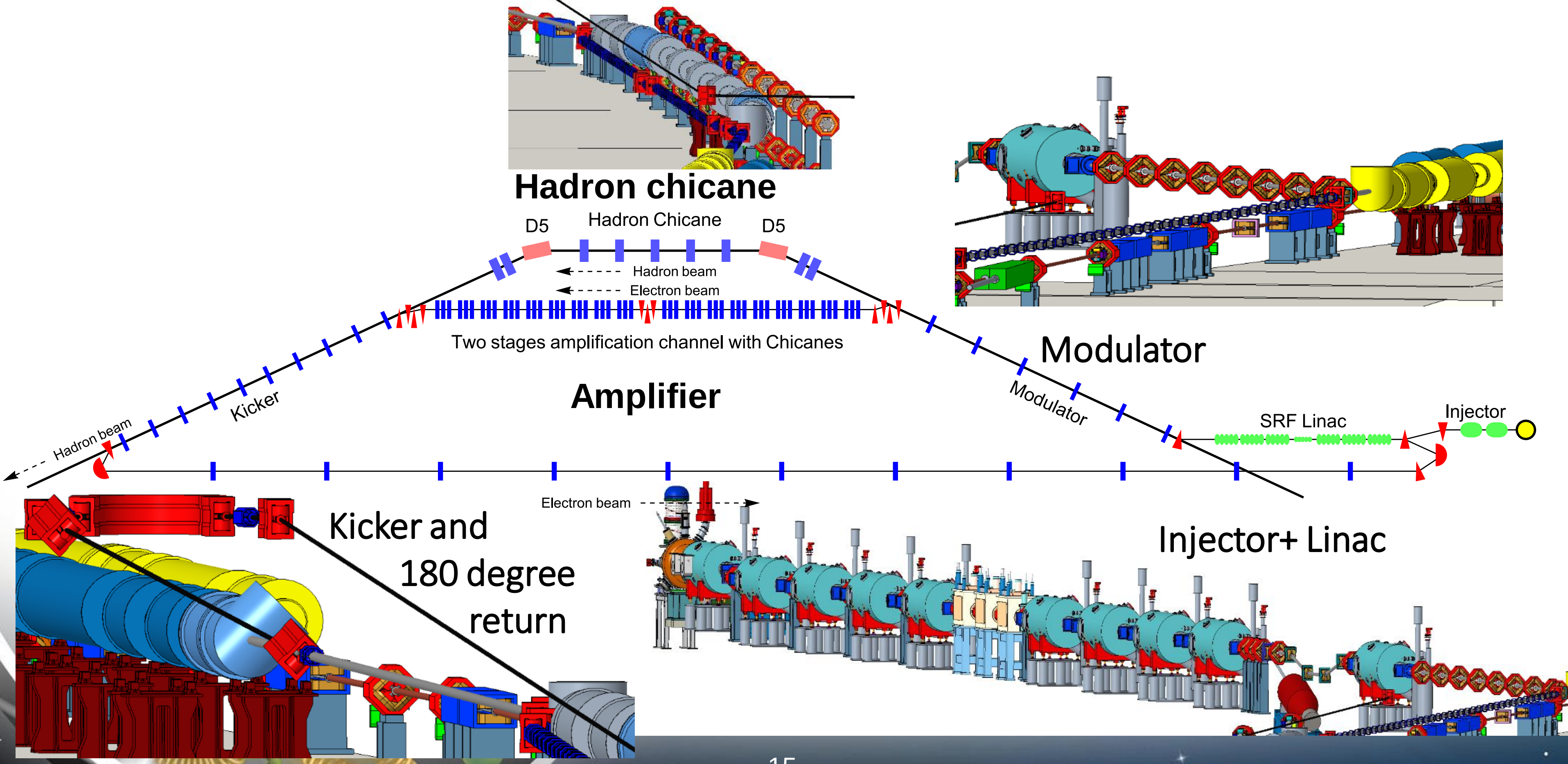
Coherent Electron Cooling with μ-bunching amplification



- The EIC cooler requires up to 150 MeV electron beams with average electron beam current of ~100 mA => 15 MW
- Requires use/design of a world-class SRF **energy-recovery linac** (ERL)
- Electron/hadron beams separate and rejoin each other
  - Adjustable R_{56} for electrons to tune amplification
- Electron source/accelerator must be **extremely "quiet"** (no substructure)
  - avoid amplification of "shot noise", electron beam structure not from hadrons

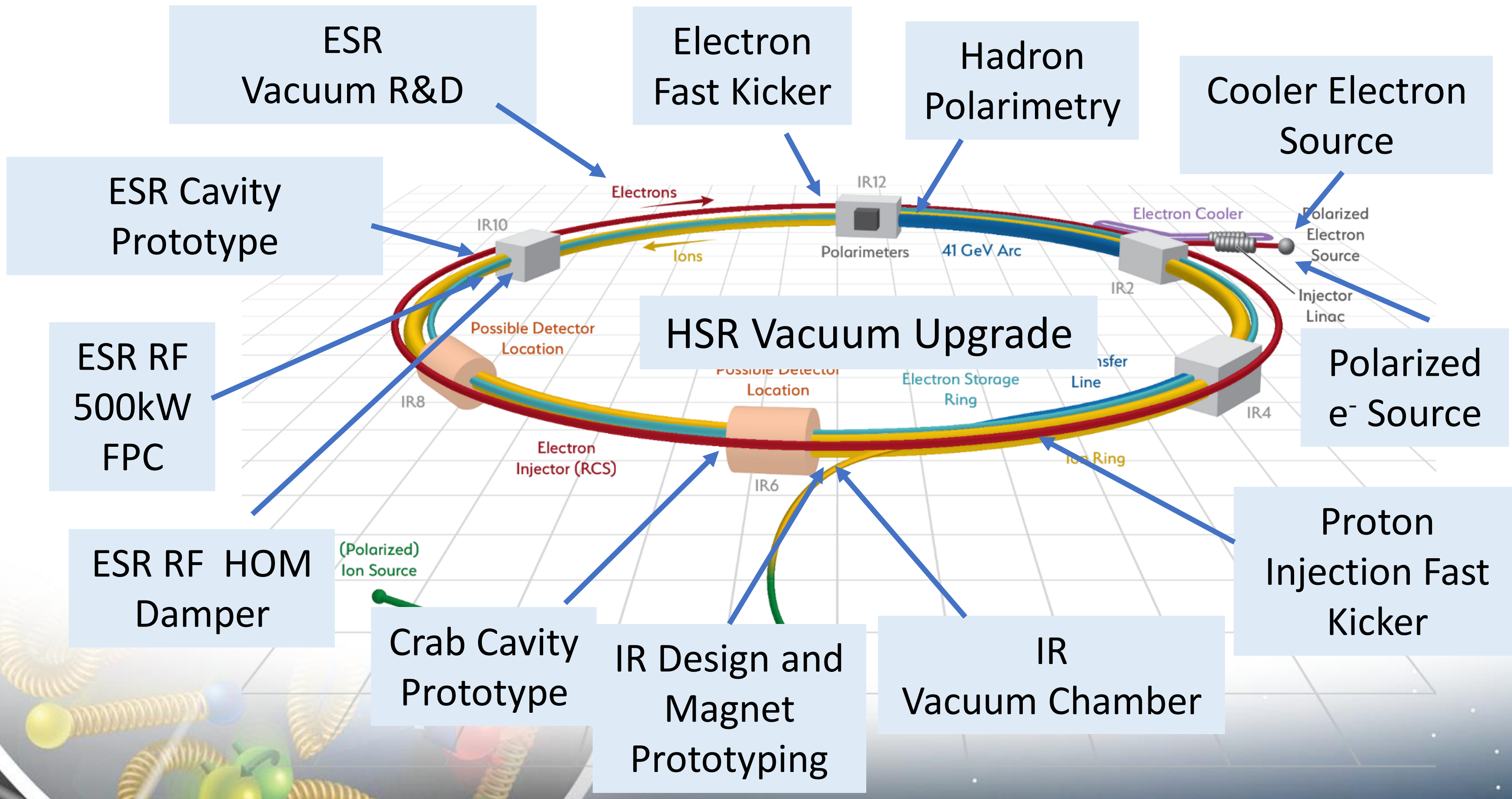
EIC Strong Hadron Cooling

- Cooling theory and simulations, good progress, cooling in transverse & longitudinal plane
- Good progress in electron acceleration, beam-transport, and cooling simulation
- Detailed accelerator layout and beam optics, interface with building, 3D modeling
- CeC Proof of Principle experiment in progress, a lot of valuable knowledge gained, giving us confidence in design of SHC beamlines

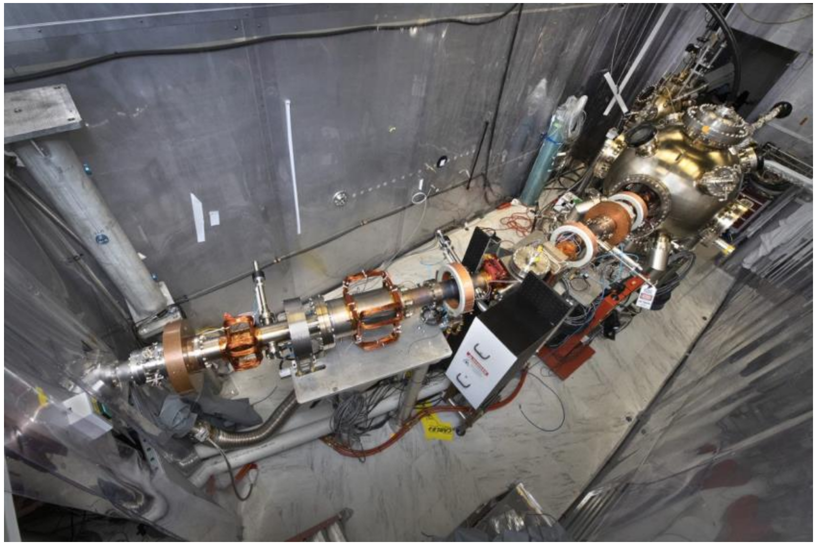


Accelerator R&D Overview

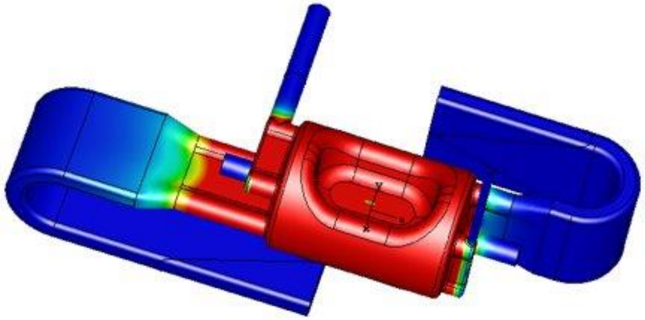
EIC R&D is prototyping of novel, challenging, or critical components to obtain confidence for final design and production of the components in industry or in-house



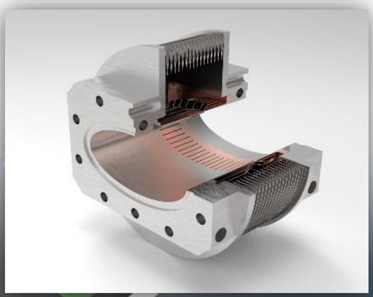
R&D Highlights



Polarized Electron Source Prototype
Spectacular performance shortly after start commissioning earlier this year, cathode lifetime very large under EIC operational conditions
Cathode cooled with Flourinert™ (C_6F_{16},…)
➔ Is the base for the 100mA gun for strong hadron cooling



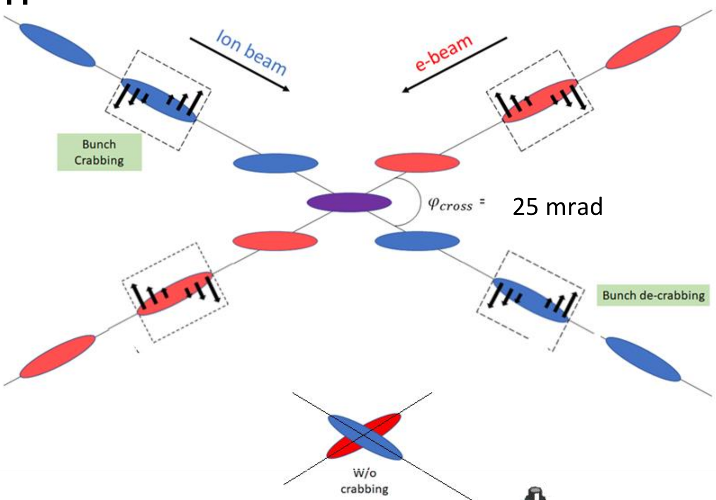
EIC Crab cavity prototype: Choice was made to move forward with the RF kicker design
Conceptual design of the prototype well advanced



e-Vacuum R&D
Prototype of RCS Cu vacuum chamber and 3D rendering of the sliding bellow prototype design

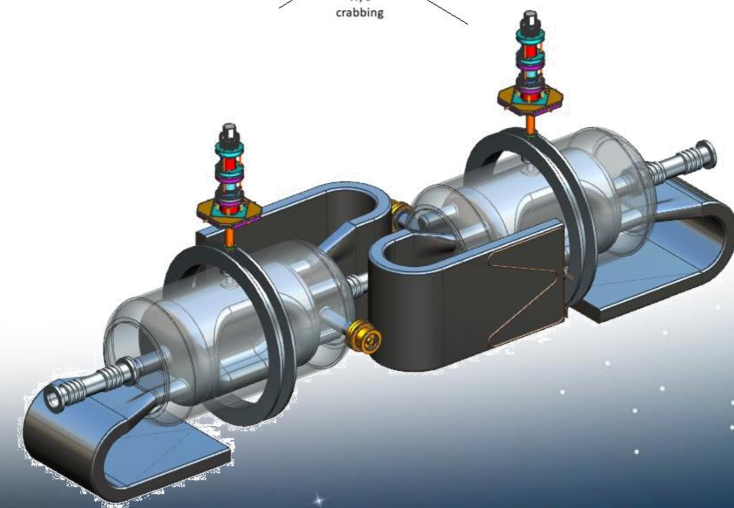
EIC High Luminosity with a Crossing Angle

- **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**



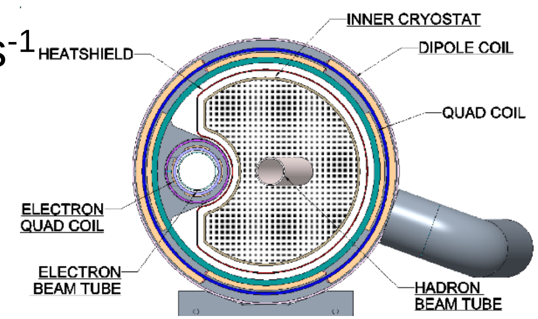
Then :
  - Effective head-on collision restored
  - Beam dynamic issues resolved

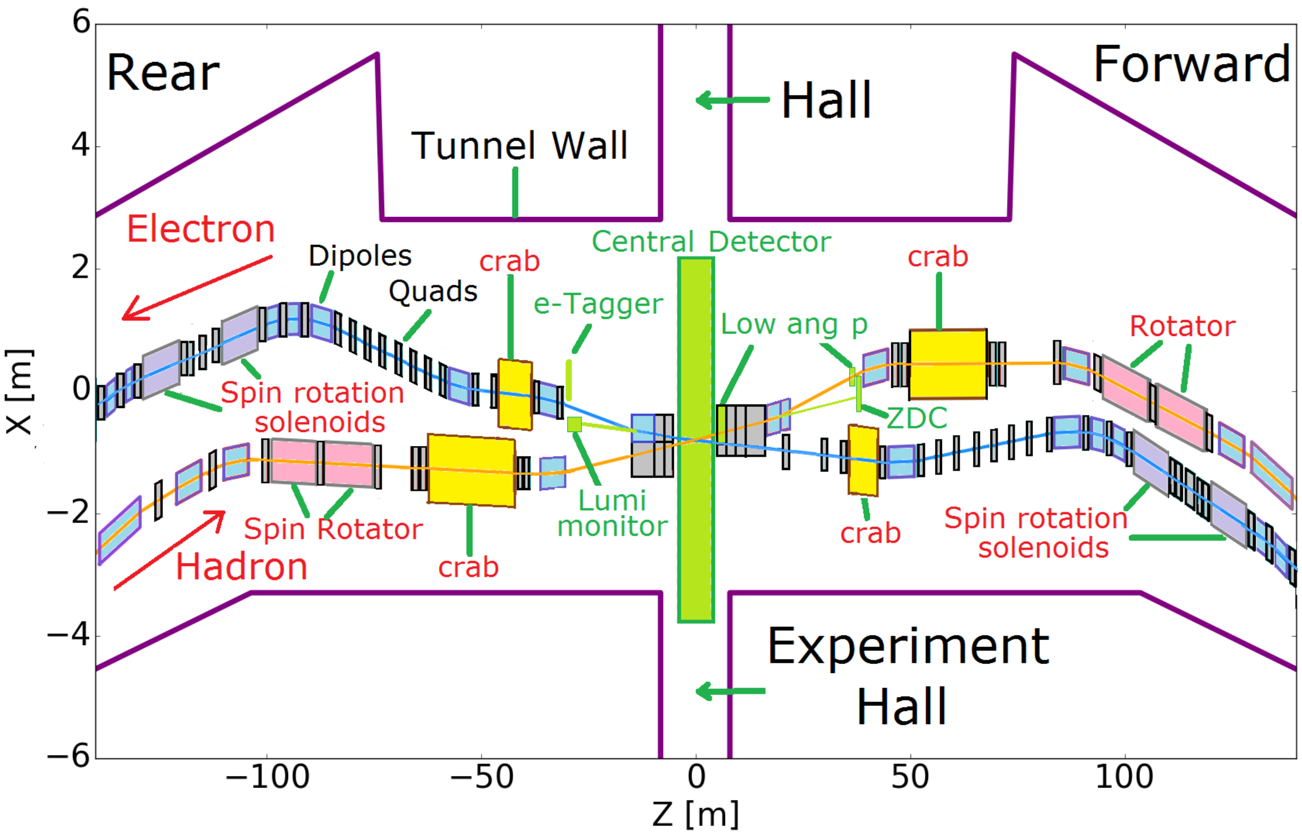
- RF resonator (crab-cavity) prototypes built and tested with proton beam in the CERN-SPS
  - The EIC crab-cavity need large waveguide ports to allow the trapped modes to escape

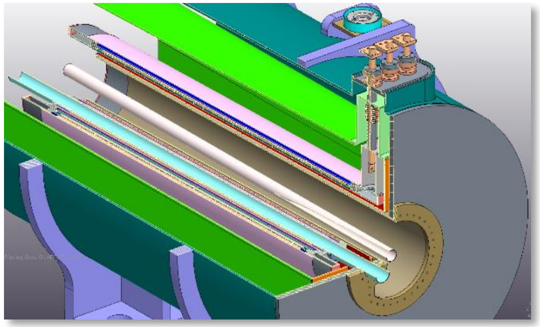


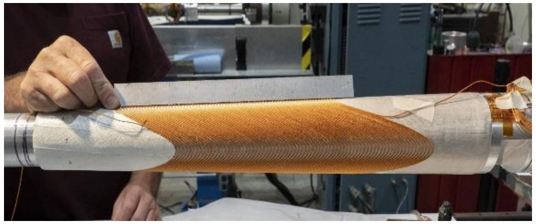
Interaction Region

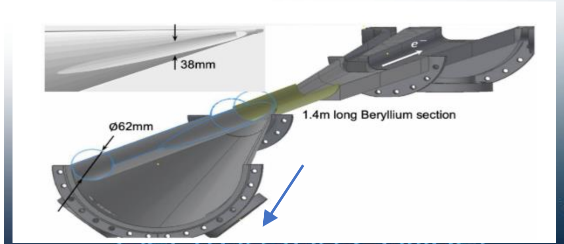
- Beam focused to $\beta_y \le 5$ cm @ $\sigma_y = 5\ \mu$m, => $L=10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Manageable IR chromaticity and sufficient DA
- Full acceptance for the colliding beam detector
- Accommodates crab cavities and spin rotators
- Synchrotron radiation and impedance manageable
- Conventional NbTi SC magnets, collared & direct wind

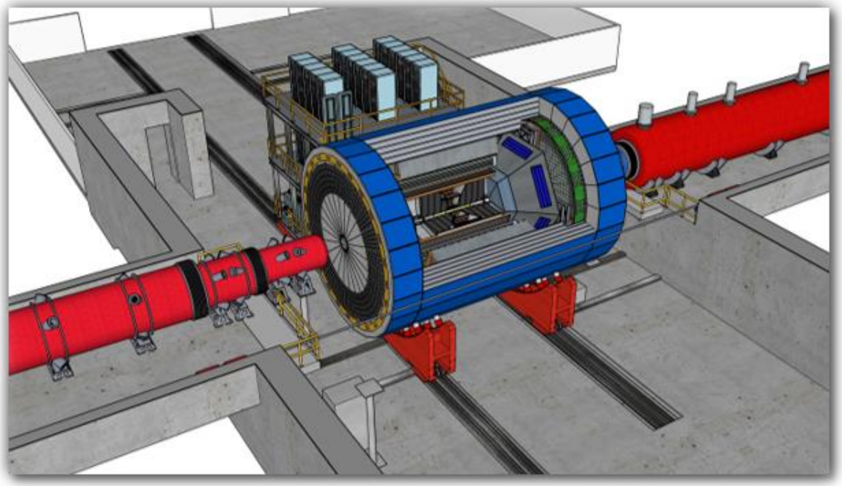




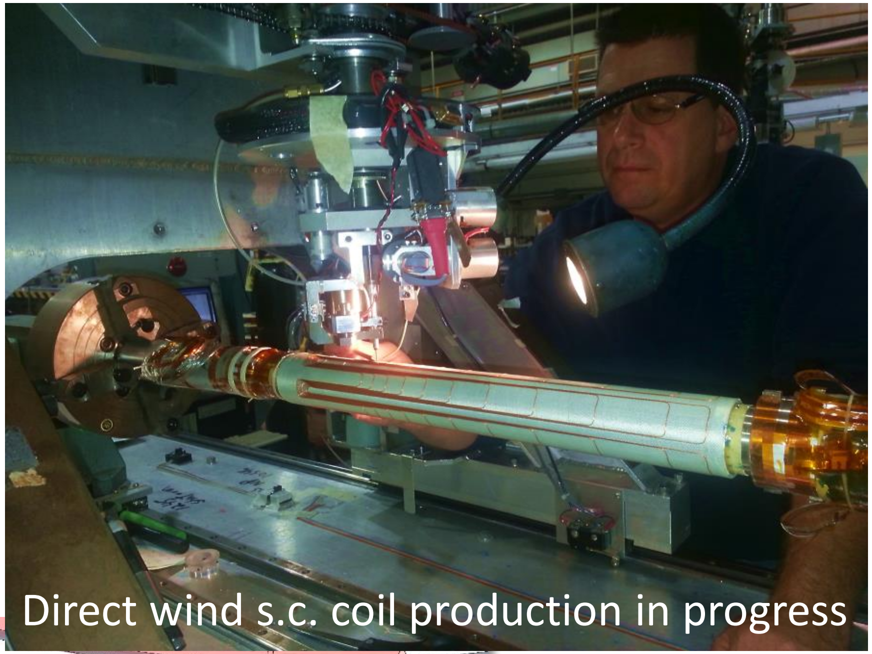


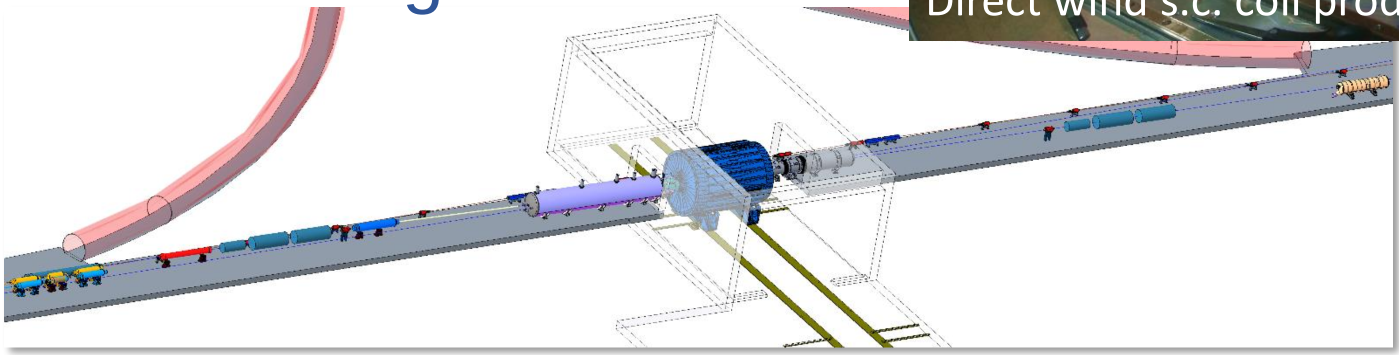


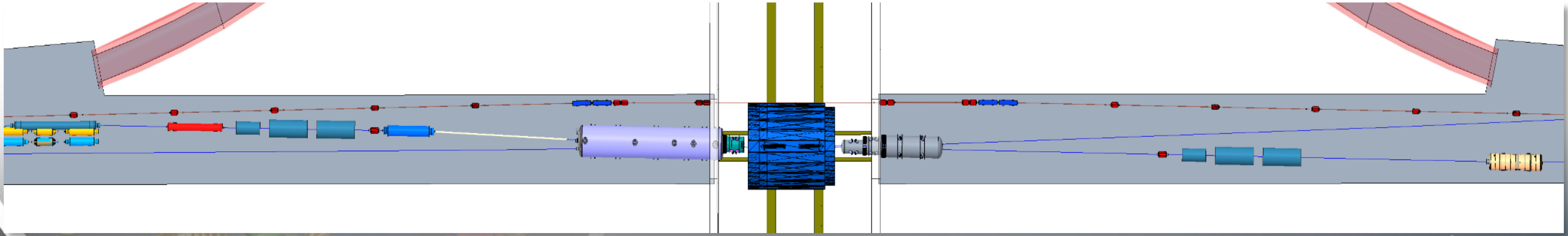




Interaction Region



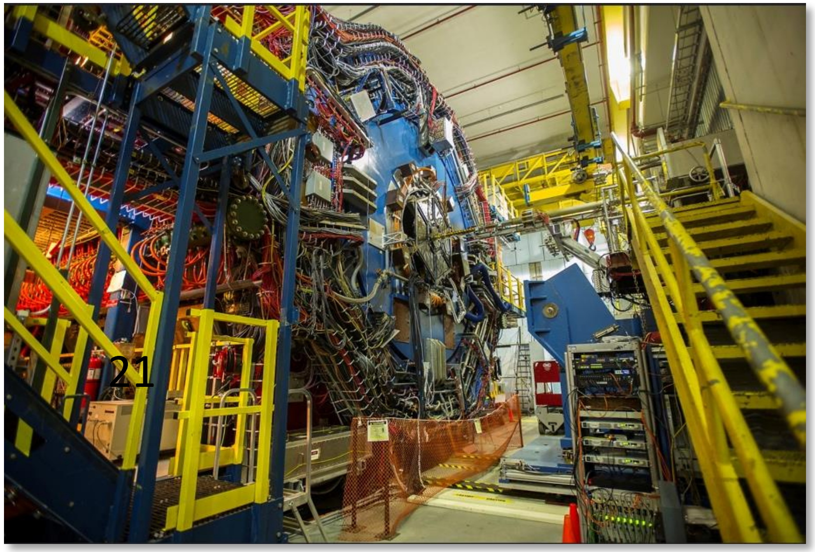




The EIC will benefit from two large existing detector halls in IR 6 and IR 8

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

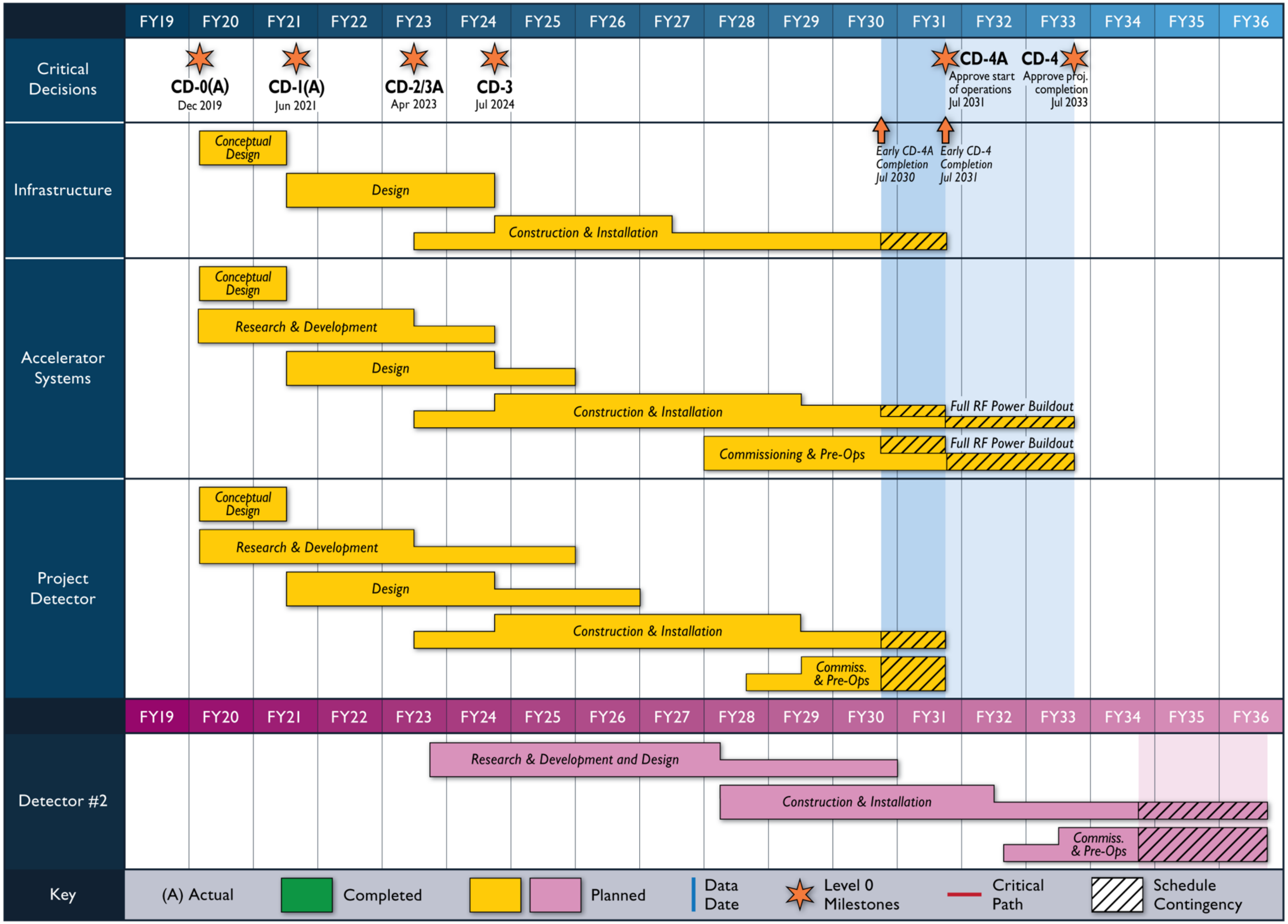
IR 8 detector hall with PHENIX detector (transitioning to sPHENIX)



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}

Reference Schedule



EIC Partnerships

- 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 and 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.
- The Experimental Program Partnership Activities
  - Expressions of Interest (EoI) submitted in 2020
  - Call for Collaboration Proposals for Detector(s) - March 2021
  - Collaboration Proposals Due – December 2021
  - EIC Project Detector Defined – March 2022

Accelerator Partnership Workshop 2021

- 2021 Accelerator Partnership Workshop will focus on areas where there are advanced technical discussions between EIC and potential partners
- Workshop sessions are targeted to areas of possible collaboration and on the second IR:

Acc workshop sessions & conveners

- **Crab Cavities**
  - G. Burt (CI), R. Laxdal (TRIUMF), J. Preble (EIC/JLAB)
- **IR SC magnets and spin rotators**
  - P. Vedrine (CEA Saclay), H. Witte (EIC/BNL)
- **HSR vacuum system**
  - R. Cimino (INFN), S. Verdu Andres (EIC/BNL)
- **ESR vacuum system**
  - R. Losito (CERN), C. Hetzel (EIC/BNL)
- **ESR high current elements**
  - R. Losito (CERN), A. Blednykh (EIC/BNL)
- **ESR SRF and CM**
  - R. Losito (CERN), R. Rimmer (EIC/JLAB)
- **Lessons from SuperKEKB**
  - M. Tobiyama (KEK), M. Blaskiewicz (EIC/BNL)
- **ERL Satellite meeting**
  - W. Kaabi (IJCLab), P.Williams (CI), S. Benson (EIC/JLAB)
  - Satellite meeting by invitation only
- **MDI, First and Second IR**
  - In Soo Ko (PAL), A. Drees (EIC/BNL), W. Wittmer (EIC/JLAB)
- **Second IR based on Nb3Sn option**
  - P. Vedrine (CEA Saclay), A. Seryi (EIC/JLAB)

If you interested to participate, please register at:

https://meetings.triumf.ca/event/254/

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. CD1 approved in June 2021. The project team is working towards CD2
- EIC will be state of the art collider pushing the frontiers of accelerator science and technology
- 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!**

Thanks to many members of EIC project for materials presented in this talk