Electron-Ion Collider accelerator development

Andrei Seryi, Jefferson Lab
EIC Project Associate Director for Accelerator Systems and International Partnership

Canadian Association of Physicists Congress

7 June 2022

Electron-Ion Collider

Brookhaven National Laboratory · Jefferson Lab · U.S. Department of Energy Office of Science

Electron-Ion Collider Accelerator Development

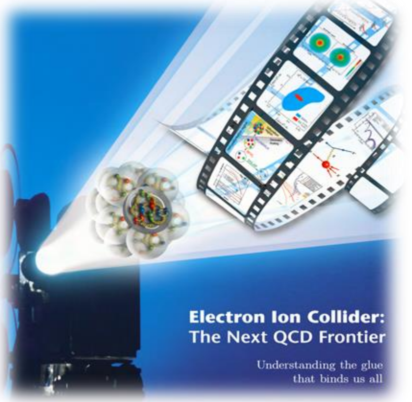
The Electron-Ion Collider will be a new discovery machine for unlocking the secrets of the "glue" that binds the building blocks of visible matter in the universe. The EIC will consist of two intersecting accelerators, one producing an intense beam of electrons (Electron Storage Ring), the other a high-energy beam of protons or heavier atomic nuclei (Hadron Storage Ring), which are steered into collisions of spin-polarized beams in the Interaction Region. The EIC design will make use of existing ion sources, a pre-accelerator chain, a superconducting magnet ion storage ring, and other infrastructure of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The Rapid Cycling Synchrotron will provide injection into ESR, while preserving beam polarization. The Strong Hadron Cooling system will preserve emittances of the proton beam during collision run. The EIC project has recently received Critical Decision 1 (CD-1) approval from DOE, and the project team is now working on the next milestone – CD-2. The EIC project will be delivered in a collaboration of domestic and international partners. In this talk, the status of EIC accelerator will be reviewed.

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), Erdong Wang, Alexei Fedotov, Gennadi Stupakov, Steve Benson and many other members of EIC project team

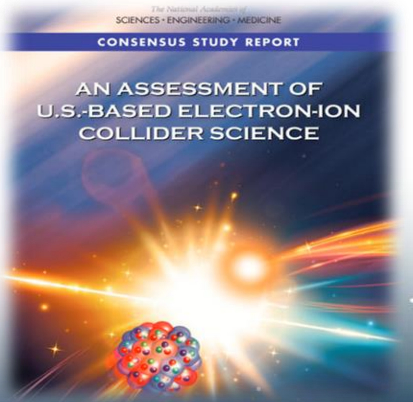
Project Requirements

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)

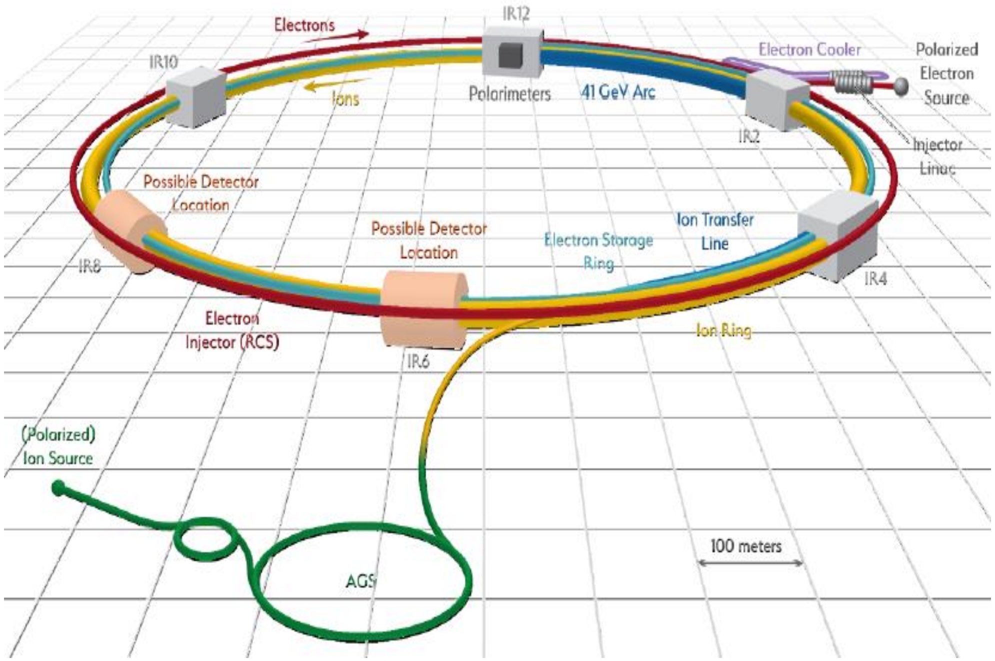


Conceptual design scope and expected performance meets or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)



NSAC – U.S. Department of Energy Nuclear Science Advisory Committee
NAS – U.S. National Academies of Sciences, Engineering, and Medicine

EIC project



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 mission need statement (CD-0) approved by DOE in Dec 2019

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.

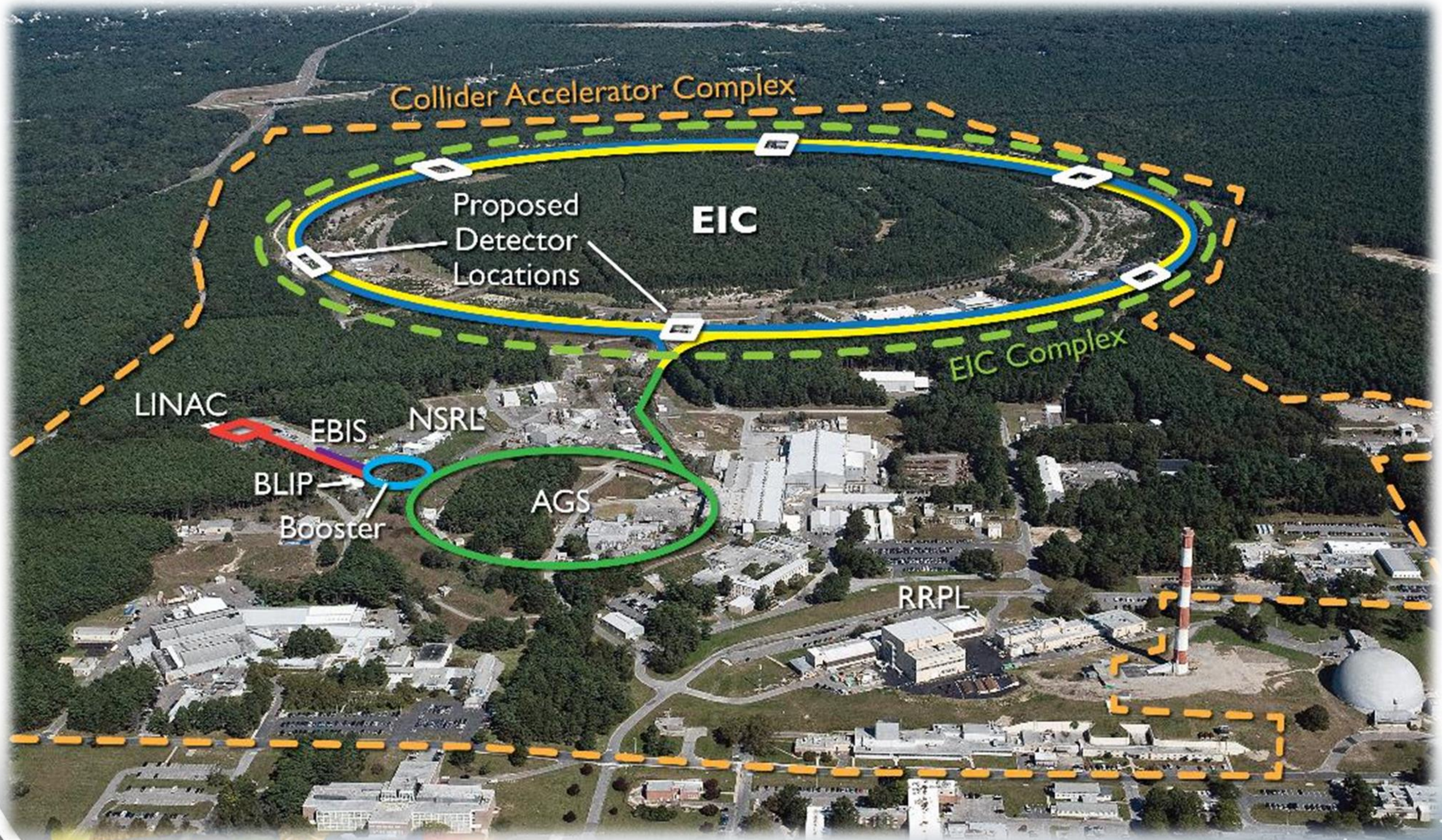
The CD1 approved in June 2021. The EIC team is working towards CD-2/3A in 2023

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.

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

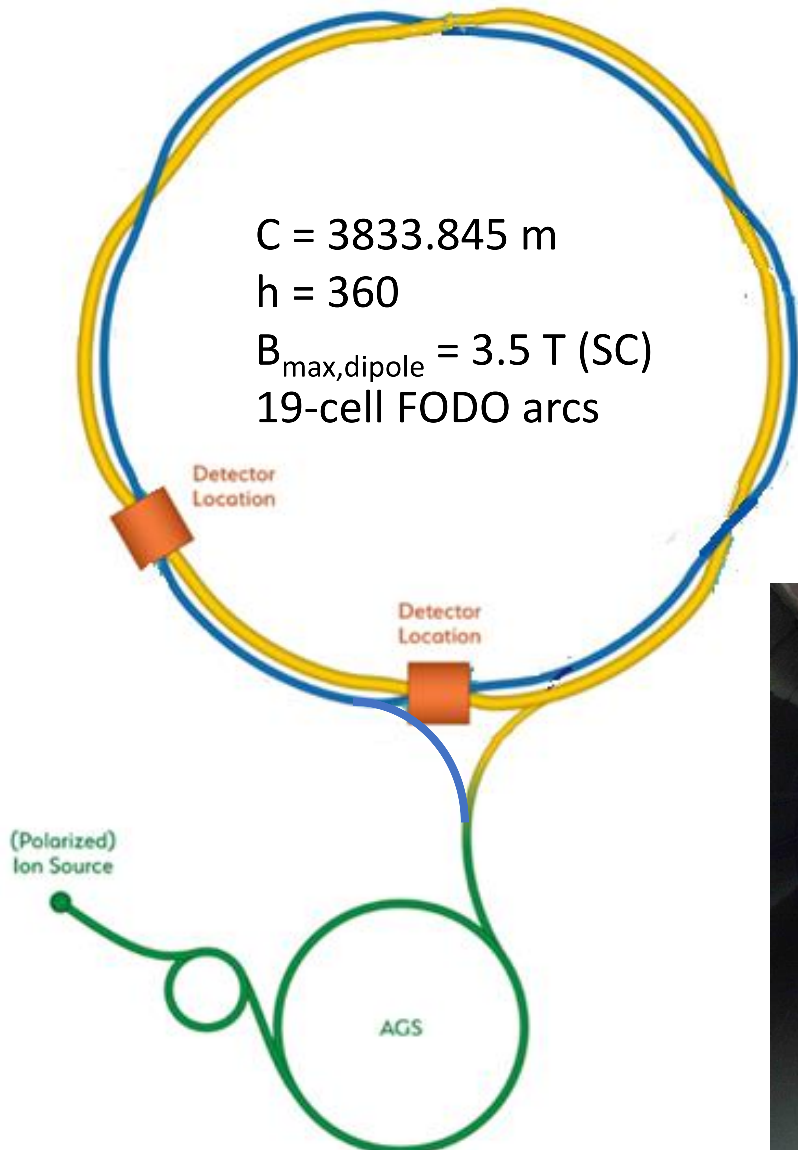
The EIC will be a game-changing resource for the international nuclear physics community. *DOE looks forward to engaging with the international community and the international funding agencies about potential collaborations and contributions to the EIC effort, in nuclear, accelerator and computer science.*

EIC Design Overview



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

From RHIC to the EIC: RHIC



- Existing RHIC facility
  - Hadron collider (h=360)
  - 6-100 GeV/u ions
  - 100-250 GeV polarized protons
  - Two independent rings
    - Asymmetric operations include e.g. d-Au collisions
- Constructed 1990-2000
- Will operate to ~2025

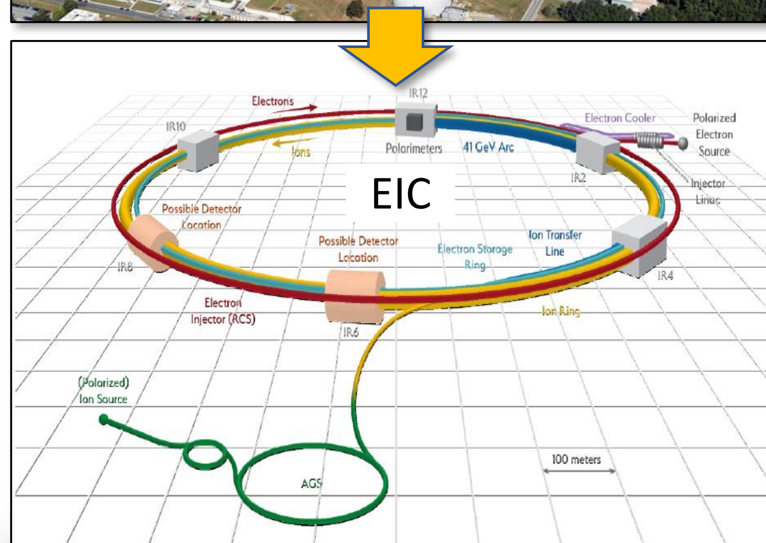
EIC Design Concept

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**

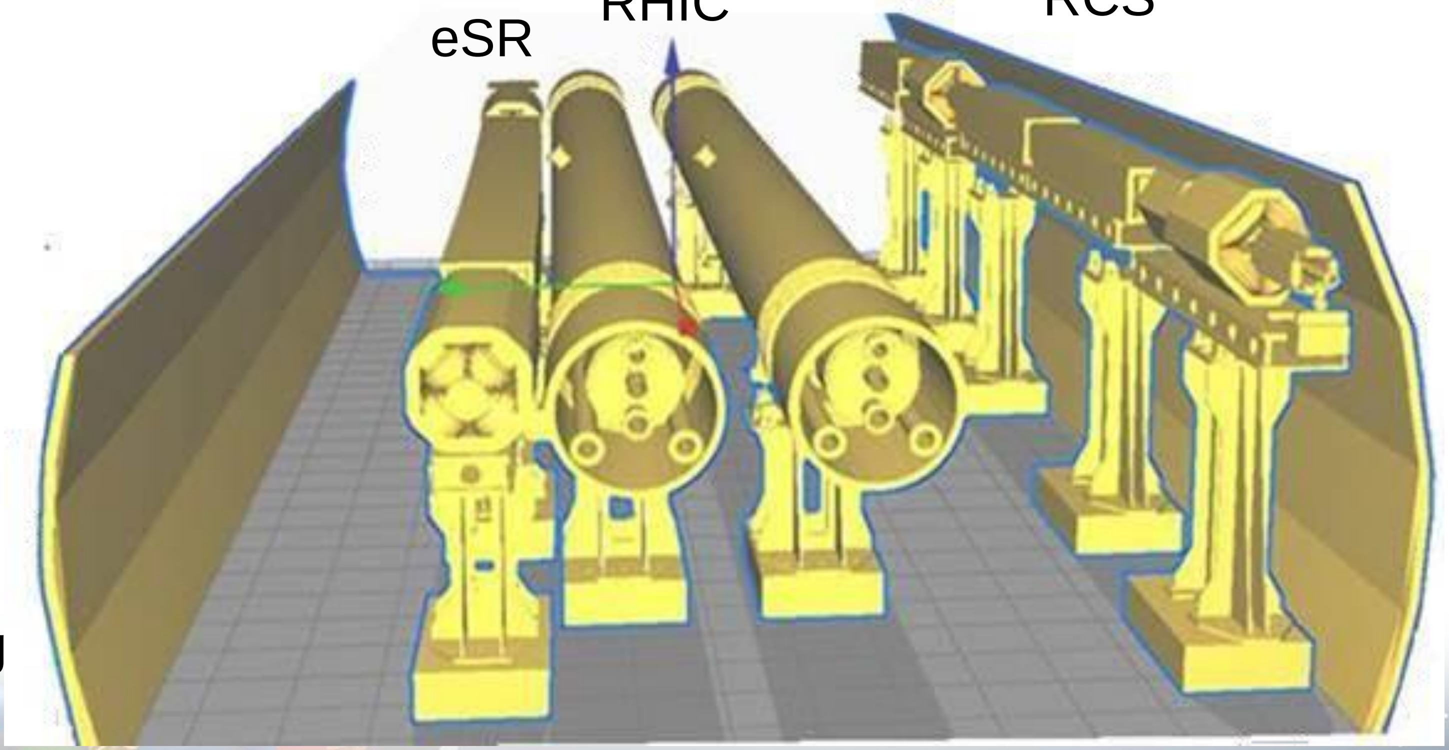
- **Electron storage ring 2.5–18 GeV** (new)
  - Many bunches (max 1160)
  - Large beam current (2.5 A) ➔10 MW SR power
- **Electron rapid cycling synchrotron** (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity

- **High luminosity interaction region(s)** (new)
  - Luminosities up to 10^{34} cm^{-2} s^{-1}
  - Superconducting magnets
  - 25 mrad crossing angle with crab cavities
  - Spin rotators (longitudinal spin)
  - Forward hadron instrumentation



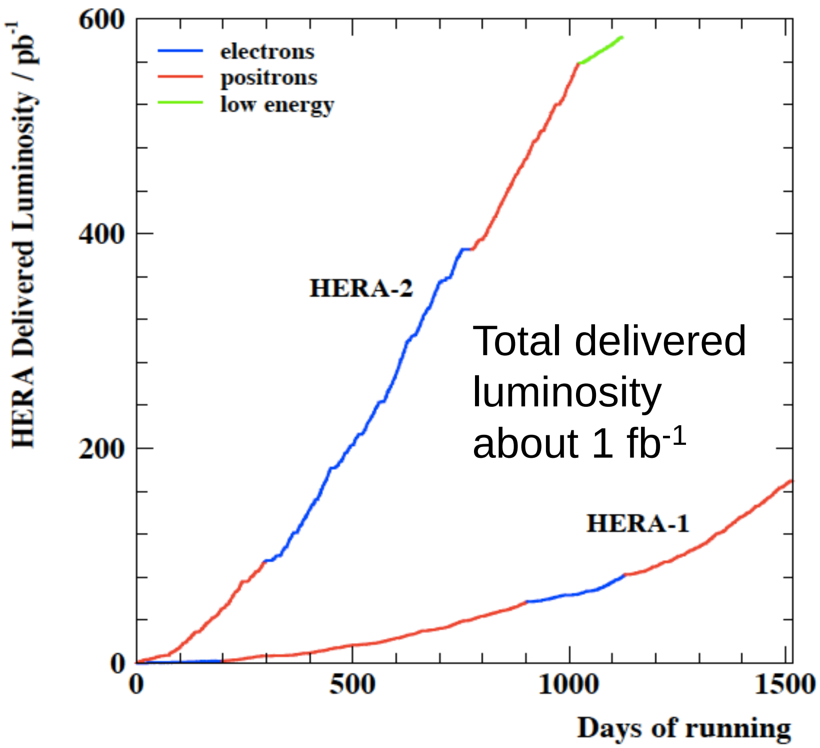
Tunnel Cross Section

All accelerators fit into the existing tunnel
Need several new equipment buildings

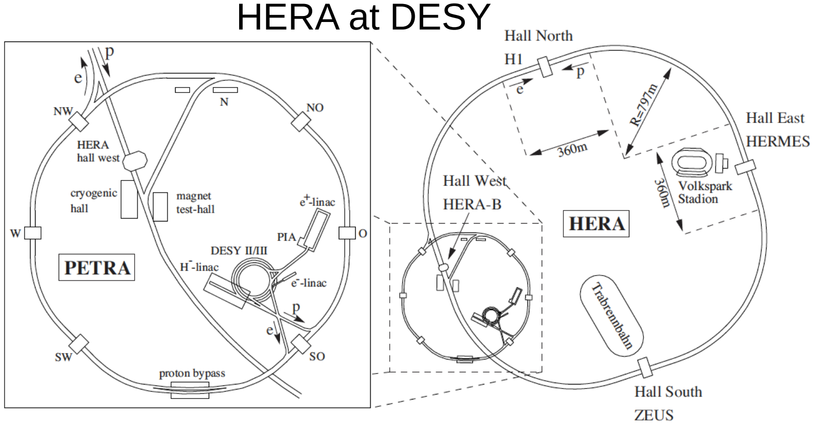


HERA lessons

- The first and only lepton-hadron collider, operated for physics 1992-2007
- Collided 27.5 GeV spin polarized leptons (e+; e-) with 920 GeV protons
- Reached luminosity of 5×10^{31} cm^{-2} s^{-1}
- HERA lessons relevant for EIC
  - Vertical beam-beam tune shift for lepton beam reached values planned for EIC
  - The necessity to minimize synchrotron radiation in the IR, IR vacuum pressure, and to avoid halo of the proton beam



HERA at DESY



F. Willeke, HERA and the Next Generation of Lepton-Ion Colliders", in Proc. of EPAC'06 , Edinburgh, paper FRXBPA01

B-Factories lessons

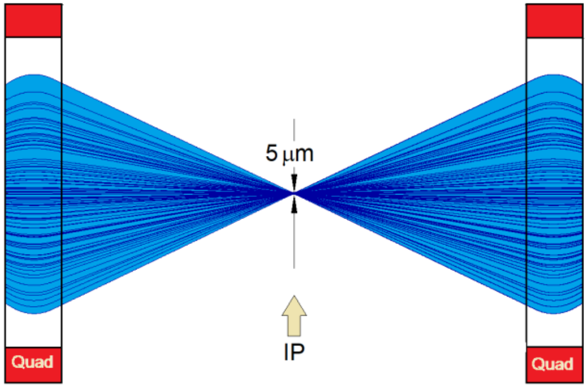
- When B factories design started ~1990, e+e- colliders barely reached 10^{32} cm^{-2}s^{-1}
- PEP-II and KEKB aimed in their design to luminosity of $0.3 - 1 \times 10^{34}$ cm^{-2} s^{-1}
  - Achieved and even exceeded the goals
- Approach: build-in necessary features to achieve high Lumi into the design
  - Crossing angle and crab cavity; Local chromaticity correction; RF cavities and vacuum chamber compatible with ampere-scale beams; Bunch-by-bunch feedback; Continuous top-up injection

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 interactions**

$\Delta\nu_p$ = 0.01 demonstrated in RHIC

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

EIC Design Parameters

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

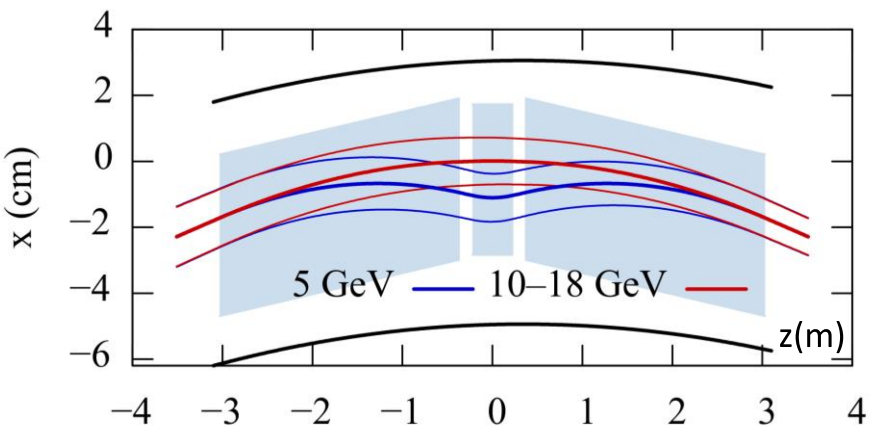
Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam 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}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

EIC Design Parameters

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

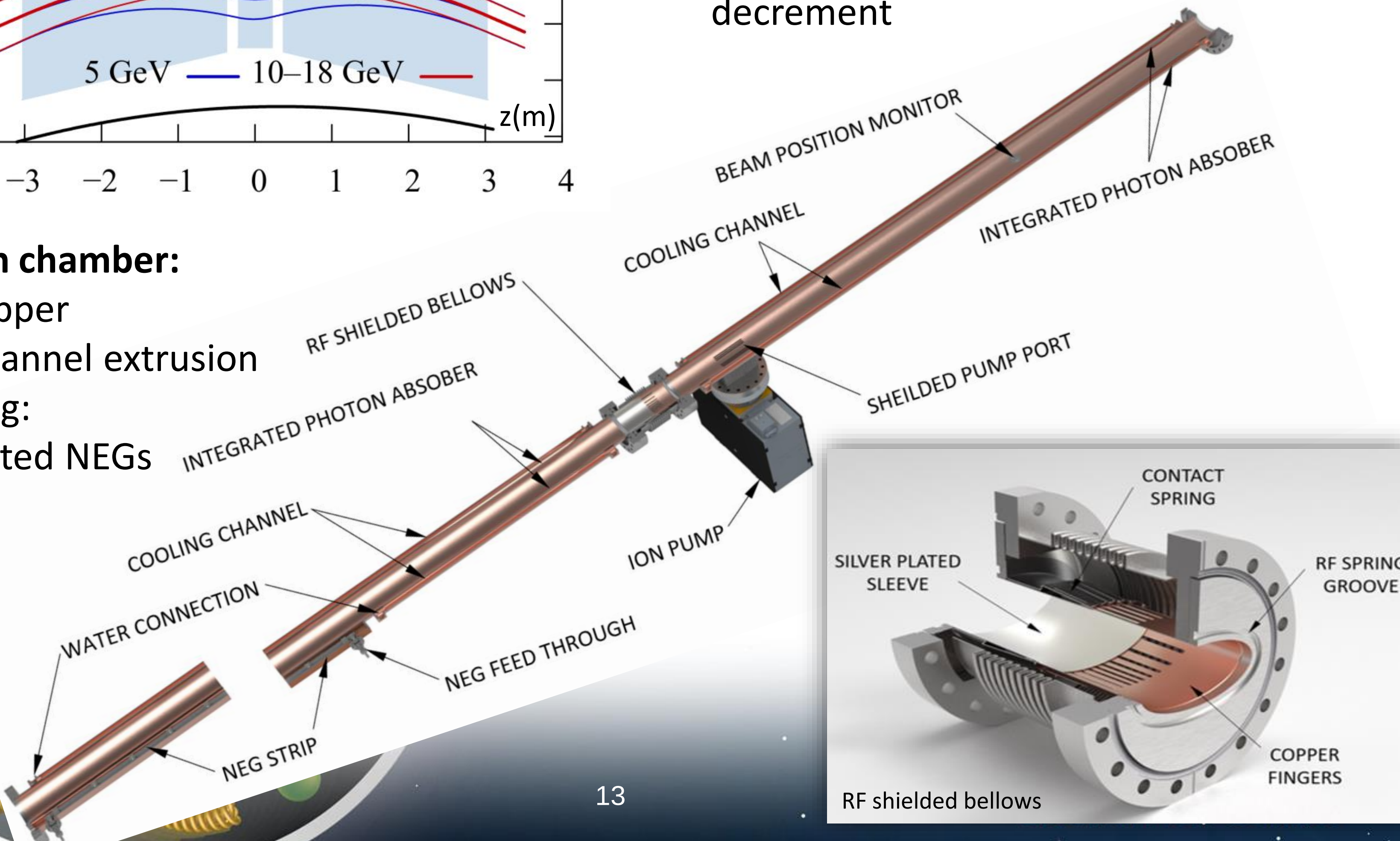
Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam 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}cm^{-2}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

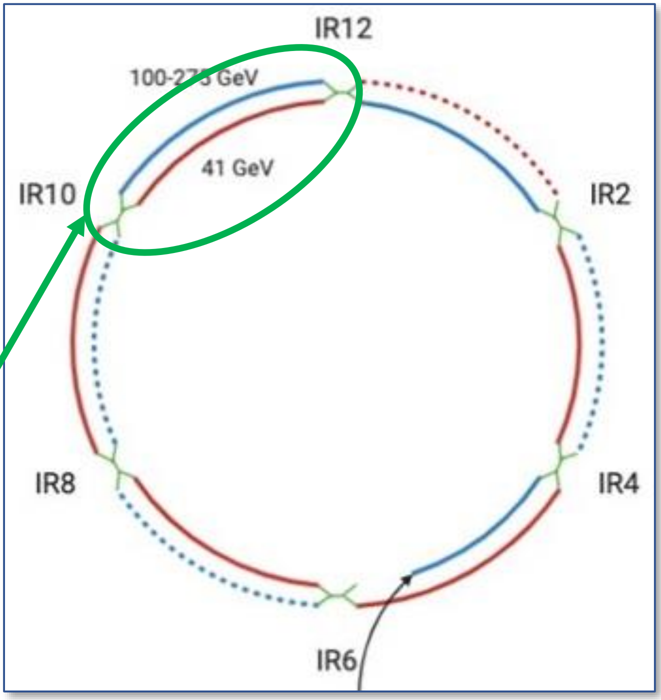
Vacuum chamber:
OFE Copper
Multichannel extrusion
Pumping:
distributed NEGs



RF shielded bellows

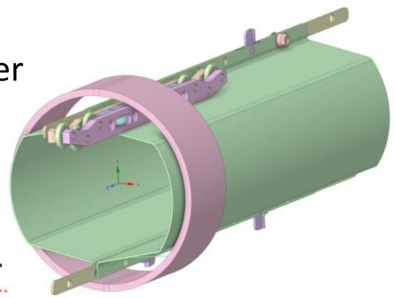
Hadron Storage Ring

- 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



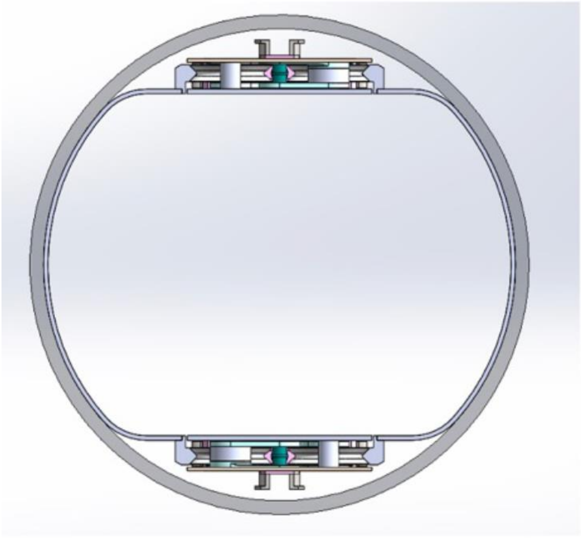
Hadron Ring Vacuum chamber upgrade:

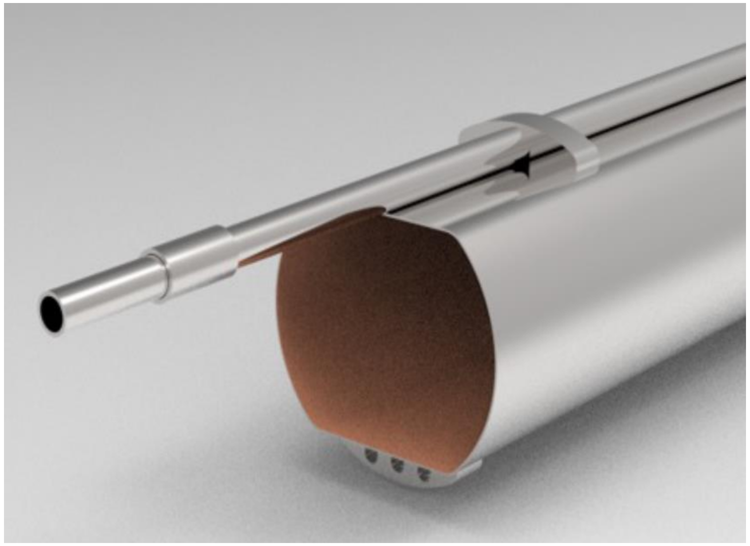
- Two main concerns towards existing RHIC vacuum pipes during EIC operation with higher current and shorter bunch length:
  - Resistive-wall impedance
  - e-cloud buildup
- Solution: **copper-clad stainless-steel screen + a-C thin film**
  - *Cu significantly reduces surface resistivity, esp. at cryo*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



conceptual design (being updated to active cooling) see next slide

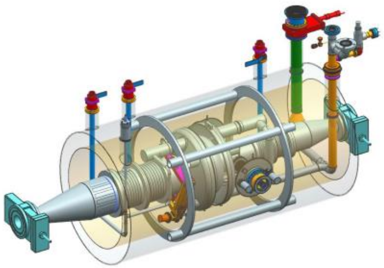
HSR Vacuum Liner



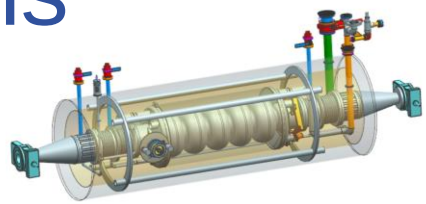


- HSR vacuum liner cooling changed from passively cooled (contact with RHIC beam pipe) to actively cooled

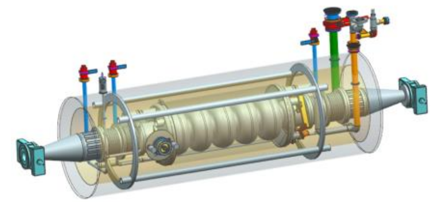
EIC RF systems



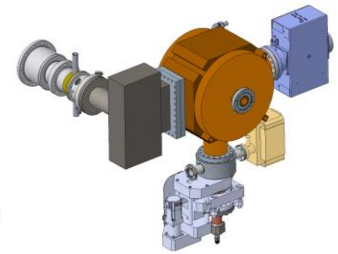
Electron - 591 MHz electron storage cavity



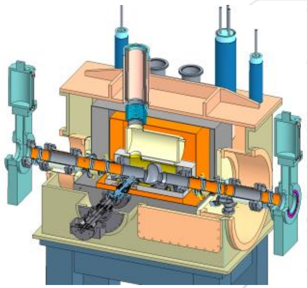
Hadron - 591 MHz bunch compression cavity



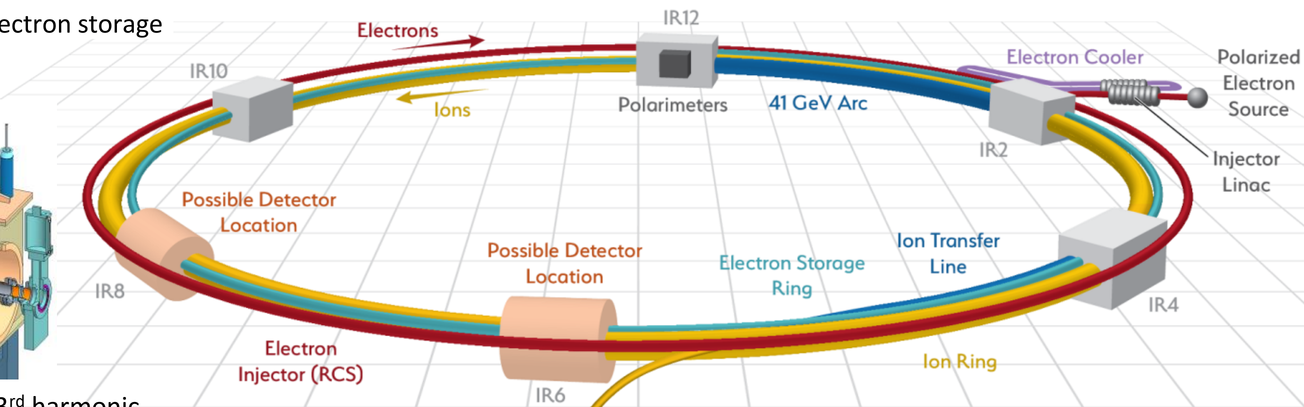
Hadron Cooling - 591 MHz acceleration cavity

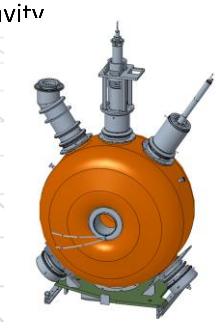


Injector - 571 MHz bunch compression cavity



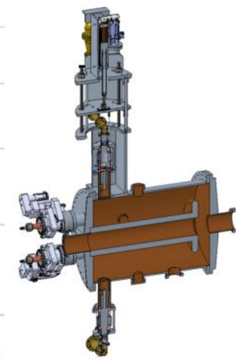
Electron - 1773 MHz 3rd harmonic cavity



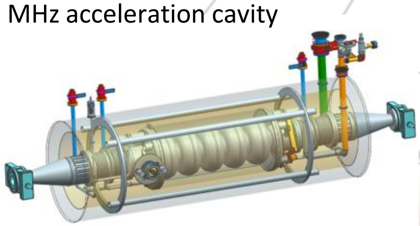


Hadron - 197 MHz bunch compression cavity

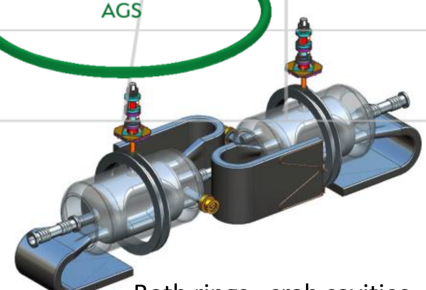
Hadron – 24.5 MHz acceleration cavity



Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity



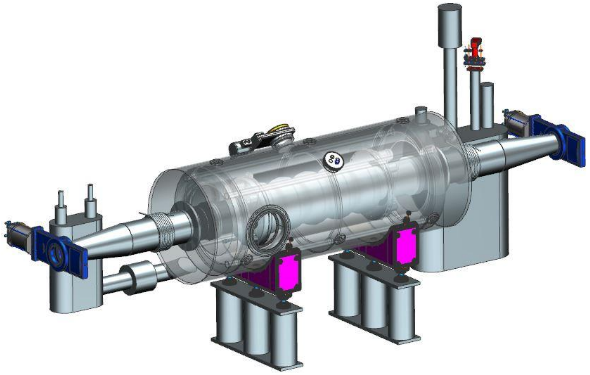
Rapid Cycling Synchrotron - 591 MHz acceleration cavity

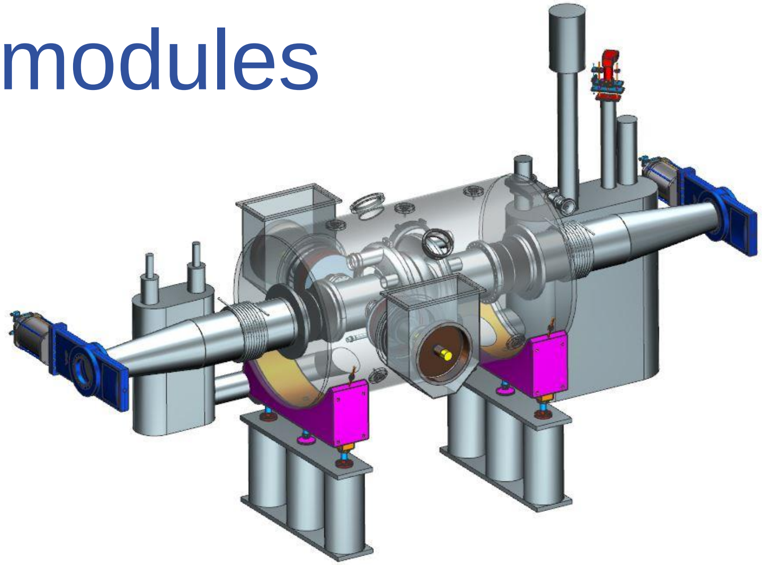


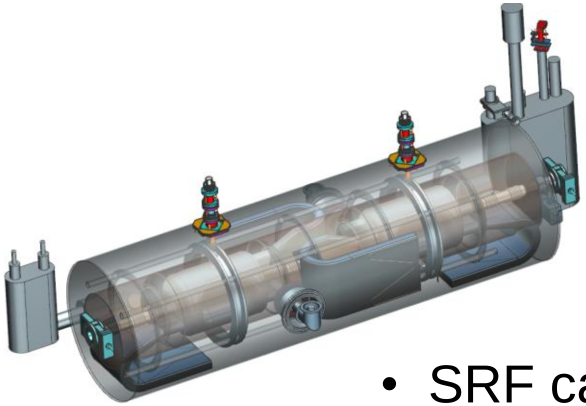
Both rings –crab cavities

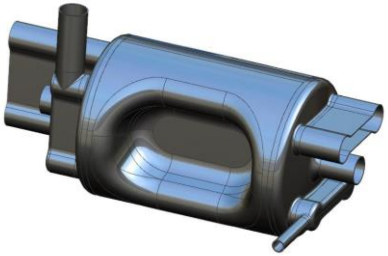
EIC SRF Cavities & Cryomodules

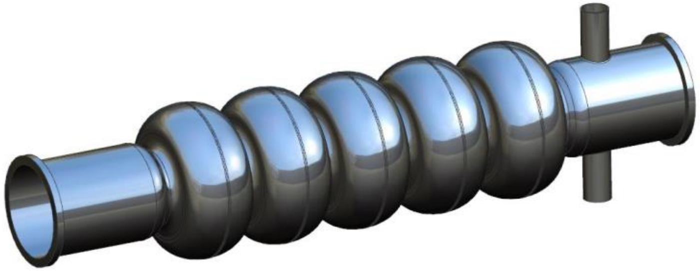
- Several CM types required, total ~50









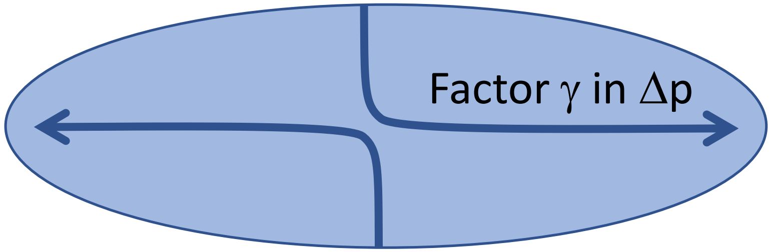


- SRF cavities, 197-1773 MHz
  - High RRR, fine grain, Niobium sheet cavities
  - 5 types, 3 elliptical and 2 non-elliptical, quantities ~ 4-20

Joe Preble, Kevin Smith, et al

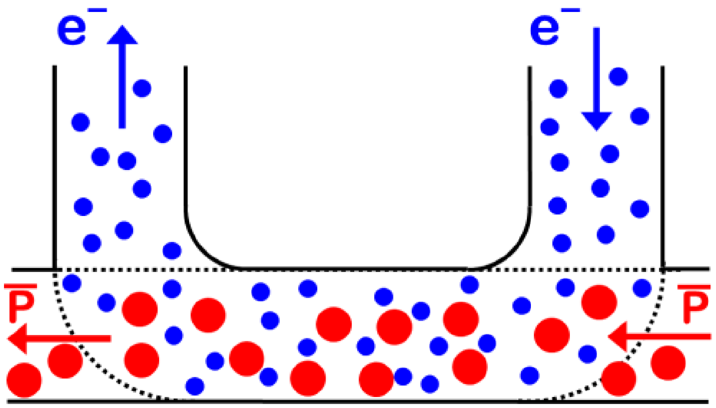
The need for beam cooling – IBS

- Intrabeam Scattering (IBS): Lorentz boosted Coulomb scattering inside bunches

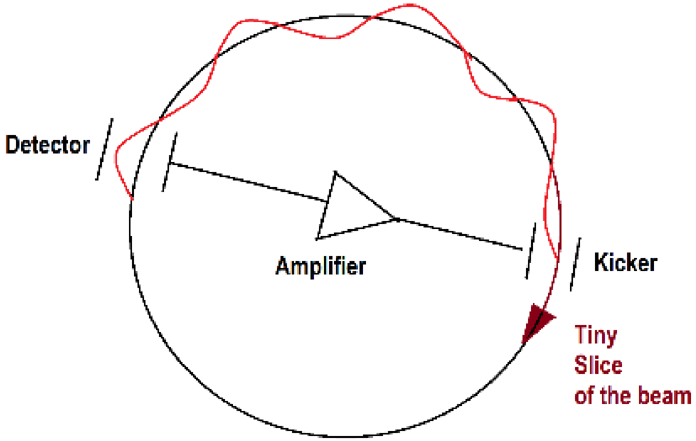


- Higher charge and smaller emittances increase IBS growth rate
  - IBS can be partially mitigated by reducing dispersion and increasing energy spread
- IBS rates for EIC parameters ~2 hour
- Beam cooling methods needed to counteract IBS

Conventional cooling methods and EIC



Electron cooling



Stochastic cooling

Cooling time:

$$\tau \propto \frac{A}{Z^2}\frac{\gamma^2}{4\pi r_p r_e n_e c\,\eta\Lambda_c}\left(\frac{\gamma\varepsilon_n}{\beta_c}+\sigma_p^{\,2}\right)^{3/2}$$

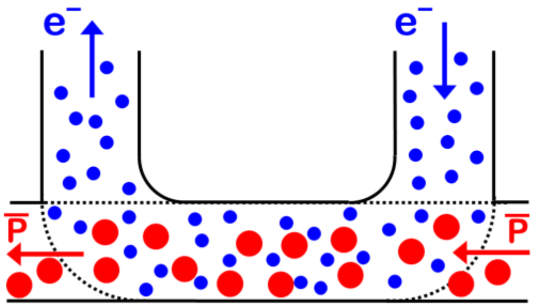
$$\tau \propto C/\sigma_z * N/\Delta F$$

Cooling gets much weaker at higher energy

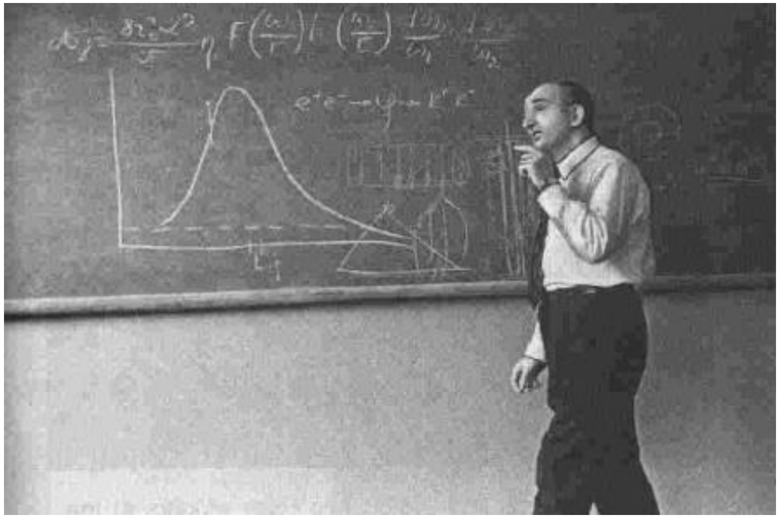
Cooling gets much weaker for denser bunch

- Either of these methods, if scaled to EIC parameters and stay within technically feasible range, will not provide sufficient cooling – they would be too weak
- For EIC “Strong” hadron cooling is needed – cooling that will provide sufficiently high cooling rate for proton bunches at EIC parameters

Electron Cooling



Electron cooling concept



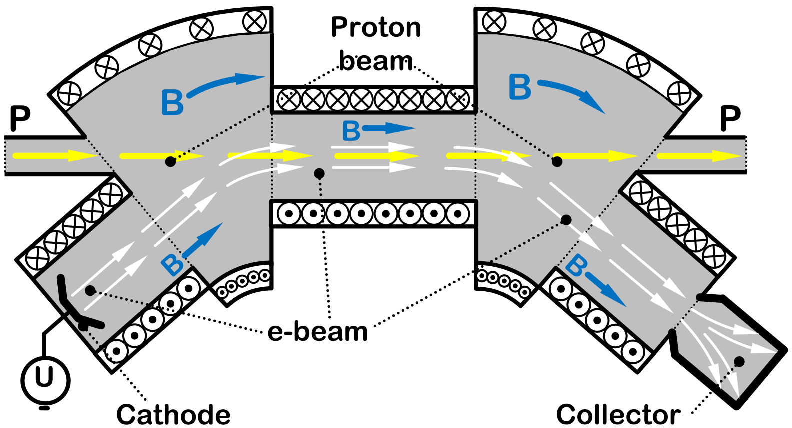
Budker G.I., Effective method of damping particle oscillations at proton antiproton storage rings, Atomic Energy 1967, v.22, №5, p.346

When electron cooling idea was first presented (1966), the common opinion of the community was – "brilliant idea, but unfortunately non-realistic"

However, less than a decade later the electron cooling was operational

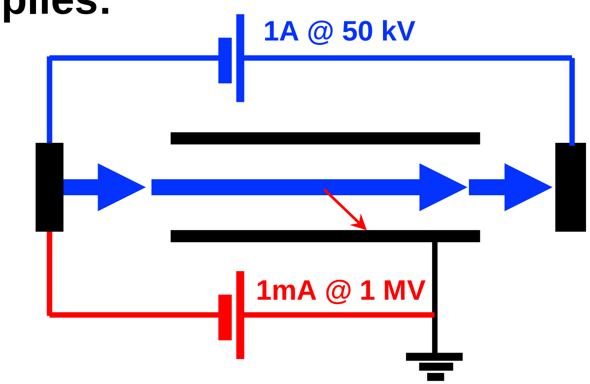
First e-cooler at INP, Novosibirsk, ~1974

Electron Cooling & Energy Recovery



Typical scheme of a standard electron cooler for low energy range (~several tens MeV of p energy)

- **Standard electron cooling use energy recovery**
  - **For example, if we need 1A @ 1MeV electron beam*, it does not mean we need 1 MW power supply**
- **Typical arrangements of e-cooler power supplies:**

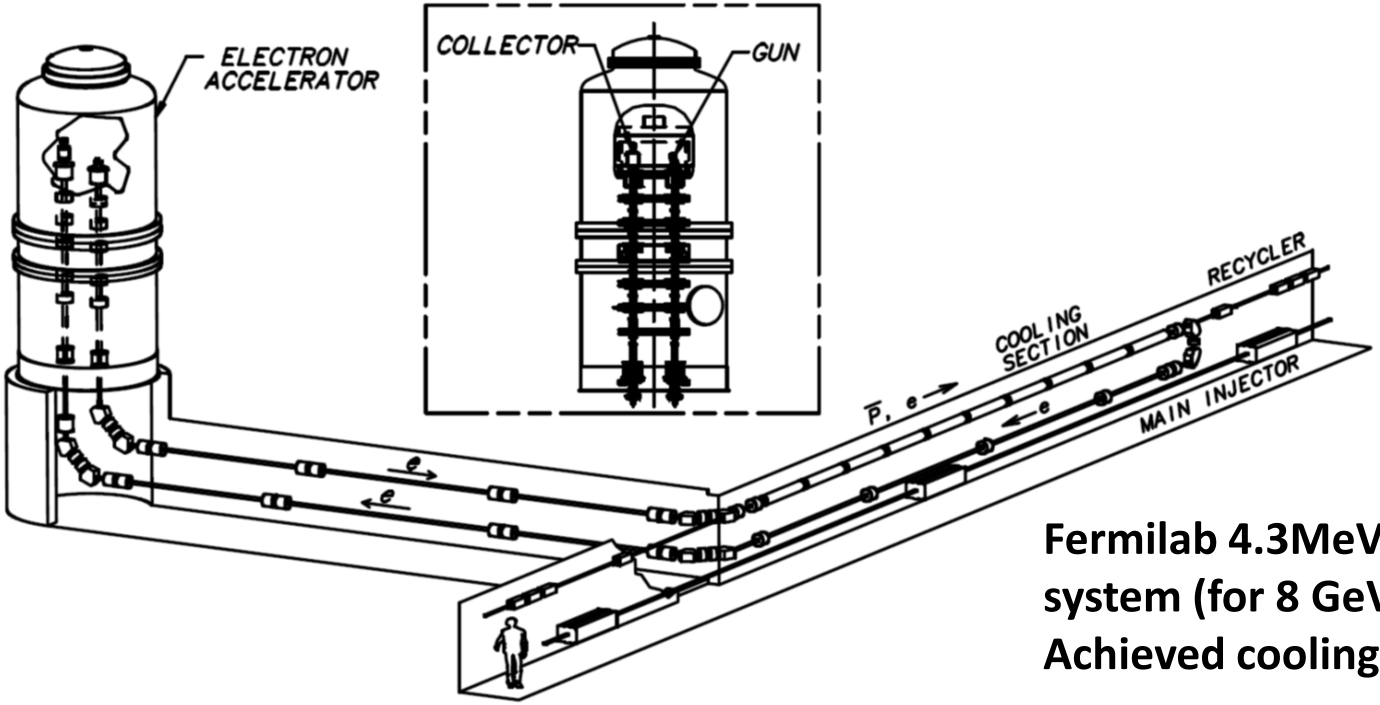


- **Losses of 1A e-beam due to interaction with p-beam or scattering are low**
- **Thus, power of 1MV power supply is defined by e-beam losses and can be much lower than 1MW, just 1kW in example above**

* Numbers are for illustration only

Taking Electron Colling to higher energy

- **Energy recovery is even more important for high energy electron cooling**



Fermilab 4.3MeV electron cooling system (for 8 GeV antiprotons) Achieved cooling times ~0.5 hours

- **The electron cooling time has a very unfavourable beam energy scaling ~$\gamma^{2.5}$**
- **Mitigating scaling dependence by a) increasing cooling section length; b) higher electron current – has practical limits**

- **For 41-257 GeV energy of EIC proton beam – standard electron cooling would be extremely challenging**

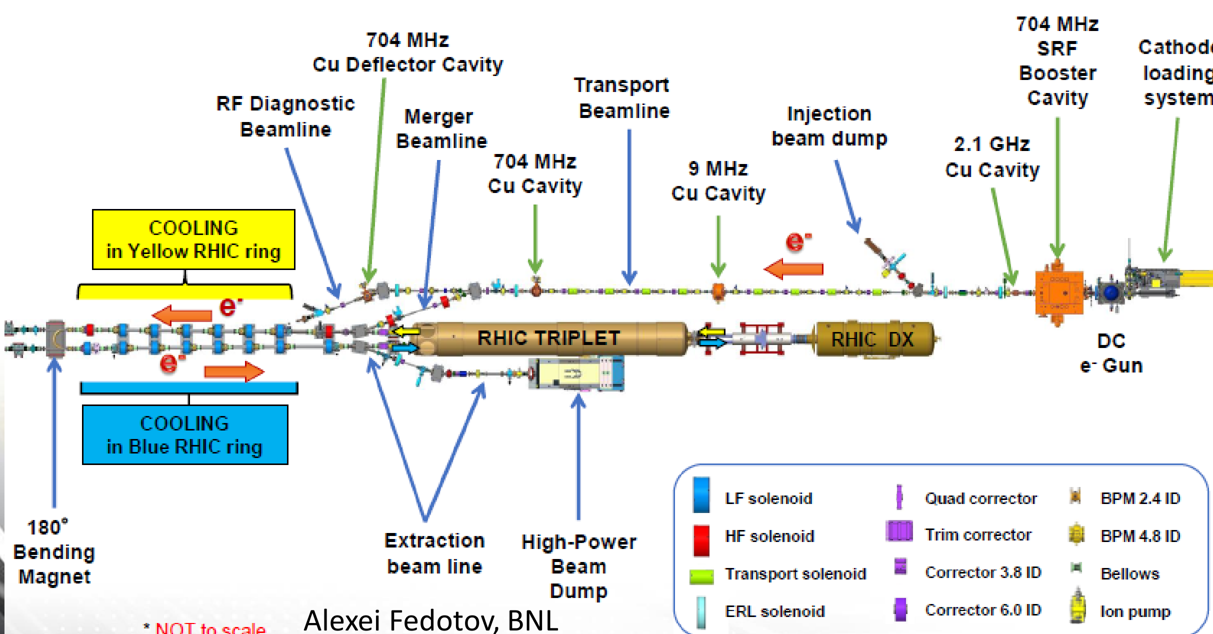
Getting electron cooling to higher energy

Low-Energy RHIC electron Cooler (LEReC) at BNL:

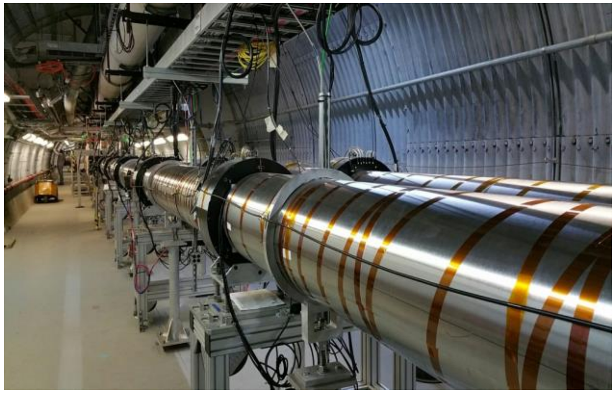
- First e-cooler based on the RF acceleration of e-beam (of up to 2.6 MeV energy)
- **Observation of first cooling using bunched electron beam on April 5, 2019**
- LEReC will be used in RHIC Beam Energy Scan II for Low energy ($\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity
- Cooling using bunched electron beam produced with RF acceleration is new, and opens the possibility of electron cooling at high beam energies

LEReC Accelerator

(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)



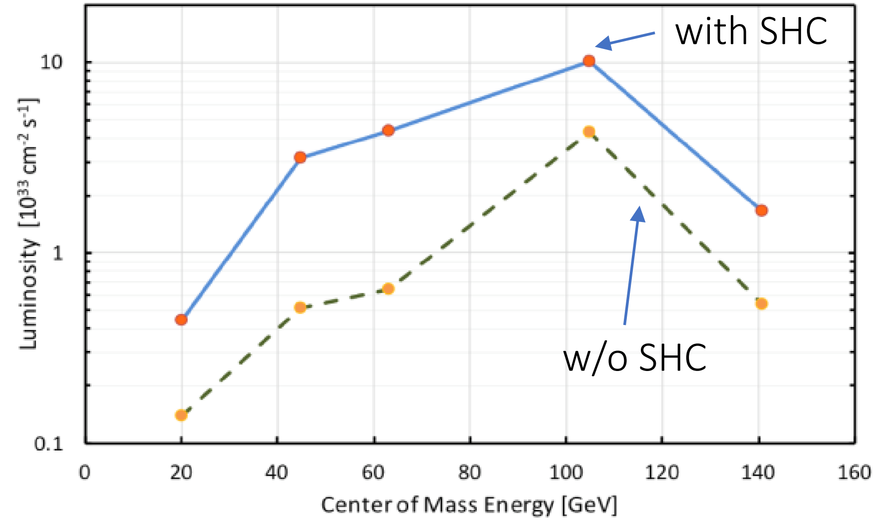
Alexei Fedotov, BNL



LEReC approach can be used for EIC as injection energy pre-cooler.
However, at collision energy enhanced/strong cooling mechanism is needed.

EIC cooling requirements

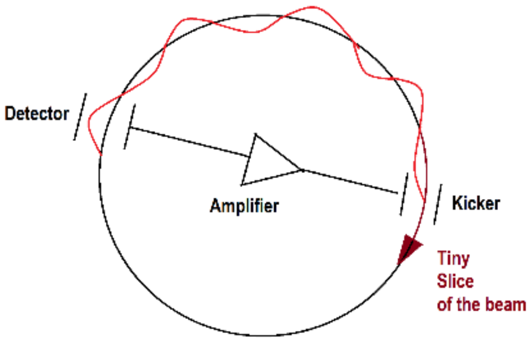
- Luminosity of lepton-hadron colliders in the energy range of the EIC benefits strongly (factor ≈ 3-10) from cooling the hadron's transverse and longitudinal beam emittance.
- Cool the proton beam at 275 GeV and 100 GeV ; 41 GeV cooling under study.
- IBS longitudinal and transverse(h) growth time is 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 0.3 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)

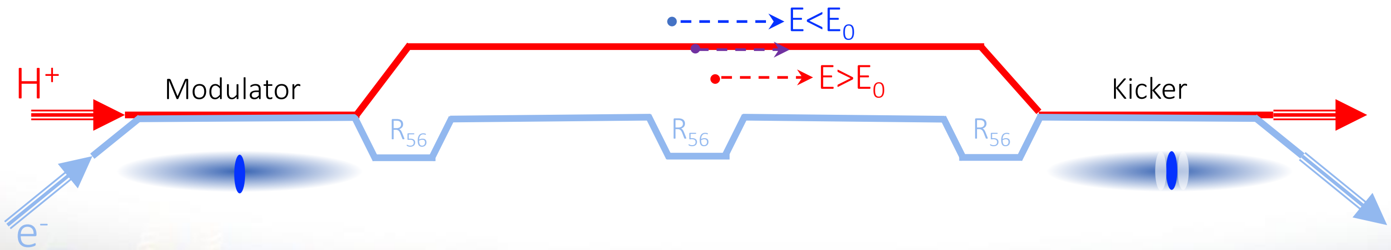
Like in stochastic cooling, tiny fluctuations in the hadron beam distribution (which are associated with larger emittance) are detected, amplified and fed back to the hadrons thereby reducing the emittance in tiny steps on each turn of the hadron beam

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



For high energy protons, a large bandwidth (tens of THz) is required:
➔ Using an electron beam to detect fluctuations, to amplify and to kick.

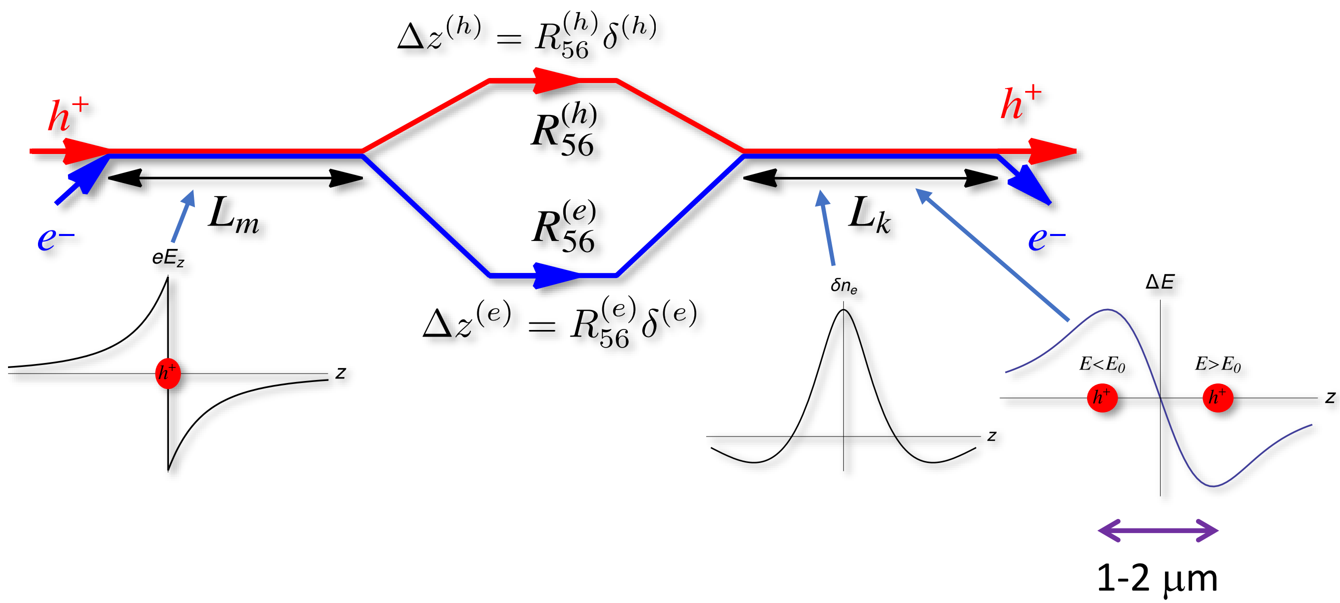
CDR baseline Amplification: micro-bunched amplifier (MBEC)



We acknowledge there are other three amplification schemes

CeC pickup(modulator) and kicker

Coherent electron cooling is a variant of the stochastic cooling with the operational frequency range raised from ~GHz to tens of THz [Ref].

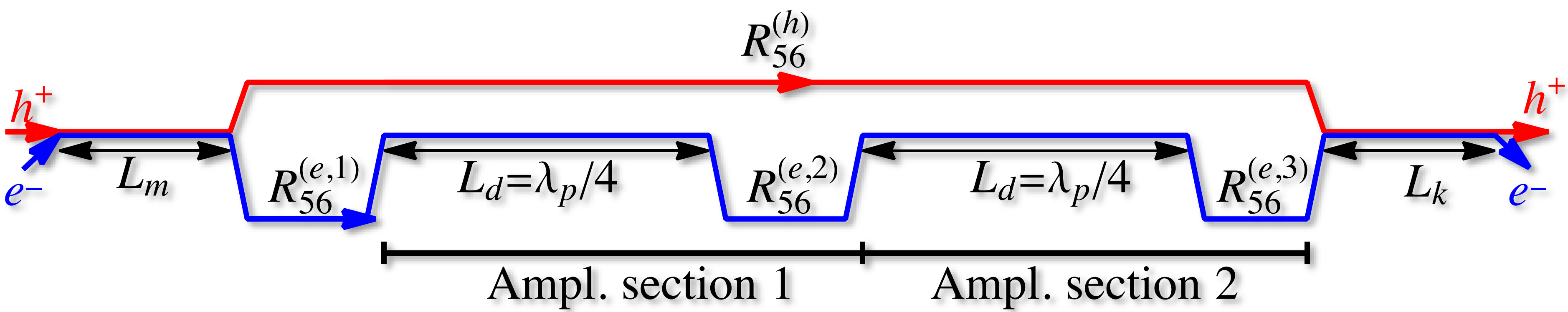


- The pickup and the kicker are implemented via the Coulomb interaction of the hadrons and electrons, $\gamma_e = \gamma_h$. Without amplification, the cooling rate is too small - the signal (the imprint in the e-beam) should be amplified.
- The extent of the longitudinal wake is 1-2 microns – sets requirement on the path length match when e and p bunches are merged in the kicker

Ref: Derbenev, AIP Conf. Proc. **253**, 103 (1992); Litvinenko, Derbenev. PRL, **102**, 114801 (2009)

CeC amplification

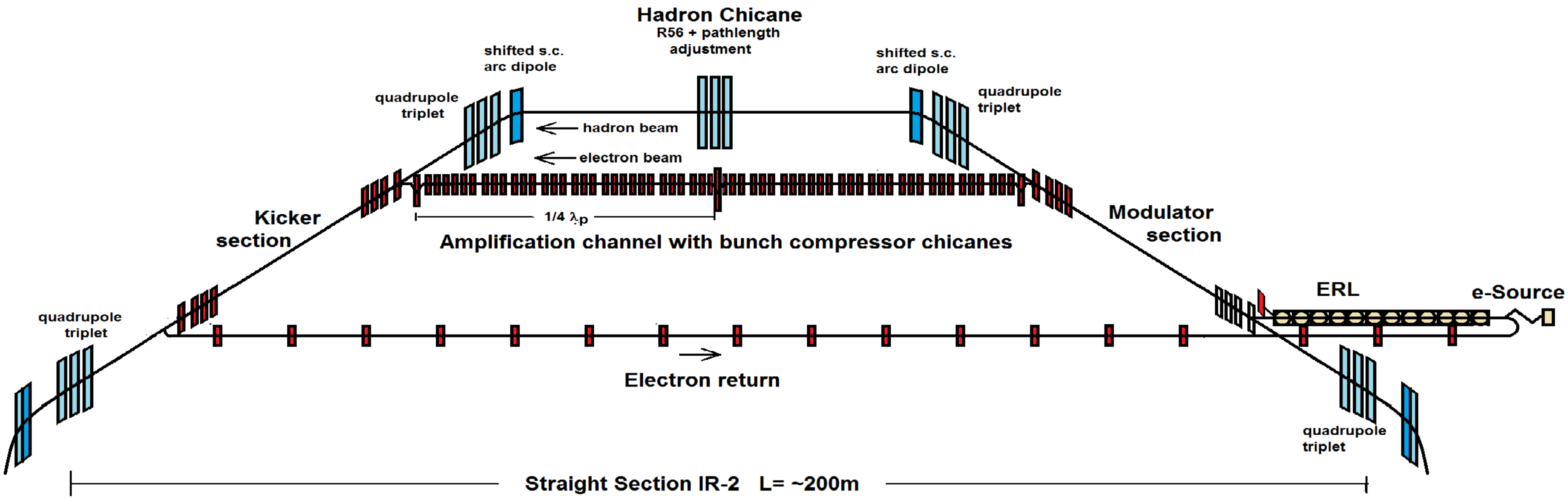
Micro-bunched amplification (well known from FELs) is the effect selected for CeC amplification - MBEC (micro-bunched electron cooling)



One stage of amplification is achieved through a combination of a drift of length=$\frac{1}{4}$ plasma oscillation length followed by a chicane. For the nominal EIC parameters, one stage amplification gain $G \approx \sigma_\delta^{-1}\sqrt{I_e/\gamma I_A} \approx 10 - 20$. The effective bandwidth of this amplifier is tens of THz.

EIC Strong Hadron Cooling

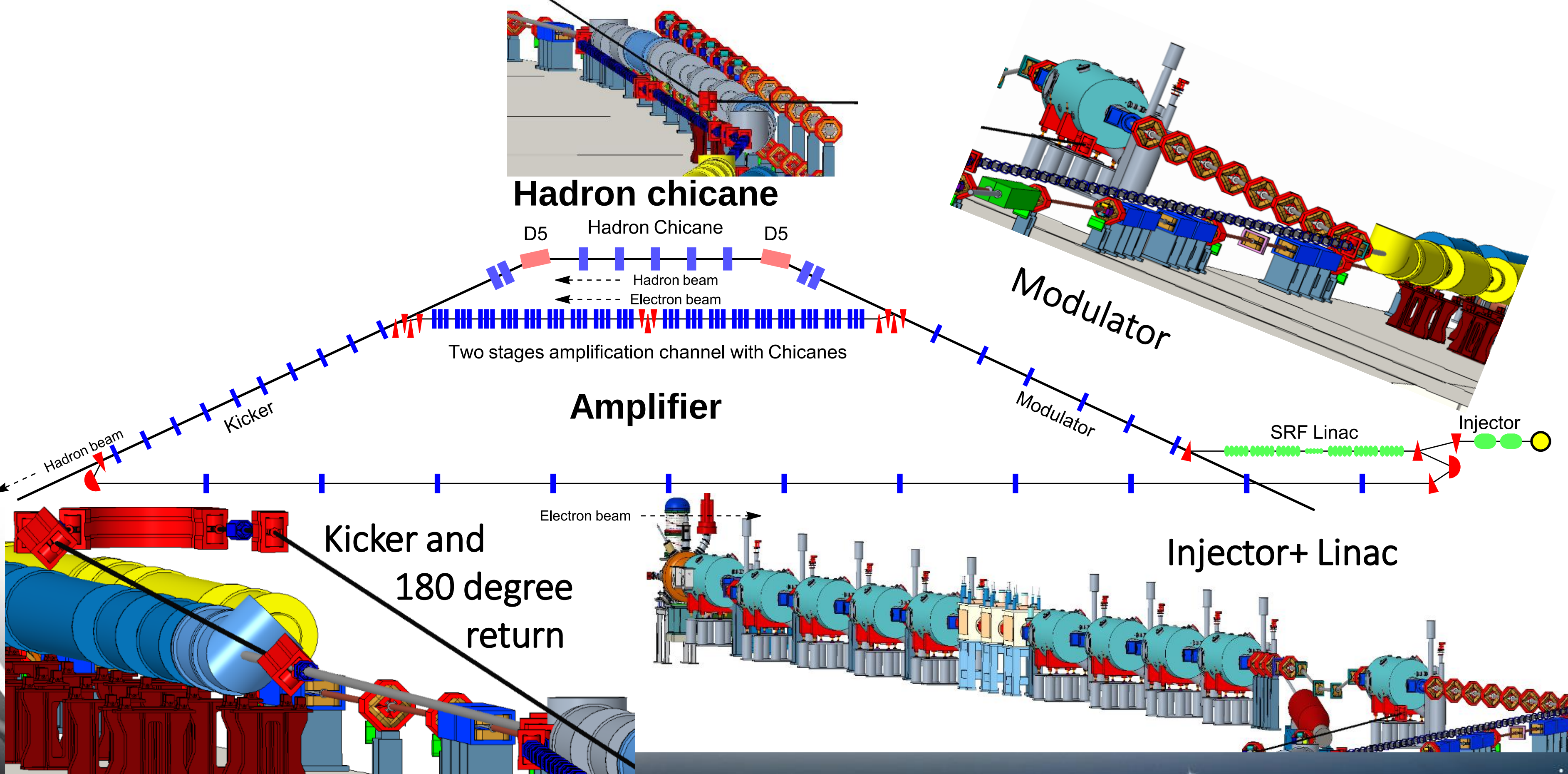
Coherent Electron Cooling with μ-bunching amplification



- 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
  - Wake extent 1-2 μm => path length accuracy and stability must be sub-micron
- Electron beam must be **extremely "quiet"** (less than twice the shot noise)
  - Avoid amplification of "shot noise", no substructure in electron beam

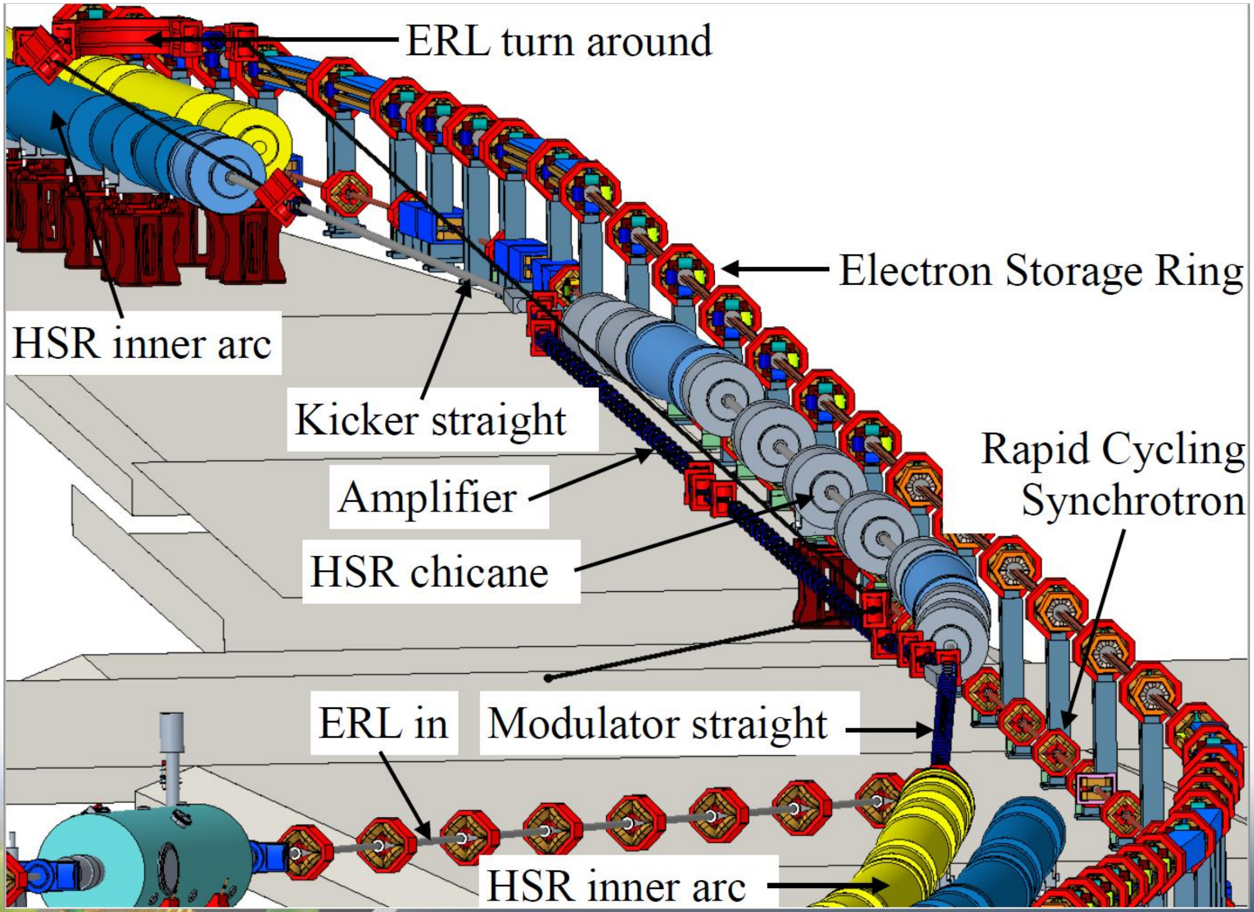
EIC Strong Hadron Cooling

- Cooling theory and simulations, from 1D models to 3D models and simulations
- Good progress in electron acceleration, beam-transport
- Started studies of SHC integration with low energy pre-cooler (LEReC type)
- CeC Proof of Principle experiment in progress, a lot of valuable knowledge gained, giving us confidence in design of SHC beamlines



EIC Strong Hadron Cooling

- Cooling theory and simulations, from 1D models to 3D models and simulations
- Good progress in electron acceleration, beam-transport
- Started studies of SHC integration with low energy pre-cooler (LEReC type)
- CeC Proof of Principle experiment in progress, a lot of valuable knowledge gained, giving us confidence in design of SHC beamlines



Electron-Ion Collider

Strong Hadron Cooling Technical Review

From the committee report

February 2-3, 2022

Review Committee:

Ralph Assmann (DESY), Hans Braun (PSI), David Douglas (JLAB-retired), Valeri Lebedev (JINR/FNAL), Patric Muggli (MPI Munich), Sasha Zholents (ANL)

The strong hadron cooling for the EIC is an outstanding accelerator physics challenge and the team is congratulated on the progress made and the insights gained. Presentations were excellent and questions were clearly answered in a very competent manner. The committee thinks that the SHC project will be an outstanding flagship in the EIC project and in accelerator science and technology overall. The committee looks forward to the CDR and the implementation of the project.

1) Is the project pursuing a good strategy to arrive at a viable design and implementation of strong hadron cooling for the Electron Ion Collider?

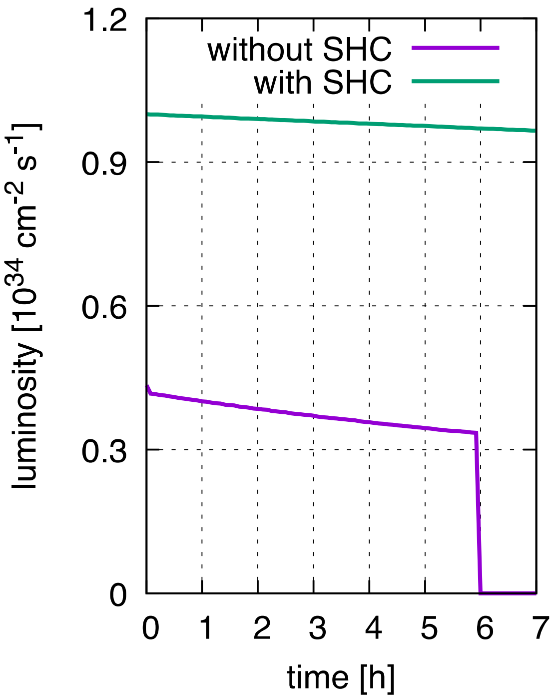
The strategy to concentrate on the most promising option and to prepare a CDR for this option is good. Several challenging technical issues remain to be studied (see answers to Q3) and a more realistic performance estimate must be produced. No evident show-stopper has been identified and efforts should be pursued and even intensified.

EIC Requires Strong Hadron Cooling (SHC) to Deliver Science Program

- **Ultimate performance of the EIC is required to deliver the full EIC physics program and answer key NAS science questions**
- The Analysis of Alternatives has concluded that **SHC is the best value solution to achieve ultimate EIC performance**
- Over the last years good progress in theory, supported by experiments, have **significantly advanced understanding of SHC, strengthening its technical maturity**
- Although SHC is not required to achieve the threshold and objective KPP, having it as part of the EIC project will allow the EIC to attain its **Ultimate Performance Parameters**

EIC needs beam cooling for high performance

- Performance metric: **average luminosity**
  - Intrinsic ion **emittance growth** limits achievable initial and average luminosity
  - Reduces average luminosity by at least factor 2-3 unless **counteracted by strong hadron cooling** (SHC)
  - Ultimate performance peak luminosity of 10^{34} cm^{-2} s^{-1} requires hadron beam cooling

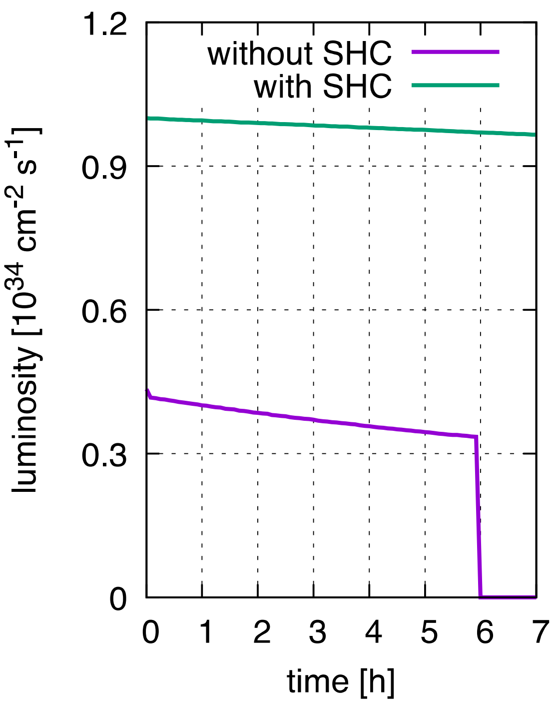


- SHC is **required to deliver the EIC physics program** in a reasonable time

Assumption: electron collision beam size matches ion beam evolution

EIC beam cooling solution is SHC

- EIC focusing SHC efforts on **coherent electron cooling**
  - **Coherent electron cooling is well-understood**, with elements independently verified
  - Would be similar **accelerator technology breakthrough** as going from incoherent light sources to free electron lasers
  - Long time scale to fully develop, large EIC science benefit and wider benefits
    - Coherent electron cooling benefits from ~10year of **R&D investment**, several experimental tests
- **SHC hardware is part of the EIC Project**
  - Supports the **full EIC science potential**
  - Coherent electron cooling **initial commissioning** is part of project scope
  - Provides time for further **experiment and simulation input**
  - Classical electron cooling is being evaluated by project as **risk mitigation**



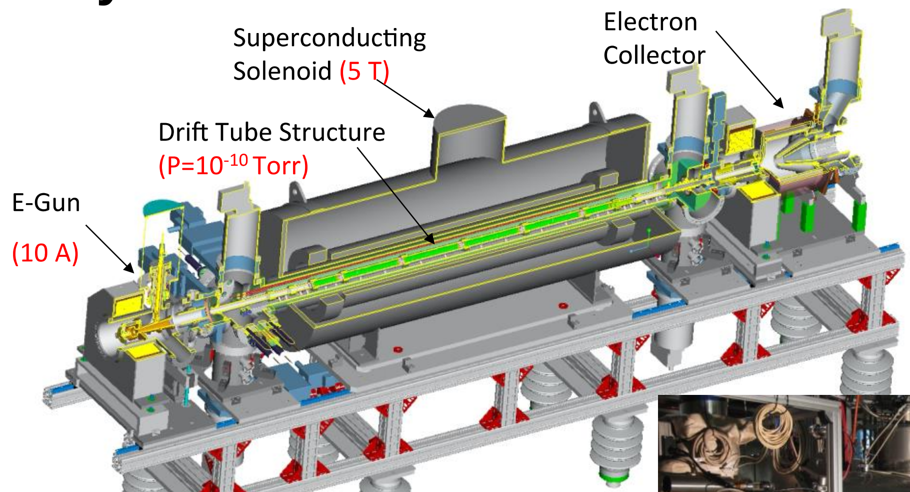
Assumption: electron collision beam size matches ion beam evolution

Ion source

- 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

Ion Pairs in the RHIC Complex

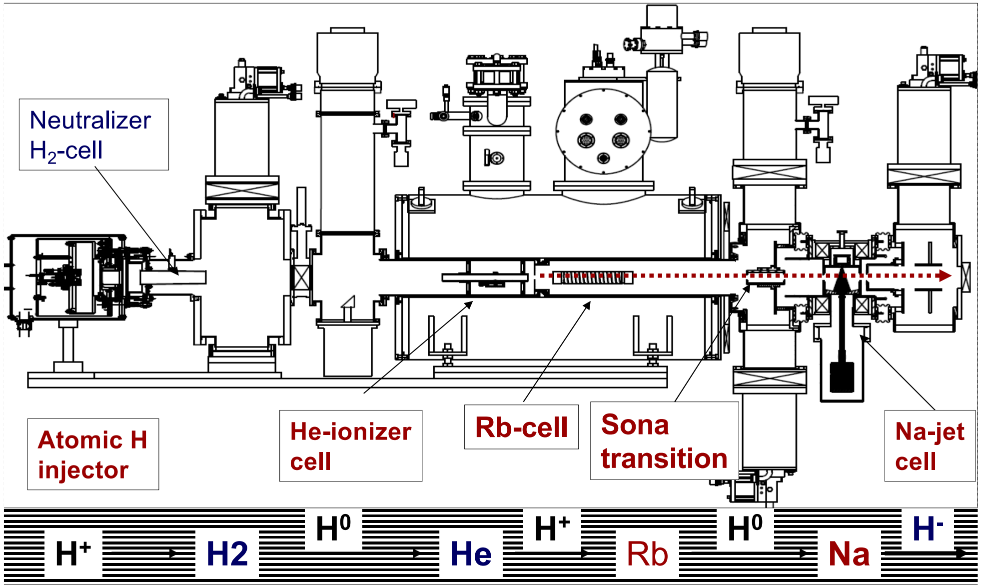
Zr-Zr, Ru-Ru	(2018)
Au-Au	(2016)
d-Au	(2016)
p-Al	(2015)
h-Au	(2015)
p-Au	(2015)
Cu-Au	(2012)
U-U	(2012)
Cu-Cu	(2012)
D-Au	(2008)
Cu-Cu	(2005)



Parameter		RHIC EBIS
Max. electron current	I_{el}=	10 A
Electron energy	E_{el}=	20 keV
Electron density in trap	j_{el}=	575 A/cm^2
Length of ion trap	L_{trap}=	1.5 m
Ion trap capacity	Q_{el}=	1.1x10^{12}
Ion yield (charges)	Q_{ion}=	5.5x10^{11} (10 A)
Yield of ions Au^{32+}	$N_{Au}{}^{32+}$=	3.4x10^9

$N = \kappa * I_e * L_{trap} * E_e^{-0.5}$

Optically pumped polarized ion source (OPPIS)

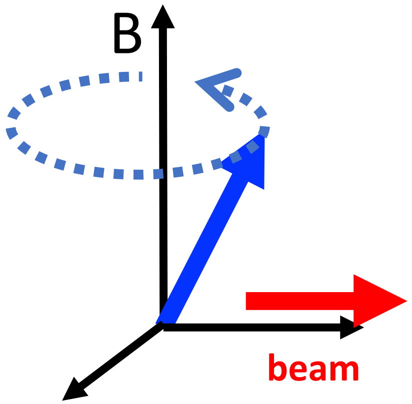


- Used for RHIC p↑+p↑ program from 2000
- Protons pickup polarized electrons in an optically pumped Rb vapor cell
- Electron polarization of H atoms is transferred to protons in a magnetic field reversal region (Sona-transition)
- H^- ions are produced then by passing through Na-cell
- Polarized protons are obtained by charge exchange injection of H^- into the Booster
- Several upgrades and modifications over years increasing polarization and intensity

up to 84% polarization
reliably 0.5 - 1.0 mA (max 1.6 mA)
up to $1 \cdot 10^{12}$ H^-/pulse polarized H^- ions

Polarization preservation

- Spin motion in accelerator: spin vector precesses around its guiding field along the vertical direction



- Spin tune Qs: number of precessions in one orbital revolution: Qs = γG
  - Anomalous g- factor for proton G= 1.793

Depolarization due to resonances:

Imperfection resonances:

Qs = n

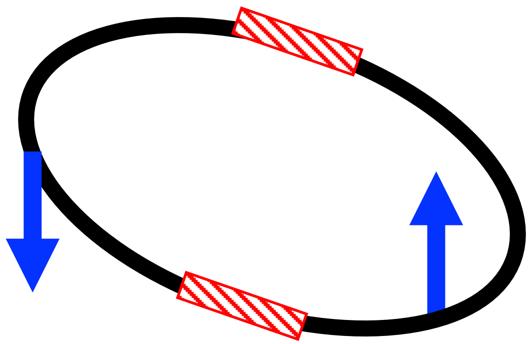
Intrinsic resonances:

Qs = nP +- Qy

Here n – integer, P – number of superperiods

Polarization preservation – Siberian snakes

- Siberian snakes – special (e.g. helical) magnets that rotate spin (preserving orbit outside)

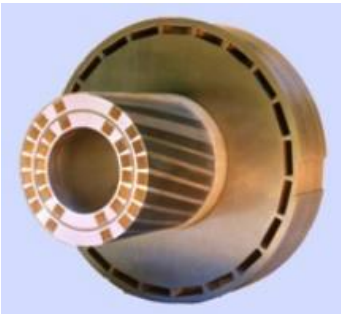


Polarization kinematics of particles in storage rings.
Ya.S. Derbenev, A.M. Kondratenko (Novosibirsk, INP) Jun 1973.
Zh.Eksp.Teor.Fiz.64:1918-1929,1973

- Full Siberian snakes flip spin 180 degrees. Two full snakes make Qs = 1/2
  - Two full snakes control:
    - Intrinsic resonances
    - Imperfection resonances
- Partial Siberian snake
  - Break coherent build up of perturbation of spin
    - Some control of imperfection resonances

Polarization preservation – Siberian snakes

- Siberian snakes in RHIC – two full snake than make Qs = ½

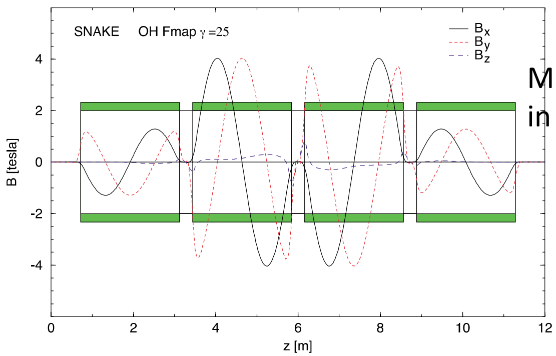


RHIC snake: 4T, 2.4m/snake, 360° twist, 100mm aperture

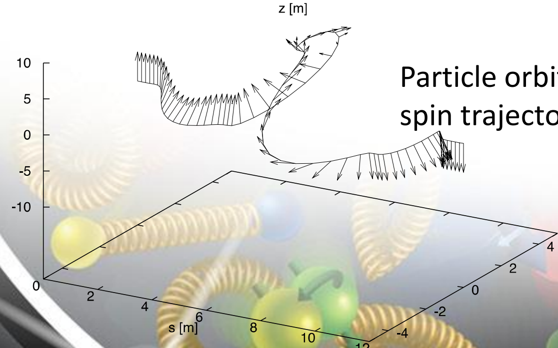
First Polarized Proton Collisions at RHIC. T, Roser, et al,
AIP Conference Proceedings 667, 1 (2003)

Warm partial AGS Snake

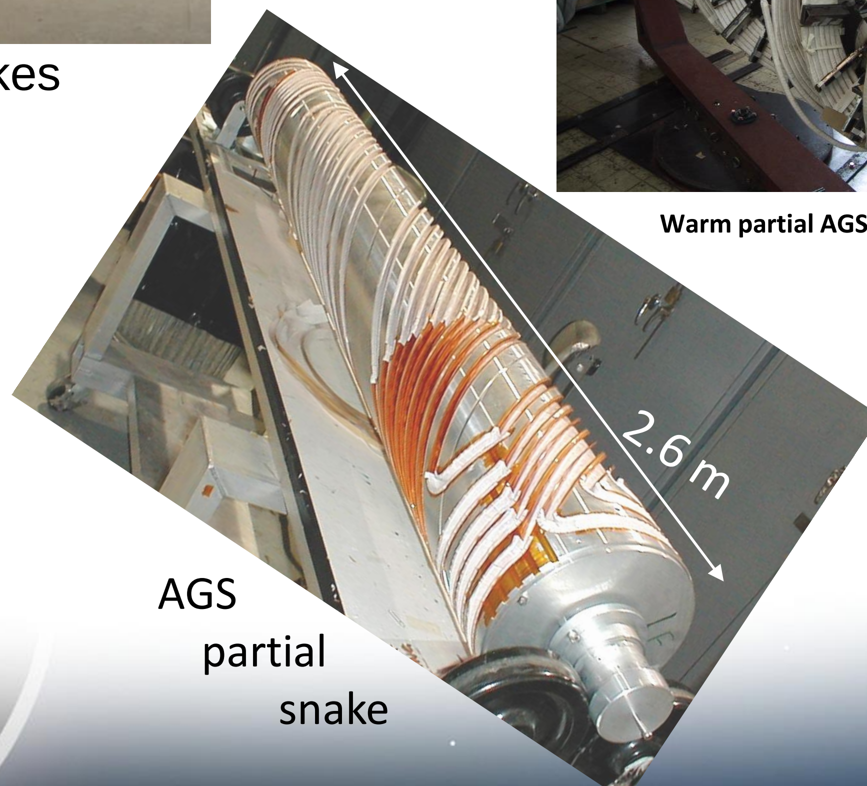
- AGS – partial Siberian snakes



Magnet field in Snake



Particle orbit and spin trajectory



AGS partial snake

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

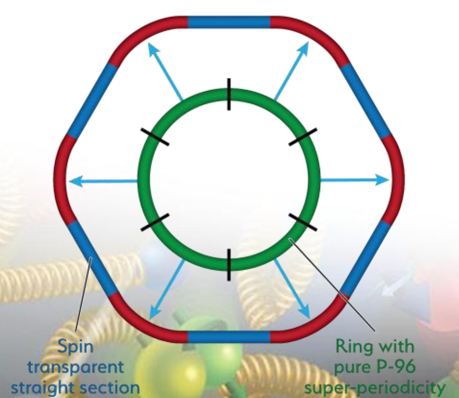
18 GeV Rapid Cycling Synchrotron enables high electron polarization in the electron storage ring

- 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

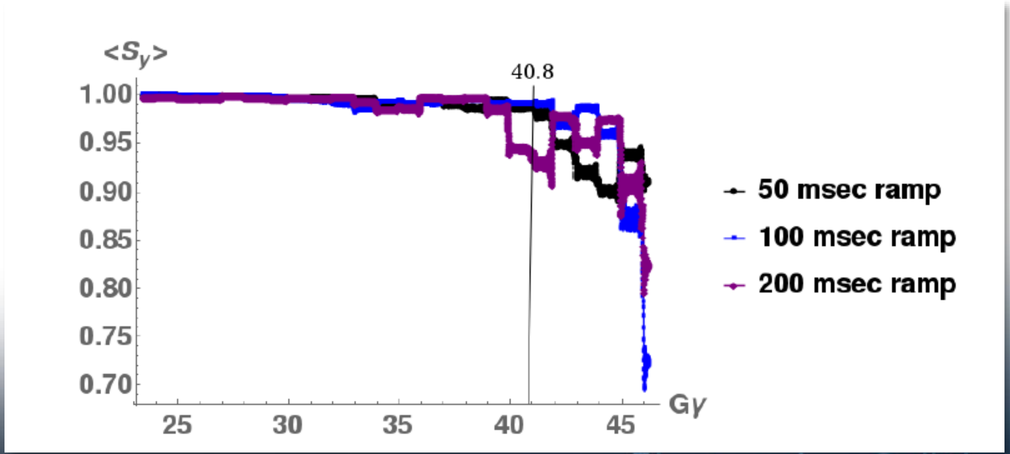
➔ No depolarizing resonances during acceleration 0.4-18 GeV
no loss of polarization on the entire ramp up to 18 GeV (100 ms ramp time, 2 Hz)

RCS Design

Rapid Cycling Electron Synchrotron



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 refilled within minutes with RCS cycling rate of 2Hz
- Need both polarization directions present at the same time

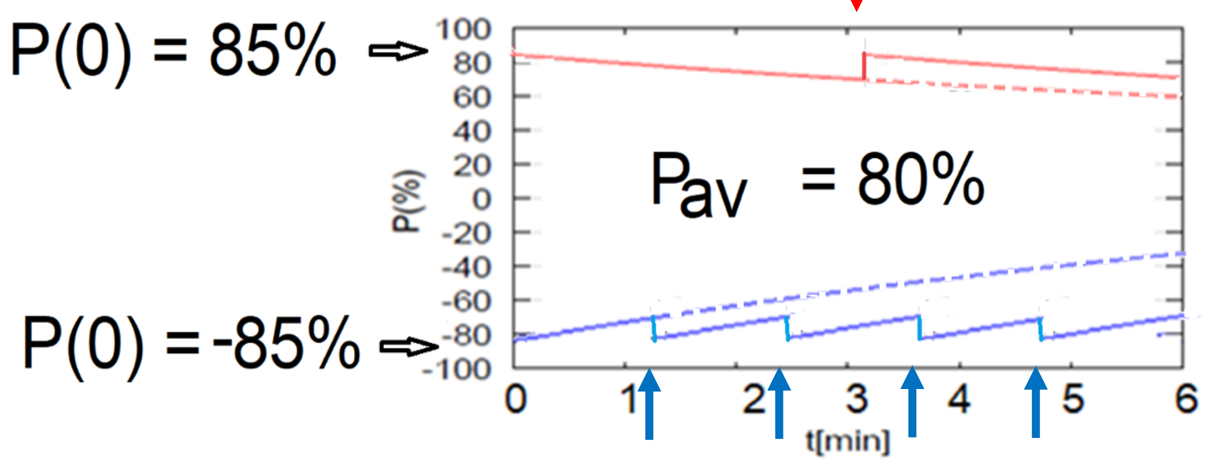
B P

Refilled every 1.2 minutes

B P

Refilled every 3.2 minutes

Re-injection



P_∞= 30% (conservative)

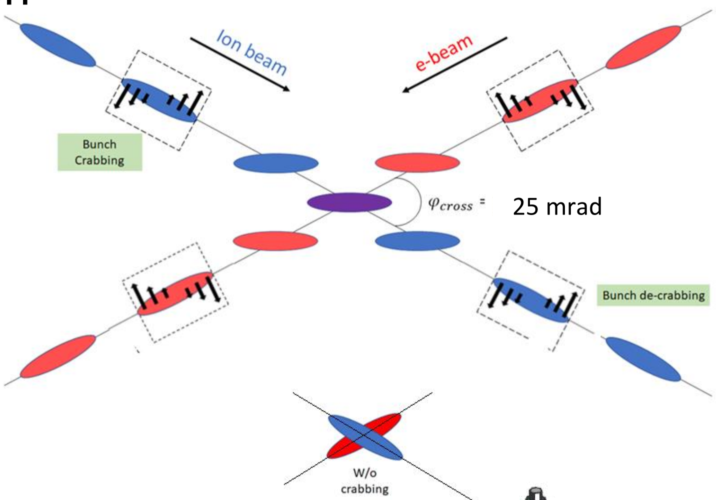
Re-injections

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

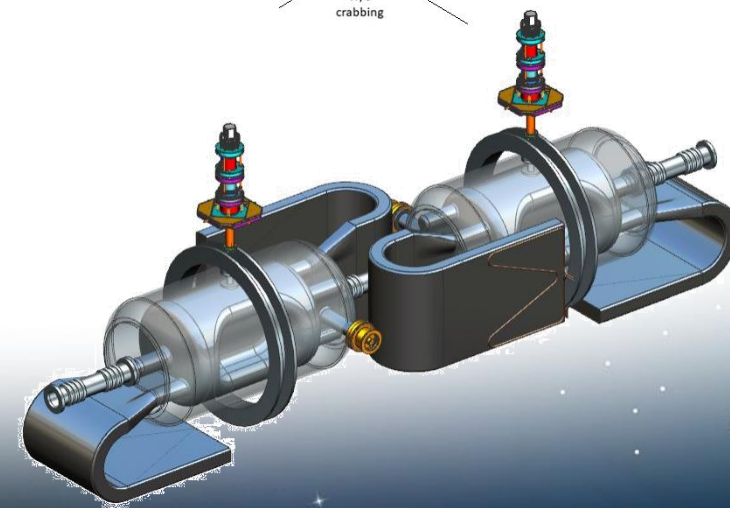
- **However**, crossing angle causes
  - Low luminosity
  - Beam dynamics issues

- **avoided by Crab Crossing**



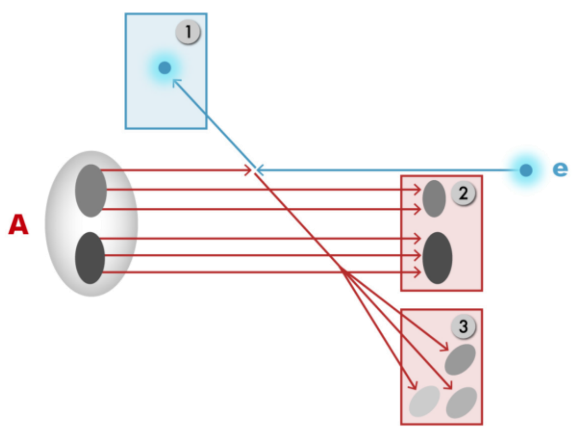
Then :
  - Effective head-on collision restored
  - Beam dynamic issues resolved

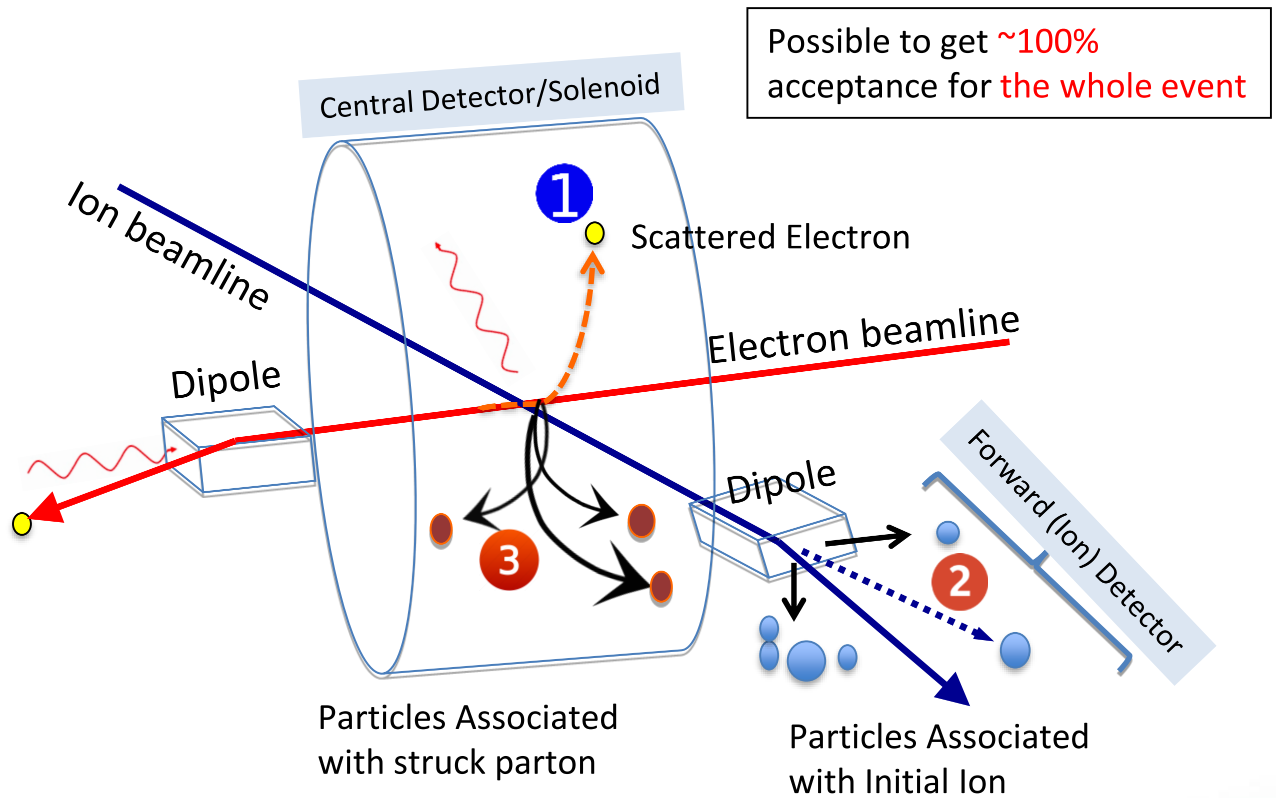
- RF resonator (crab-cavity) prototypes built and tested with proton beam in the CERN-SPS
  - The EIC crab-cavity need large waveguide ports to allow the trapped modes to escape



Interaction Region Concept

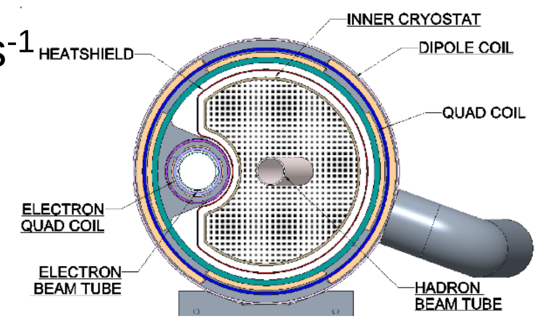
EIC detector must accept and measure *all* particles from the interaction. (Unlike existing collider detectors!)

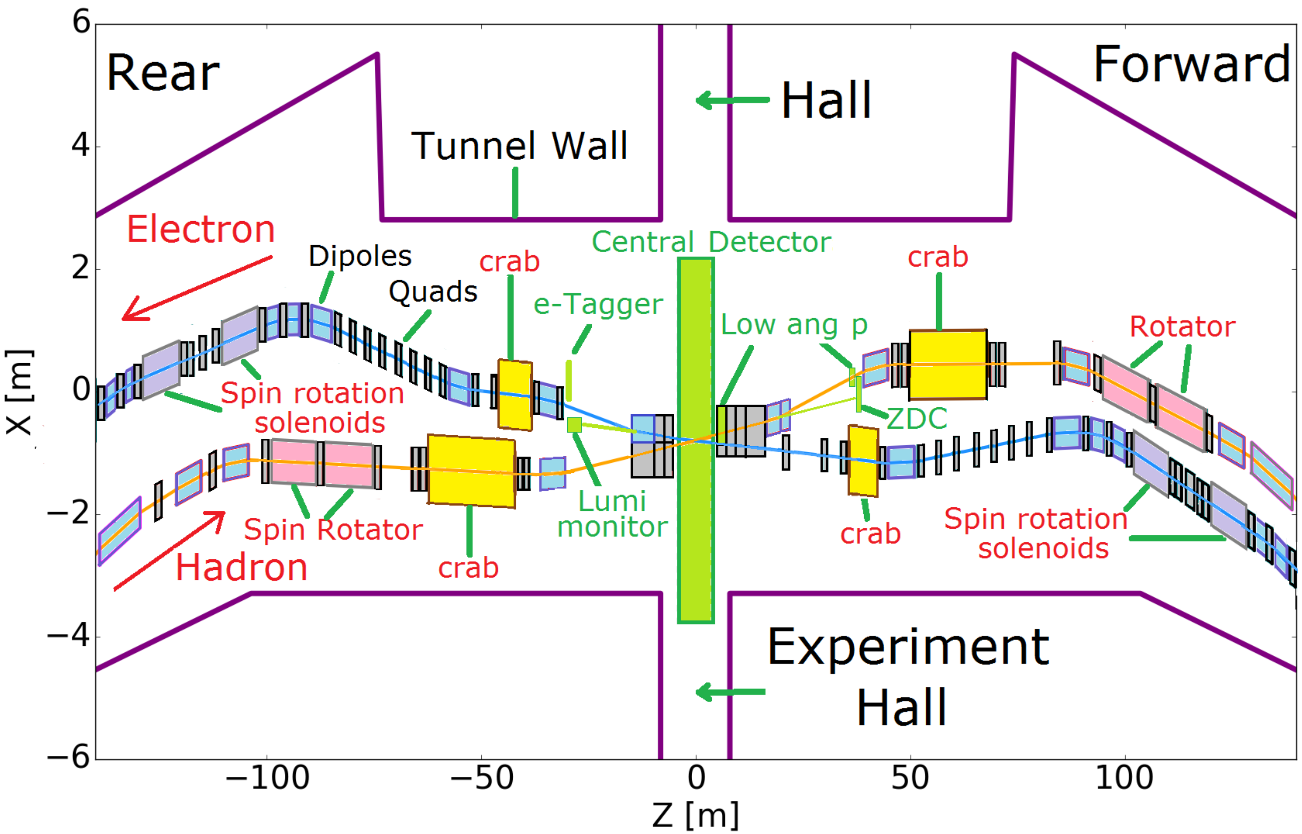


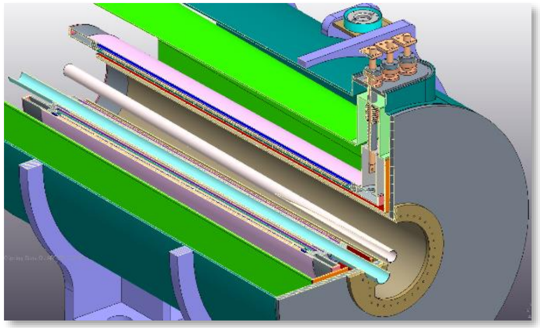


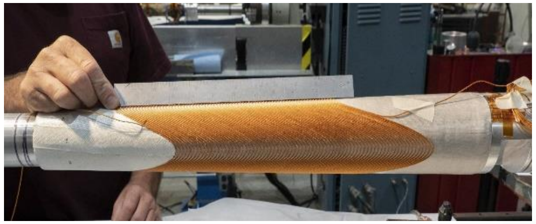
Interaction Region

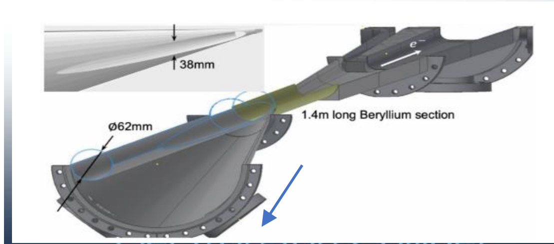
- Beam focused to $\beta_y \leq 5$ cm @ $\sigma_y = 5\ \mu$m, => $L = 10^{34}\ cm^{-2}\ s^{-1}$
- Manageable IR chromaticity and sufficient DA
- Full acceptance for the colliding beam detector
- Accommodates crab cavities and spin rotators
- Synchrotron radiation and impedance manageable
- Conventional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

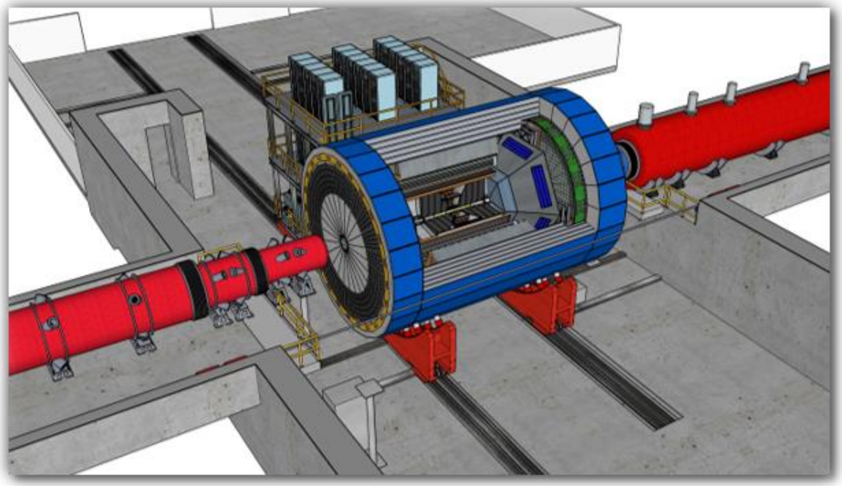


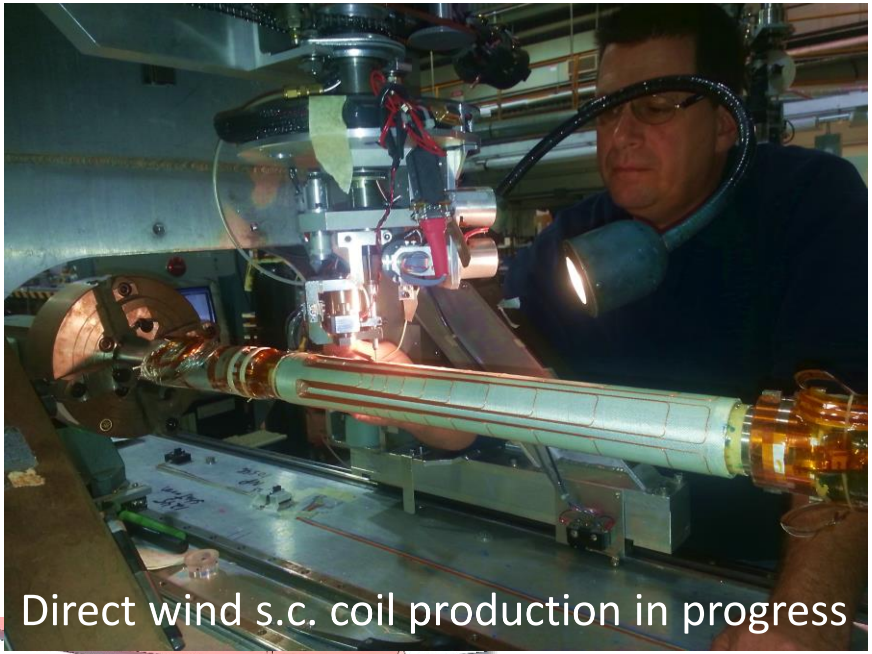




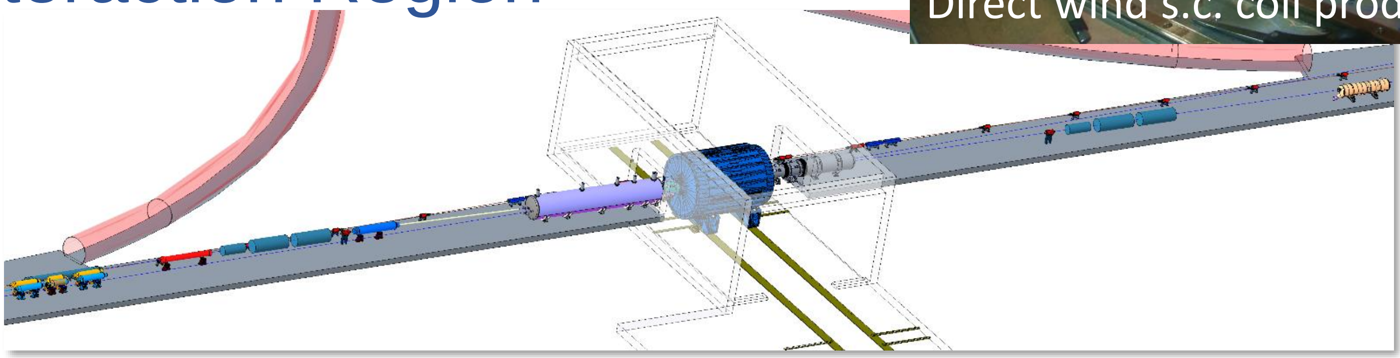


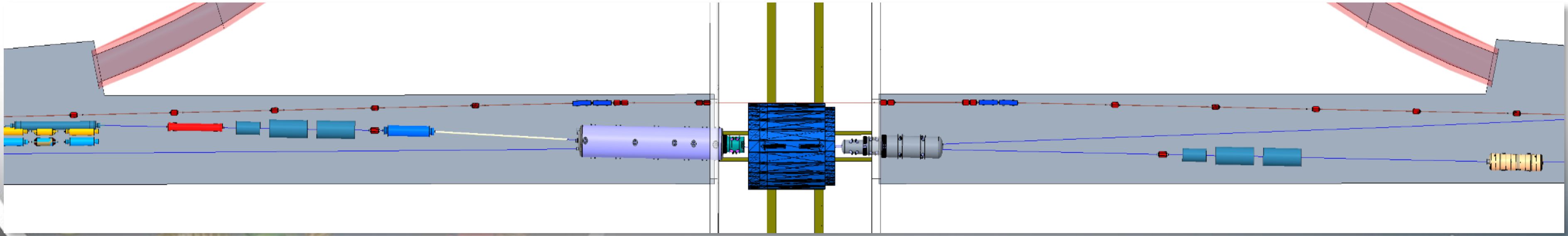






Interaction Region

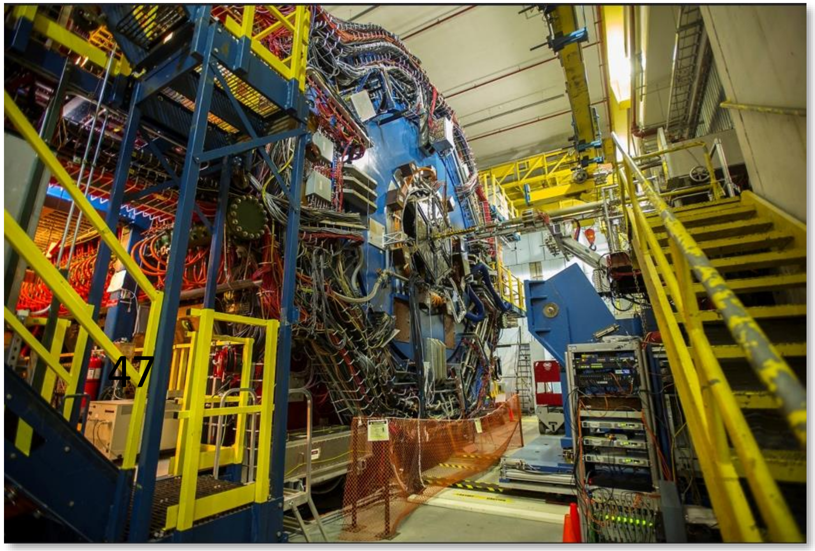




The EIC will benefit from two large existing detector halls in IR 6 and IR 8

- 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)

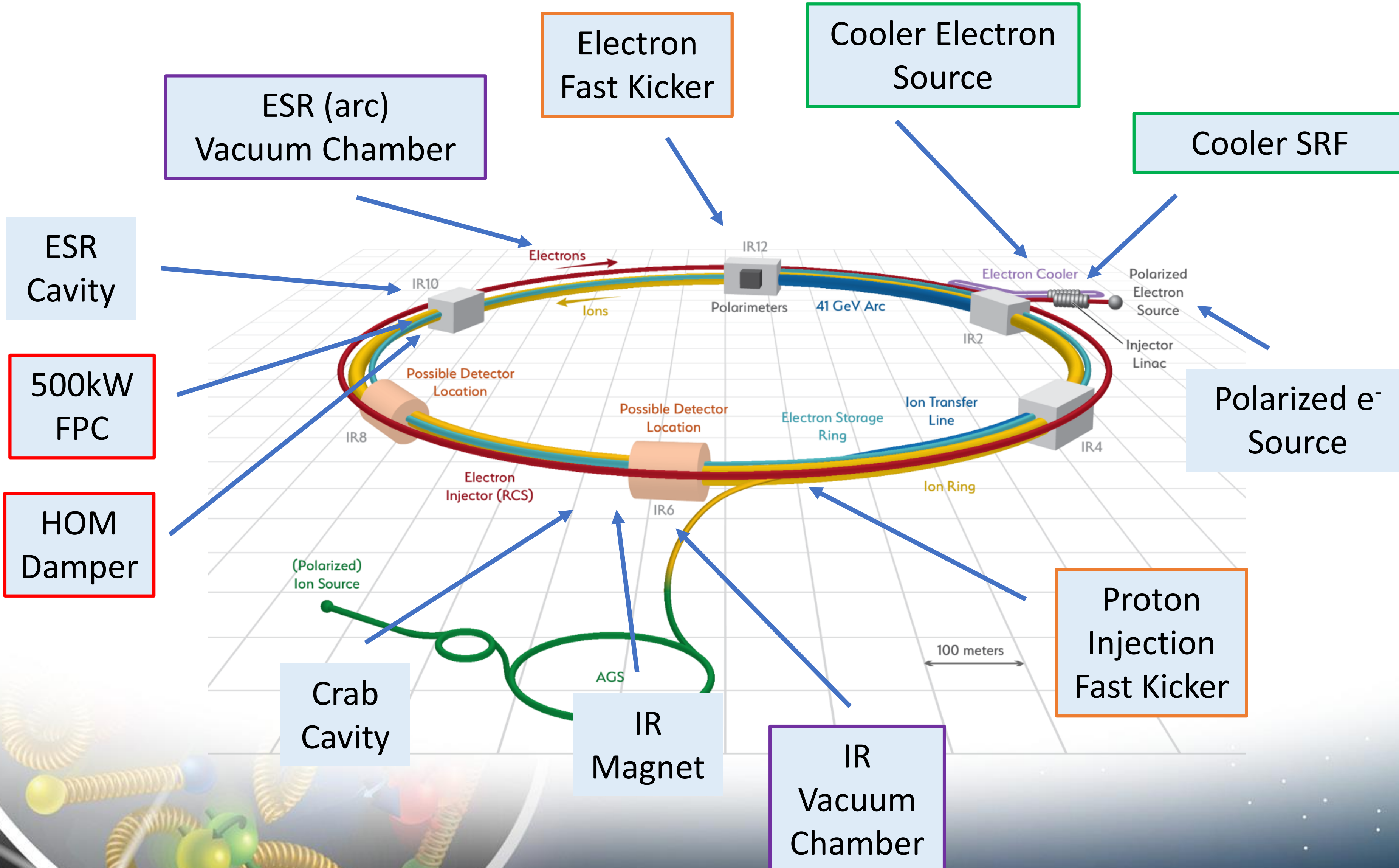


IR 6 detector hall with STAR detector

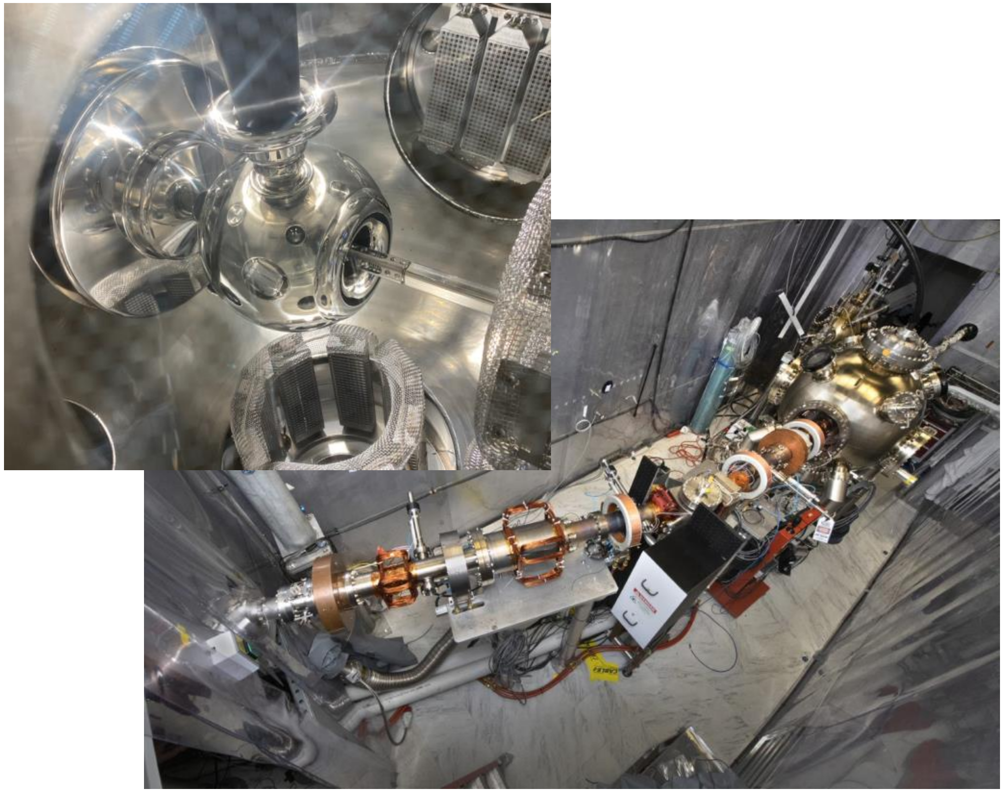
- Both IRs can be implemented simultaneously in the EIC lattice and be accommodated within beam dynamics envelope
- 2 IR's: laid out <u>identically</u> or <u>optimized for maximum luminosity at different</u> E_{CM}

  (Second IR and second detector are not in the project scope)

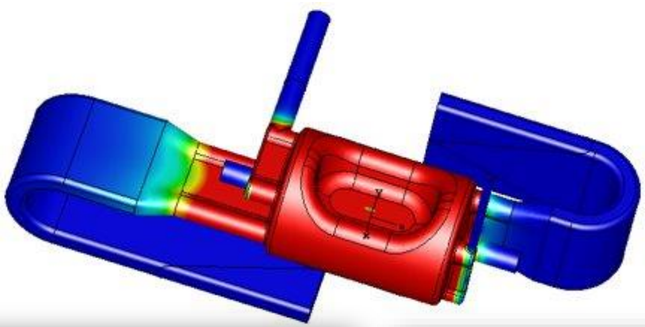
EIC Accelerator R&D Scope



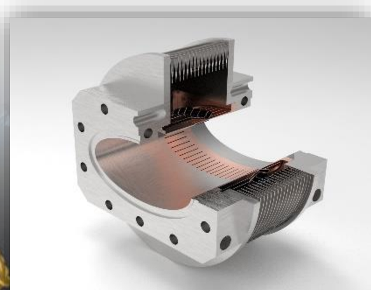
R&D Highlights



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

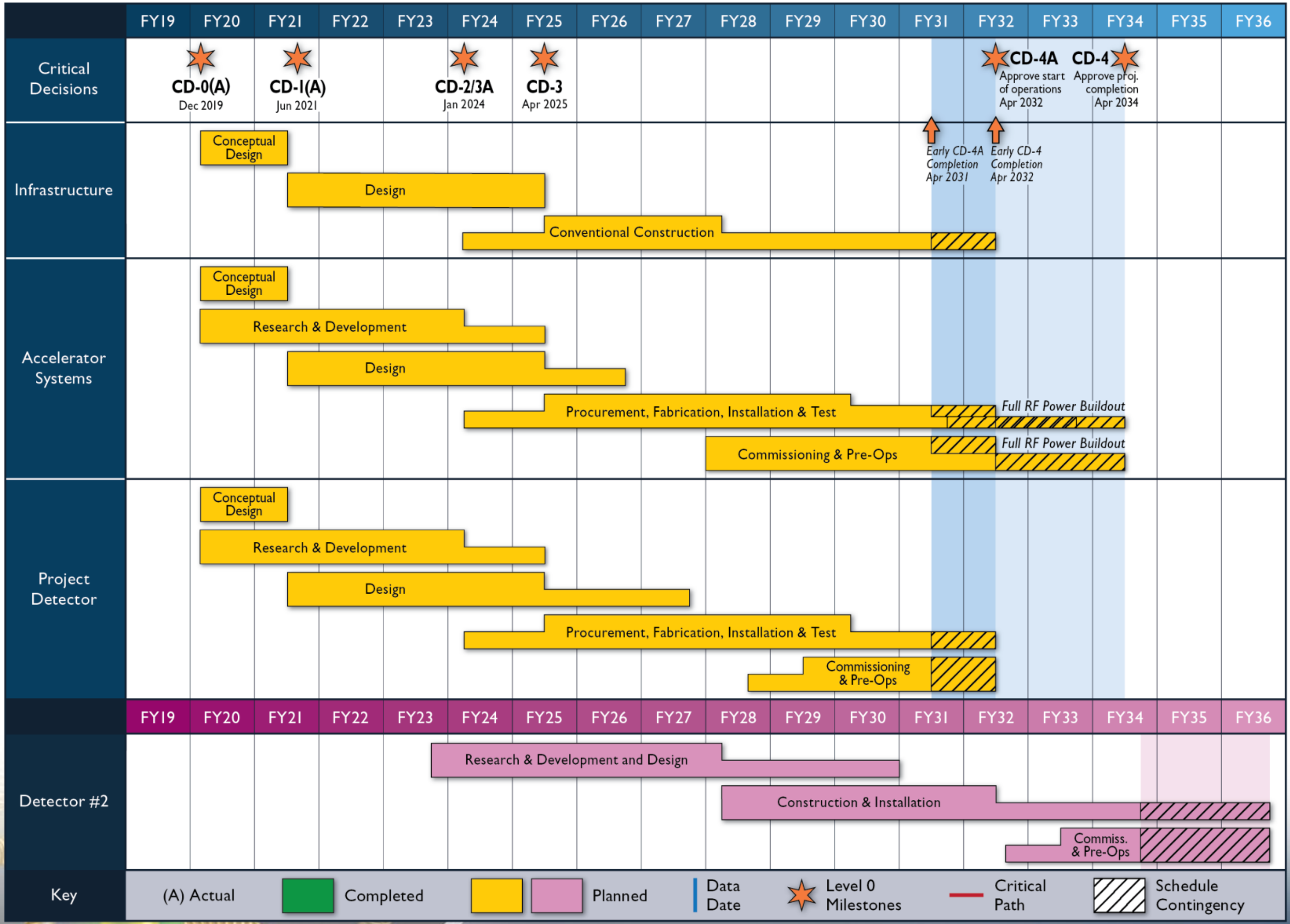


e-Vacuum R&D
Prototype of RCS Cu vacuum chamber and 3D rendering of the sliding bellow prototype design

EIC 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.
- Detector will be constructed in international collaboration, with substantial contribution from partners
- 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

Reference Schedule



International Engagement - Accelerator

- Active engagement ramped up last summer through meetings with DOE and funding agency reps, Accelerator Workshops, and dialogue with potential partners
- Collaborations contributing to both design and hardware that cover a broad range of WBS items are in development
- Bi-lateral meetings now expand from EIC L1 management to L2 & L3 EIC experts for detailed technical discussion of possible in-kind scope
  - Examples: **Crab Cavity** system information exchange meeting w/UK and Canada, meetings w/INFN-Accelerator collaboration on **HSR vac. system**, w/CERN on **ESR vac. sys.**, etc.

	Armenia	Australia	Austria	Belgium	Brazil	Canada	Czechia	France	Germany	India	Italy	Japan	Korea, Republic of	Mexico	Netherlands	New Zealand	Poland	Senegal	South Africa	Spain	Sweden	Switzerland	Thailand	Ukraine	United Kingdom
Contact / Attend EIC Accelerator Partnership Workshop 2020	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Presentation at EIC Accelerator Partnership Workshop 2020		■			■	■		■	■		■	■	■	■			■		■			■	■		■
Bi-lateral meetings with L1 management to explore interests		■			■	■		■	■		■			■			■			■		■			■
Bi-lateral meetings with L2 & L3 experts on concrete scope						■		■			■											■			■
Scope proposal ready for DOE & funding agencies																									

Potential Accelerator Contributions

- Italy, INFN
  - HSR vacuum chamber inserts
- Canada, TRIUMF
  - SC Crab Cavity system
  - Pulsed systems
- UK, ASTEC & Cockcroft Inst.
  - ERL components
- France, IJCLab
  - SHC ERL diagnostics
- France, CEA Saclay
  - IR SC magnets
  - SC spin rotators
- CERN, Switzerland
  - ESR SC cryomodules joint design
  - ESR high current elements joint design
- Japan, KEK
  - ESR collimation system

High level readiness of technical status
Possibly, first case for use of seed funds

High level readiness of technical status

Project is developing possibility of "Seed" funds for EIC international collaboration that can enable early start of EIC accelerator design efforts in partner countries

- Recent & tentative:
- Israel, SARAF
  - RF power amplifiers, collimators, controls
- Sweden, Uppsala Uni.
  - SSPA

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
- 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!**