EIC Commissioning

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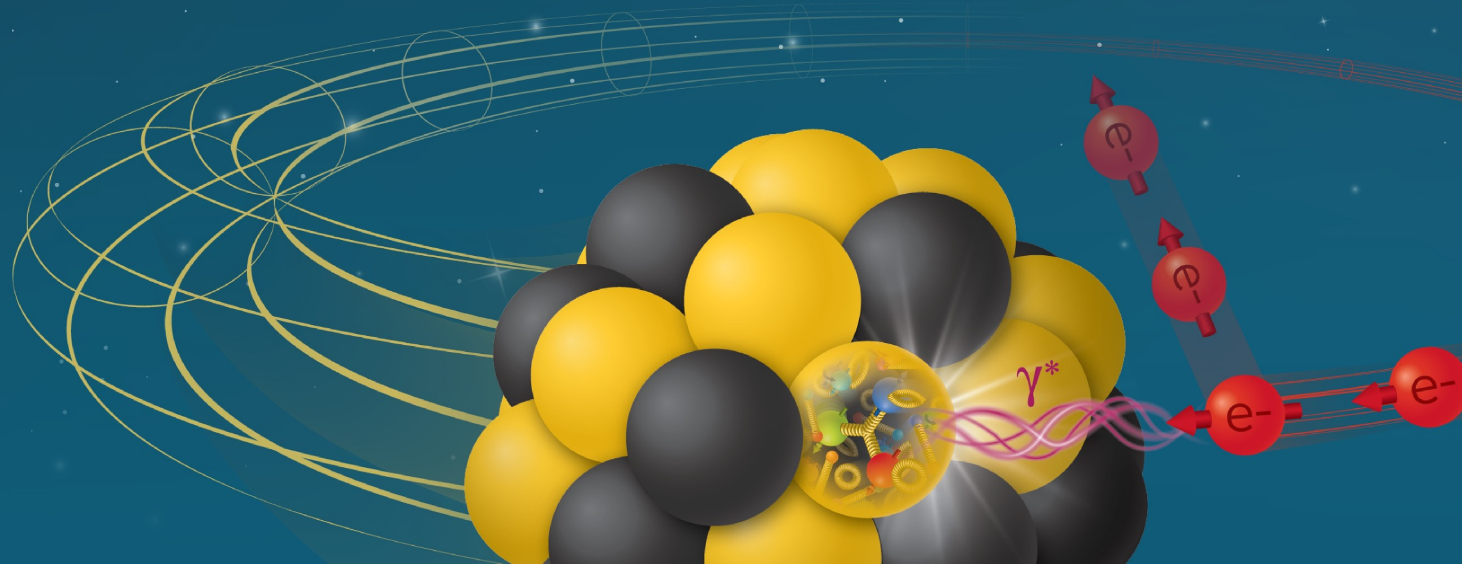
Electron-Ion Collider



Lessons from HERA @ DESY

Commissioning is the process of bringing an accelerator and its components from installation to full operational readiness, including verifying functionality, optimizing performance, and ensuring stable, high-quality beam delivery for experiments.

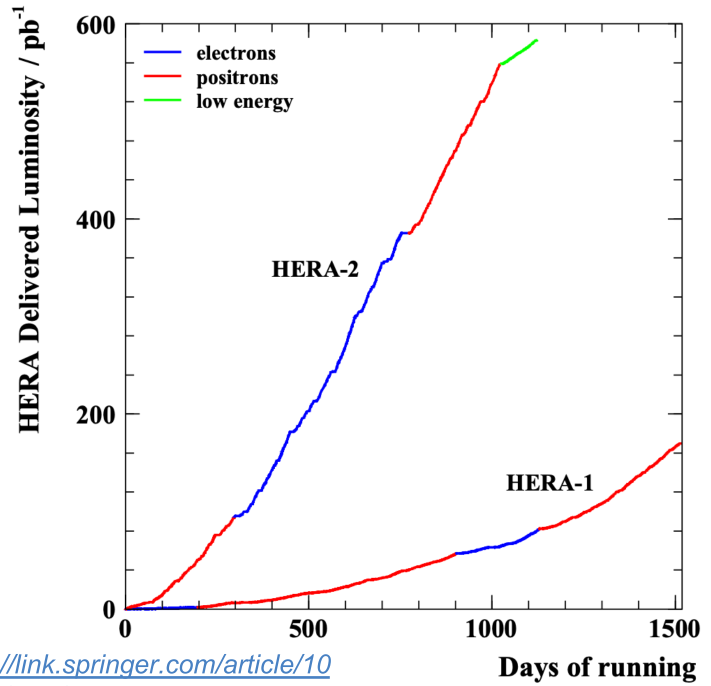
HERA-1 (1992–2000): Achieved first ep collisions in 1992; commissioning focused on **stable beam operations**, **synchronization of electron and proton rings**, and optimizing the interaction region for initial physics runs.

HERA-2 (2003–2007): Major upgrade to **boost luminosity** and **add electron polarization**; commissioning **faced significant challenges** from increased detector backgrounds, synchrotron radiation, and beam-gas interactions, limiting performance gains.

→ Took several months post-installation to re-establish stable operations.

→ Electron beam polarization never reached HERA-1 levels

Key Lessons: Importance of **early background simulations**, careful **polarization control**, and **vacuum quality** in high-luminosity, high-precision colliders.



https://link.springer.com/article/10.1140/epjc/s10052-016-4152-3

Fig. 4 A summary of the integrated luminosity delivered by the HERA collider during the HERA I (1992–2000) and HERA II (2003–2007) phases. The different electron and positron running periods are indicated, as well as the data taken at lower proton-beam energies in 2007

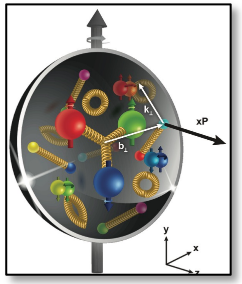
Science Highlights

Spin is one of the fundamental properties of matter.

The EIC will explore the contributions of quarks, gluons, and orbital angular momentum to nucleon spin.

Does the mass of visible matter originate from interactions between quarks and gluons?

The EIC will determine an important term contributing to the proton mass.

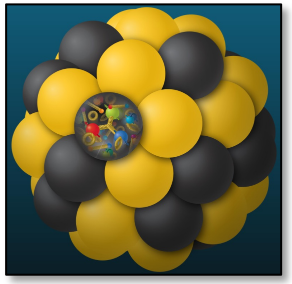


How are the **quarks** and **gluon distributed** in space and momentum inside the nucleon & nuclei?

How do the **nucleon properties** emerge from them and their interactions?

How can we understand their **dynamical origin in QCD**?

What is the relation to **confinement**?

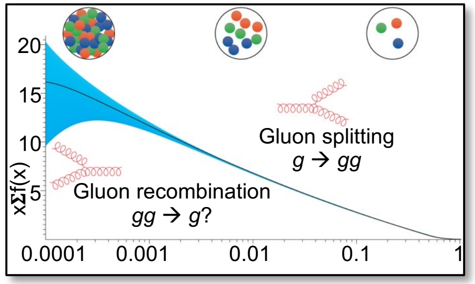


Is the **structure** of a free and bound nucleon the same?

How do **quarks and gluons interact** with a nuclear medium?

How do the **confined hadronic states** emerge from these quarks and gluons?

How do the quark-gluon interactions create **nuclear binding**?



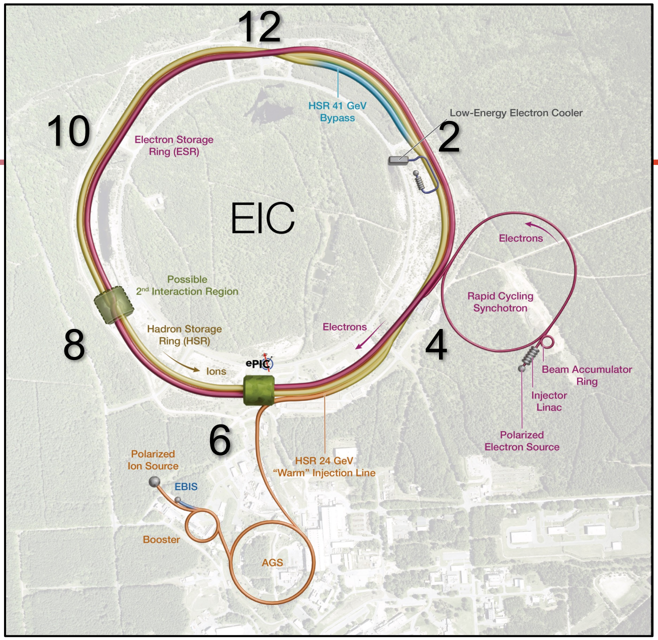
How many gluons can fit in a proton?

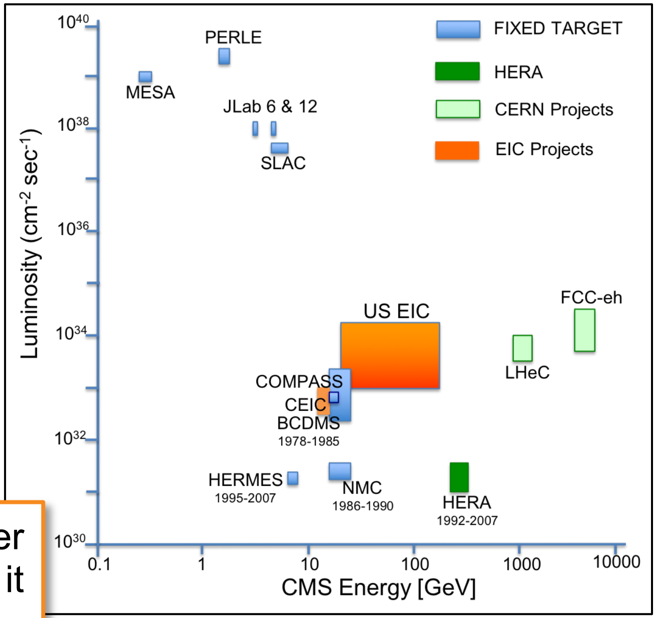
How does a **dense nuclear environment** affect the quarks and gluons, their correlations, and their interactions?

What happens to the **gluon density** in nuclei? Does it **saturate at high energy**?

EIC Design Overview

- **Hadron Storage Ring (RHIC Rings) 40, 100-275 GeV**
  - Based on **existing, well maintained, well performing RHIC**
  - Superconducting magnets (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - Bright vertical beam emittance 1.5 nm ("flat beams")
  - Cooling at injection and later upgrade → high energy cooler
- **Electron Storage Ring 5–18 GeV**
  - Large beam current, 2.5 A, 9 MW S.R. power, S.C. RF
  - Need to inject polarized bunches
  - Swap-out injection for electron bunches (at 1 Hz) to maintain high polarization
- **High current, highly polarized (88%) electron source**
- **Electron Pre-Injector (750 MeV linac)**
- **Electron Rapid Cycling Synchrotron (RCS), 1Hz, 0.75 → 18 GeV**
  - Spin transparent due to high quasi-periodicity
- **High luminosity Interaction Region(s)**
  - Large bore superconducting final focusing magnets
  - 25 mrad crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation
  - Bunch Crossing ~ 10.2 ns/98.5 MHz





US-EIC: polarization, ion species together with its luminosity and √s coverage makes it a completely unique machine world-wide.

Accelerator at Day One and at full Capability

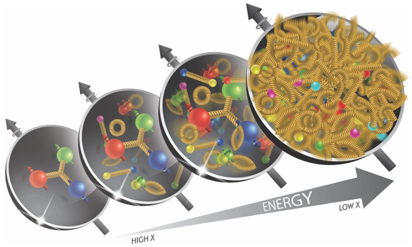
EIC commissioning and Ramp Up		Full EIC Capabilities
RCS: 7nC / bunch 5 – 10 GeV polarized e-	→	Add an accumulation ring to reach 28 nC / bunch and add RF to accelerate to 18 GeV electrons
ESR: 7nC / bunch 5 – 10 GeV polarized e-	→	Add more RF cavities to operate at 18 GeV electrons and 28 nC / bunch
HSR: 100 – 250 GeV polarized p 100 GeV/u nuclear beams cooling at injection energy	→	Update PS to reach 275 GeV protons and 110 GeV/u nuclei add 41 GeV bypass to get full HSR beam

Proposal for initial years of science during EIC commissioning and ramp up, is driven by

- Start of the promised NSAC/NAS science program
- Alignment with expected order in commissioning the collider and ramp up of performance that comes with gain of operational experience
- Having access to new physics results early to get high impact publications, i.e. PRLs, ……

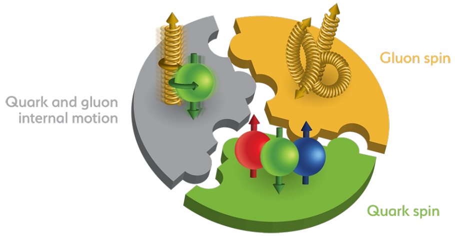
Accelerator Performance for NAS Science

- Map the out nucleon and nuclei structure from high to low x
  - Span center-of-mass energy √s: 45 – 100 GeV
  - Wide center-of-mass energy: √s: 30 – 140 GeV

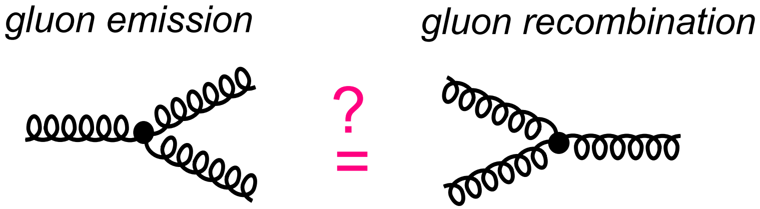


Science program during EIC commissioning and ramp up
Full EIC capabilities

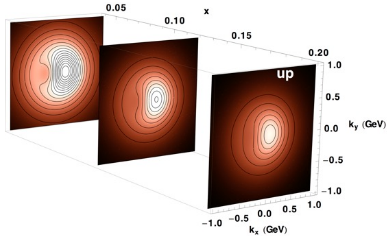
- Access to spin structure of nucleons and nuclei
- Spin vehicle to access the spatial and momentum structure of the nucleon in 3D
- Quark-gluon structure of light nuclei
  - Polarized electron and hadron (p, He-3) beams

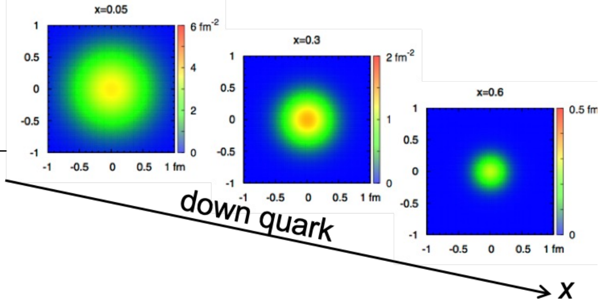


- Accessing the highest gluon densities → *saturation*
- How quarks and gluons interact with a nuclear medium
  - Nuclear beams: d to Pb at √s: 45 – 63 GeV
  - Nuclear beams: d to Pb at √s: 30 – 90 GeV → *access to highest & lowest x*



- Mapping the spatial and momentum structure of nucleons and nuclei in 3D
  - High luminosity ~10^{33} $cm^{-2}s^{-1}$
  - Large acceptance in p_T (0.2 – 1.3 GeV) through forward focusing IR magnets
- Access to rare probes, i.e. Ws and BSM Physics
- Precision mapping the spatial and momentum structure of nucleons and nuclei in 3D
  - High luminosity: > 10^{33} $cm^{-2}s^{-1}$

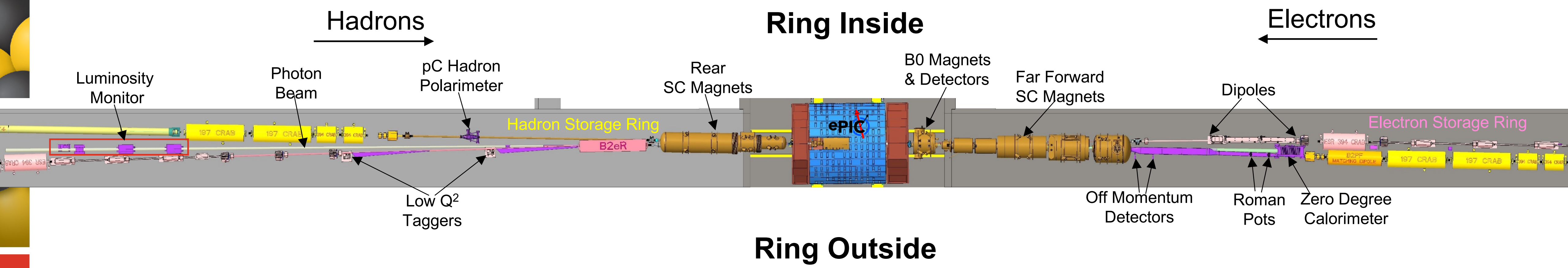




ePIC Setup at EIC Start Up

Goal:

- Central ePIC has all subsystems installed
- All supports for auxiliary detectors are installed, but some of the detector packages are not installed for safety reason for Year-1
  - ZDC and Lumi-detector are fully installed
  - Off-Momentum Detectors (OMDs) should be in save position, so they can be used if beam is stable
  - Roman Pots will not be installed
  - Low-Q^2 Tagger should be discussed
  - hadron and electron polarimetry will be installed from day-1 operating EIC



What Does EIC Need to Commission?

- **RCS:**
  - Operate the RCS
  - Get polarization in the RCS
  - Swap-out of electron bunches in the ESR

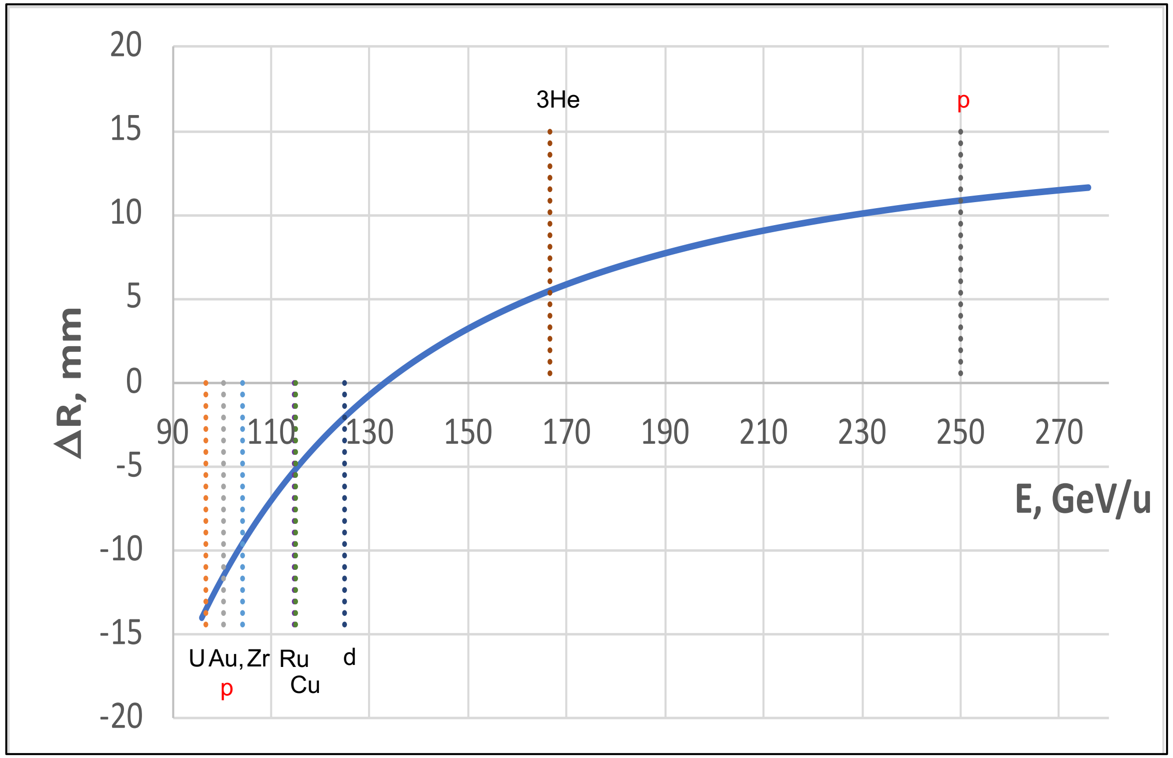
- **ESR:**
  - Operating with spin rotators to get longitudinal polarization
  - Swap-out of electron bunches to preserve polarization, needed because the Sokolov-Ternov effect of depolarization

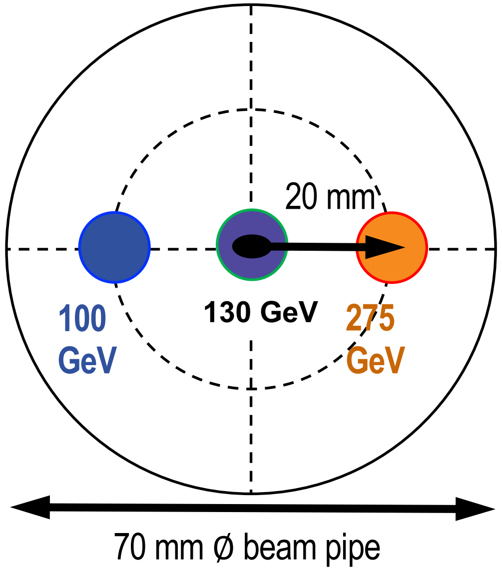
Energy [GeV]	5	10	18
bunch charge [nC]	28	28	11
number of bunches	1160	1160	290
max. replacement time (up/down/total) [min]	150/232/182	96/359/151	4/11.5/6
equilibrium emittance (h/v) [nm]	20/1.8	20/1.2	24/2.0
RMS momentum spread	6×10^{-4}	6×10^{-4}	10×10^{-4}

Maximum replacement times (= max. allowable storage times in ESR) are based on 85% injected polarization and 70%-time averaged polarization.

- **HSR:**
  - Operating beams off-center
  - Transverse and longitudinal beam polarization (needs spin rotator) for protons and He-3
  - Pre-cooling of hadron beams
  - Operating with crab cavities

Beam Energy and Average Orbit Radius in the HSR





Since the electron revolution frequency is fixed, the hadron orbit must be adjusted with energy to keep the collisions in sync.

1. Prefer ~130 GeV/u, which corresponds to a 'centered' hadron beam (path length difference ΔR ~ 0, this is achieved for a beam where Z ~ 0.5A) → Ru, Cu, Ag, …
2. Do not want to exceed the present RHIC maximum dipole fields (corresponds to 250 GeV protons or 833 T-m)

EIC-ePIC Commissioning

Q2/2033 | ~ Calendar Year 2034 | ← *exact dates are under development* →

ePIC no-beam commissioning → ePIC commissioning with a beam

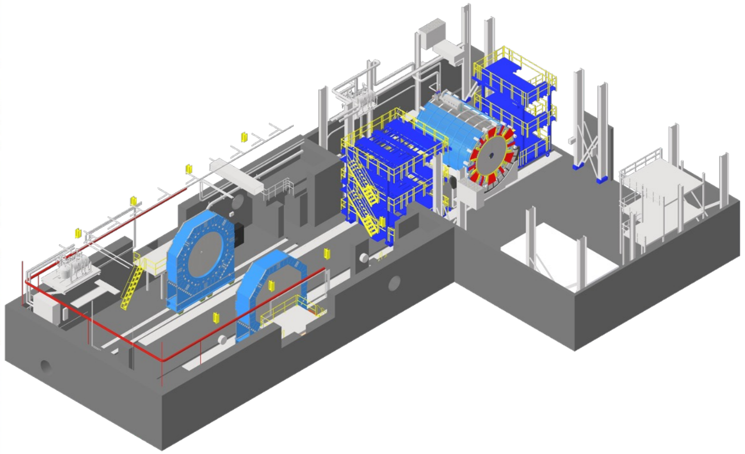
- ePIC is fully assembled
- Ready for Cosmic Data Taking

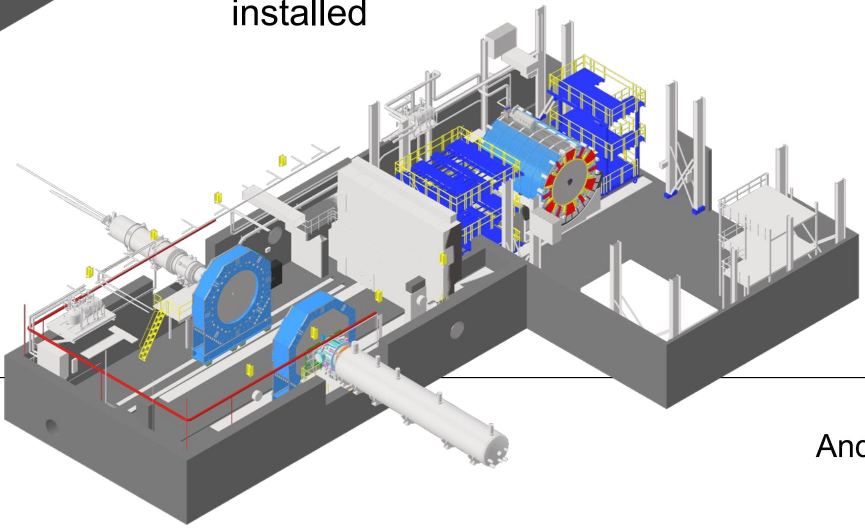
- EIC first beam commissioning
- Central ePIC is in the assembly hall
  - Endcap calorimeters and beam pipe with instrumentation to have a first look on backgrounds
  - Luminosity detector and hadron & electron polarimeters are fully installed

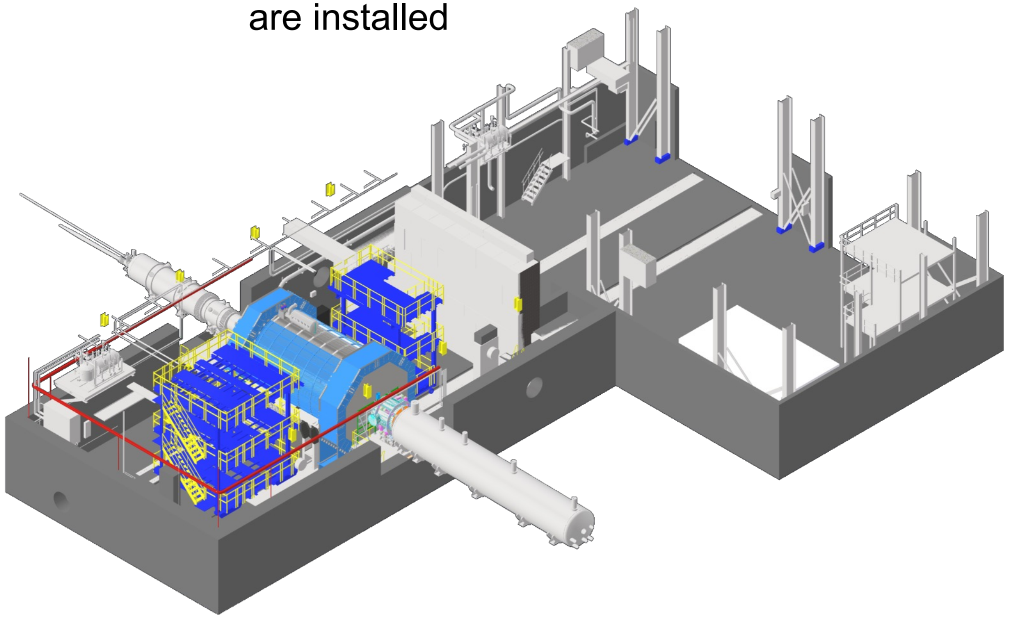
- Move the central ePIC into the wide-angle hall

- Commission ePIC with a beam
  - All auxiliary detectors, but RPs and OMDs are installed

- Start of the Science Program
- RPs and OMDs will be installed in Year-2







Proposal for the Science Program in the First Years of EIC

Year - 1

Start with Phase 1 EIC

New Capability:
Commission electron polarization in parallel

Run:
10 GeV electrons on 115 GeV/u heavy ion beams (Ru or Cu)

Year - 2

Phase 1 EIC
+ long. electron polarization

New Capability:
Commission proton polarization in parallel

Run:
10 GeV long. polarized electrons on 130 GeV/u Deuterium

Run:
Last weeks 10 GeV long. polarized electrons and 130 GeV polarized protons

Year - 3

Phase 1 EIC
+ long. electron polarization
+ proton polarization

New Capability:
Commission running with hadron spin rotators

Run:
10 GeV long. polarized electrons on 130 GeV transverse polarized protons

Run:
Last weeks switch to longitudinal proton polarization

Year - 4

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators

New Capability:
Commission hadron accelerator to operate with not centered orbits

Run:
10 GeV long. polarized electrons on 100 GeV Au

Run:
10 GeV long. polarized electrons on 250 GeV transverse and longitudinal polarized protons

Year - 5

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits

Run:
10 GeV long. polarized electrons on 100 GeV Au

Run:
10 GeV long. polarized electrons on 166 GeV transverse and longitudinal polarized He-3

Time to install additional ESR RF and HSR PS to reach **design current** and **max. energies**

Proposal for the Science Program in the First Years of EIC

Year - 5

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits

Run:
10 GeV polarized electrons on 100 GeV Au

Run:
10 GeV long. electrons on 166 GeV transverse and longitudinal polarized He-3

Year - 6

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits

New Capability:
Commission ESR & HSR at max. energy and beam currents

Run:
18 GeV long. polarized electrons on 275 GeV/u polarized (longitudinal & transverse) proton beams

Year - 7

Phase 1 EIC
+ long. electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits
+ operation of ESR & HSR at max. energy and beam currents

New Capability:
Operate HSR with 41 GeV bypass

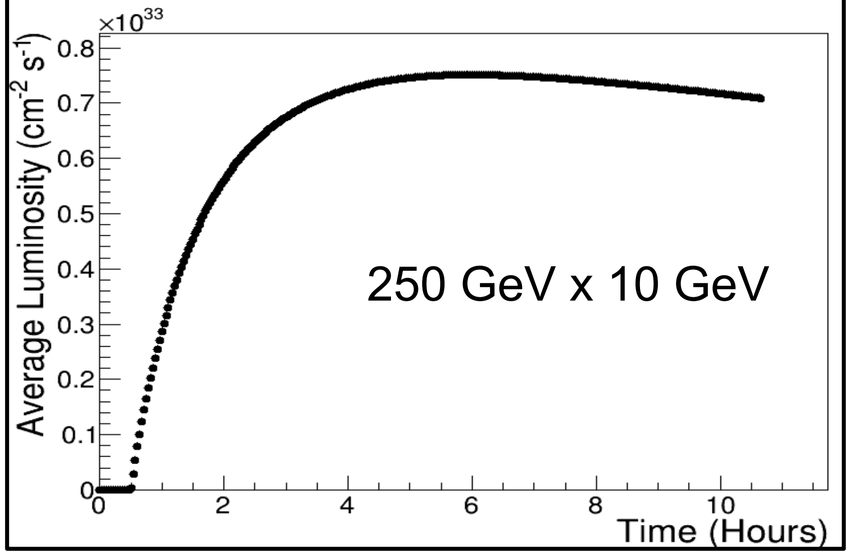
Run:
5 GeV long. polarized electrons on 41 GeV transverse polarized proton beams

Enable precision studies at the highest Q^2 and smallest x, a regime never explored before with polarized beams

Assumptions and Luminosity Calculation

- 7 nC electron bunch charge compared to 28 nC (CDR)
- Constant proton beam IP divergencies are maintained throughout the store by gradual increase of proton IP beta-functions as the beam emittance increases.
- The electron IP beta-functions are adjusted accordingly to match electron and proton transverse beam size.
- Ion beam is cooled at low energy (24 GeV/u) but no stochastic cooling is used in the store
- 1 Run is ½ year operation at 80% uptime
- 2 h store turnaround time
- 30 min at the beginning of the store is taken by the ESR fill and detector turn-on
- Not yet included a ramp up of luminosity through the Run (see Table)

$$\text{Ave. lumi} = \frac{\text{Integral}}{\text{store length} + 2.5\ \text{hr}}$$

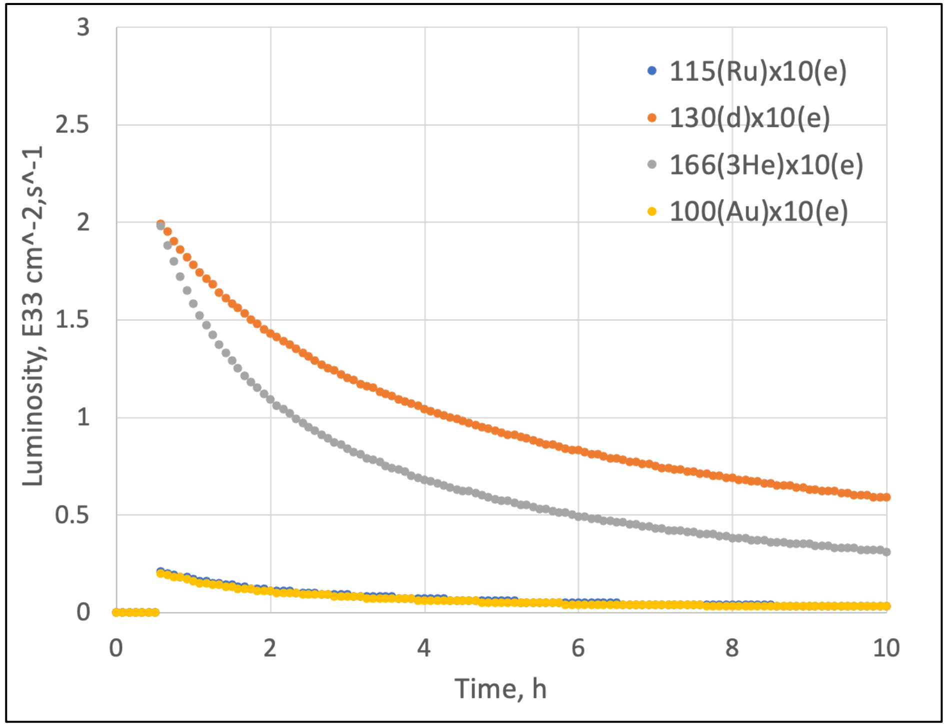


RHIC	EIC Early Years (assumption)
• 1st week 25% of projected lumi / week • 2nd week 50% of projected lumi / week • 3rd week 75% of projected lumi / week • 4th week 100% of projected lumi / week	• 1st week 10% of projected lumi / week • Then increase by 10% every week → *10 weeks to reach projected lumi / week*

Luminosity Estimation

Possible beam energies:

- e-: 5 GeV, 10 GeV and ultimately 18 GeV
- p: 41 GeV, 100 GeV to 255 GeV ultimately 275 GeV
- Au: 41 GeV, 100 GeV to 110 GeV ultimately
- A: 41 GeV, 100 GeV to Max ~255 / (A/Z) ultimately ~275 / (A/Z)



eA luminosities for Phase-1

	Lumi per Fill (5 h)	Lumi per Year
10 GeV e x 115 GeV Ru	1.3 pb^{-1}	0.9 fb^{-1}
10 GeV e x 100 GeV Au	1.2 pb^{-1}	0.84 fb^{-1}
10 GeV e x 130 GeV d	16 pb^{-1}	11.4 fb^{-1}
10 GeV e x 166 GeV ^{3}He	12 pb^{-1}	8.65 fb^{-1}

Note: eA luminosity is per nucleon

ep Luminosity for Early Years

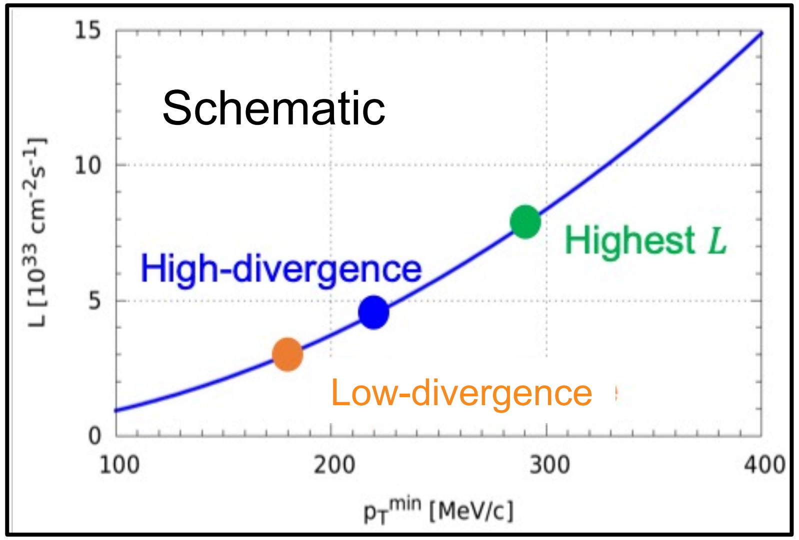
High Divergence	Lumi per Fill (5 h)	Lumi per Year
5 GeV e x 250 GeV p	9.26 pb^{-1}	6.48 fb^{-1}
10 GeV e x 250 GeV p	13.12 pb^{-1}	9.18 fb^{-1}
5 GeV e x 130 GeV p	6.3 pb^{-1}	4.36 fb-1
10 GeV e x 130 GeV p	7.6 pb^{-1}	5.33 fb^{-1}

Low Divergence	Lumi per Fill (5 h)	Lumi per Year
5 GeV e x 250 GeV p	6.81 pb^{-1}	4.78 fb^{-1}
10 GeV e x 250 GeV p	8.8 pb^{-1}	6.19 fb^{-1}
5 GeV e x 130 GeV p	5.8 pb^{-1}	4.1 fb^{-1}
10 GeV e x 130 GeV p	7.1 pb^{-1}	4.95 fb^{-1}

Compare to **HERA** integrated luminosity **1992 – 2007**: **~0.6 fb^{-1}** per experiment

Remember:

- **high divergence** → higher lumi, but reduced acceptance for low forward particle p_T^{min}
- **low divergence** →lower lumi, but increased acceptance for low forward particle p_T^{min}
  → *important for exclusive processes*



EIC Commissioning: Summary

- **Commissioning Scope:** Transition from installation to full operational readiness, ensuring stable, high-quality, polarized beam delivery.
- **Lessons from Other Colliders:**
  - Early background simulation is critical.
  - Electron polarization and beam-gas interactions require proactive mitigation.
  - Vacuum quality and synchrotron radiation must be tightly controlled.
- **EIC Machine Highlights:**
  - Reuses RHIC tunnel and infrastructure.
  - Polarized e^- (5–18 GeV) and ion beams (up to 275 GeV).
  - Unique capabilities: high polarization, flexible ion species, high luminosity.
- **Commissioning Strategy:**
  - Year-by-year phased approach (electron, proton, He-3 polarization; spin rotators; non-centered orbits).
  - Initial runs target early science with heavy ions, followed by increasing complexity.
- **Detector Readiness:**
  - ePIC central detector + key auxiliary systems installed on Day One.
  - Gradual inclusion of Roman Pots, Low-Q^2 taggers, and forward detectors.
- **Goal:** Deliver impactful early physics (e.g., PRLs), fulfill NAS/NSAC science objectives, and enable precision 3D mapping of nucleons and nuclei.

Acknowledgements

I extend my sincere gratitude to all colleagues from the ePIC and EIC teams for their outstanding efforts in the design and construction of this unique machine.

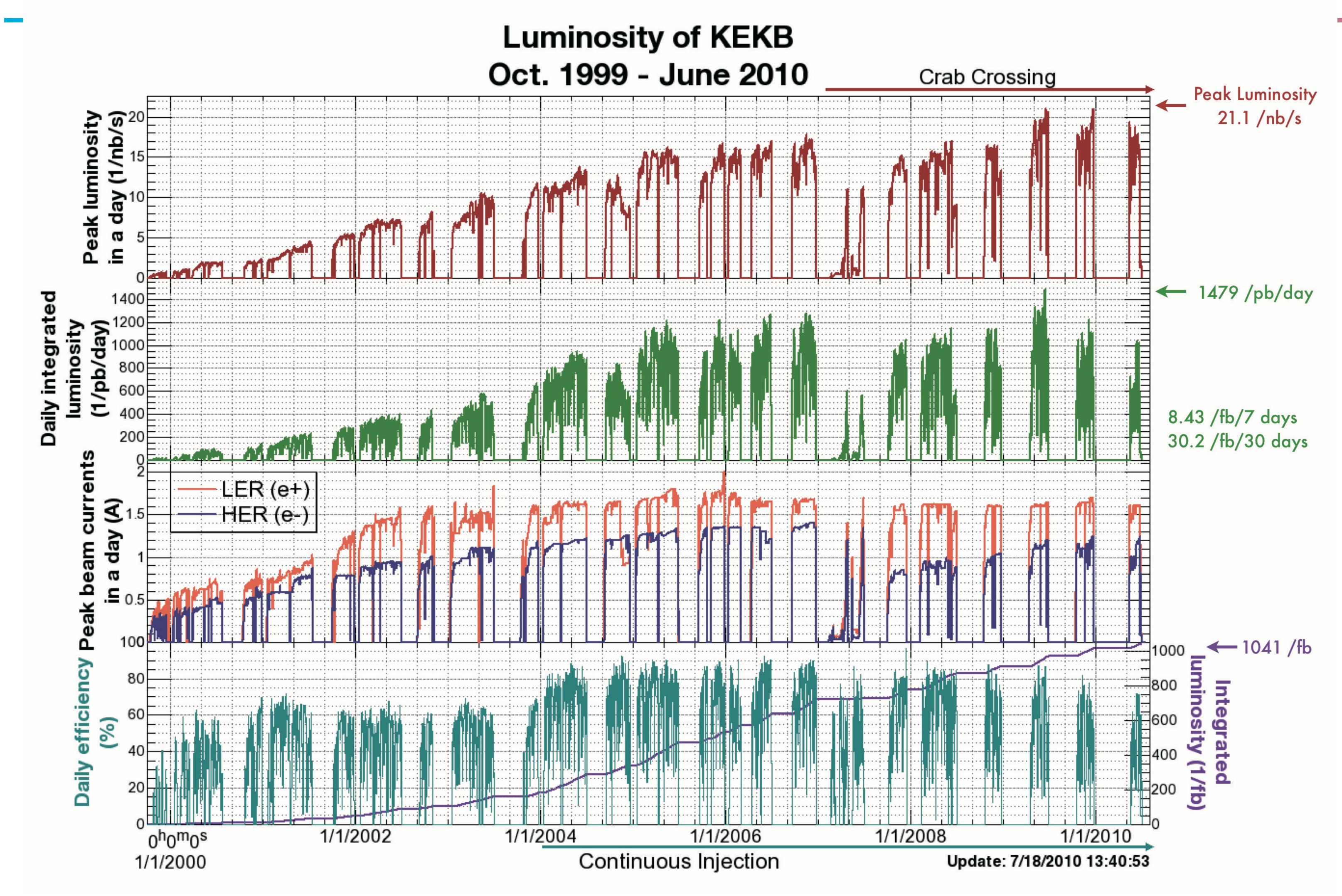
A special thanks to Elke-Caroline Aschenauer for her invaluable support and for providing materials that greatly contributed to the preparation of this presentation.

Thank you for your attention!

Questions?

Backup

Experience ramping up KEKB and SuperKEKB



KEKB took ~5 years to reach design luminosity

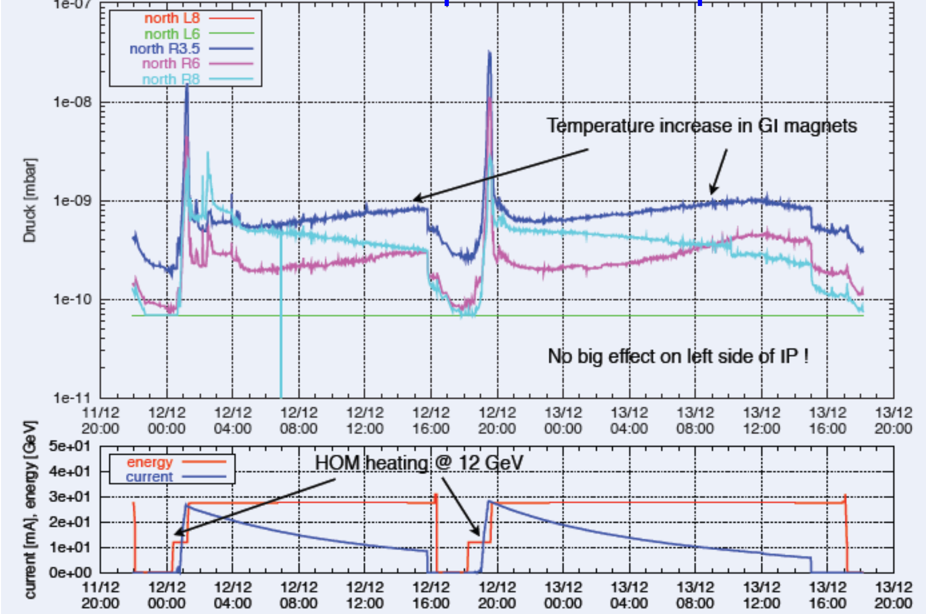
SuperKEKB has not yet reached design luminosity
> 20 below goal
operating since 2019
Several reasons, beam instabilities and beam backgrounds

Lessons from HERA II upgrade

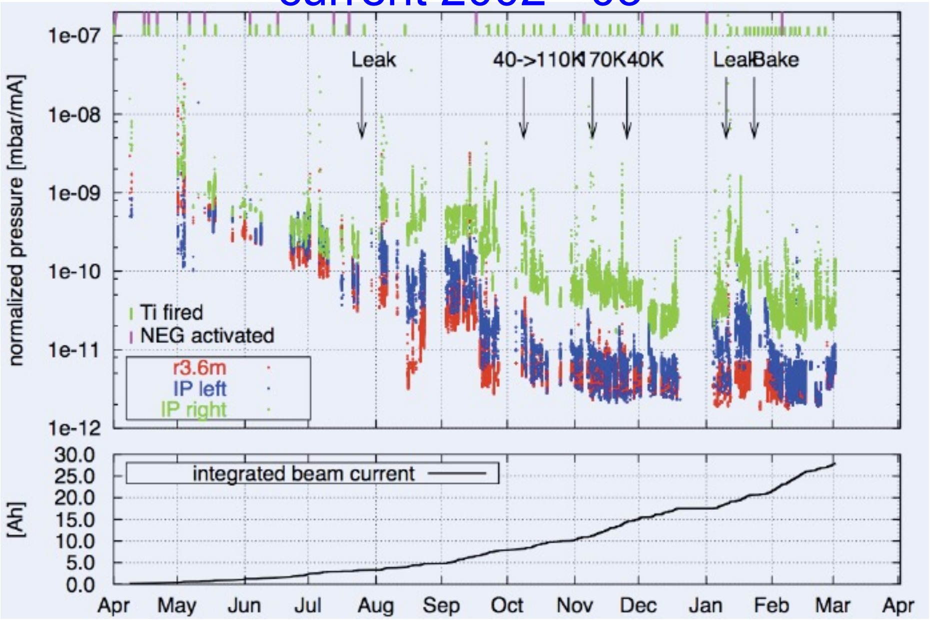
- HERA performed an upgrade to increase luminosity by a factor of 5
  - Mainly by squeezing the beam more at the IP by redesign of the IR
- The upgrade increased backgrounds dramatically → Several month shutdown to implement improvements
- Electron beam polarization never reached HERA-I levels, H1 and Zeus solenoids (~1T) not well compensated
- Main culprits:
  - no careful simulations prior to the upgrade
  - Proton beam-gas interactions most severe background
    - Needed an extremely good vacuum to mitigate this
  - Synchrotron radiation background
    - Background to detectors
    - Excess heating of beam pipe
      - Can damage flanges, etc.
      - Can heat beam pipe, decreasing vacuum
  - Electron beam-gas

Lessons from HERA II upgrade

Dynamic pressure increase due to thermal and photo desorption



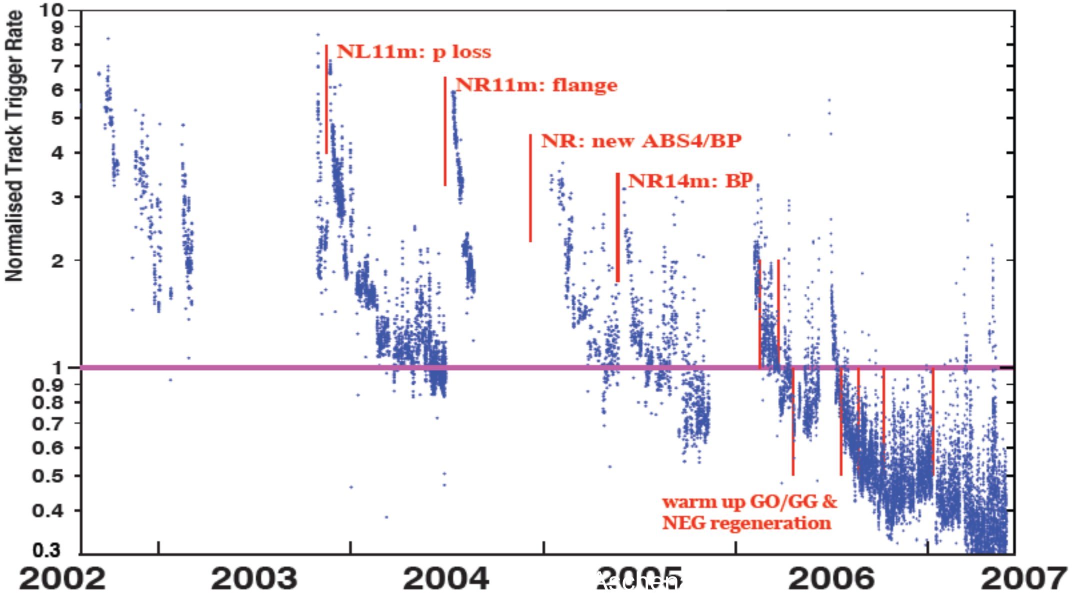
Pressure vs. integrated electron current 2002 - 03



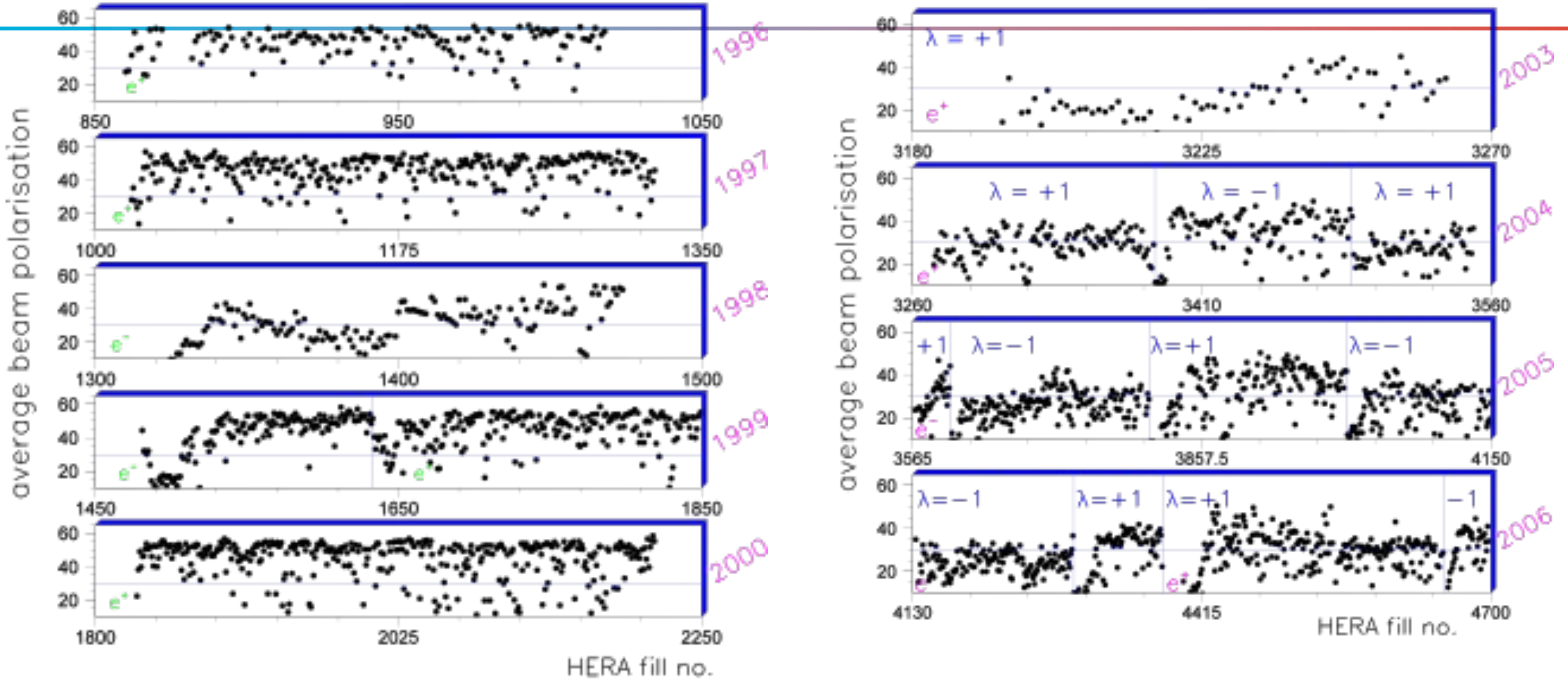
Proton Beam Gas Background

Two time constants for vacuum conditioning

- Short term after leaks 20 – 30 days
- Long term 600 days



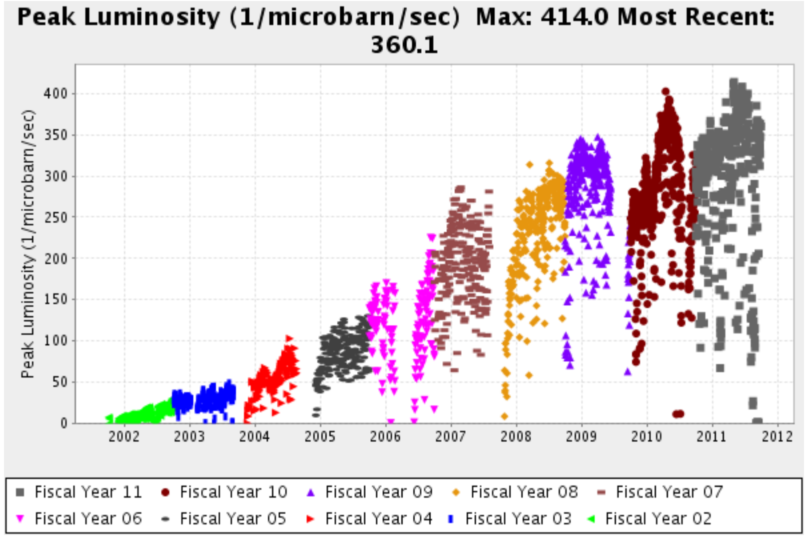
Lessons from HERA II upgrade



Electron polarization through Sokolov Ternov
Luminosity and Polarization have been strongly anti-corelated

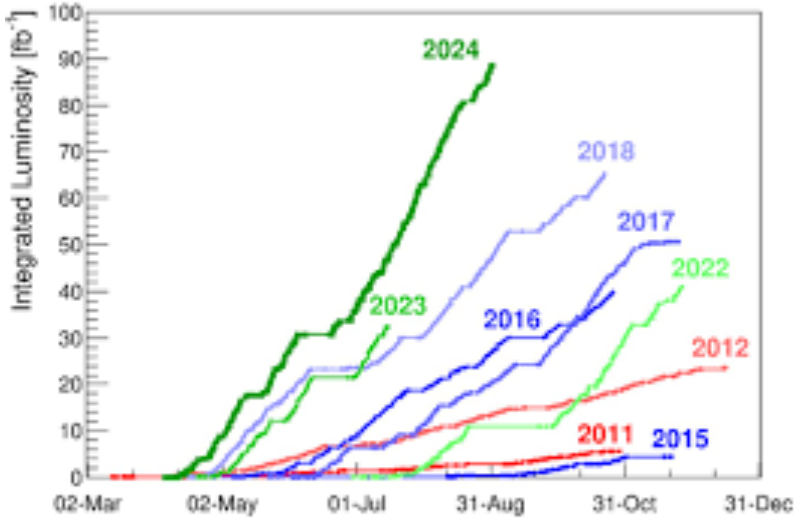
Lessons learnt from pp Colliders

Tevatron



The pbar electron cooler was added in July of 2005. The initial luminosity increased by ~50% at first and then it took many years to take advantage of the cooler by optimizing the store length, beam-beam interactions, etc.

LHC

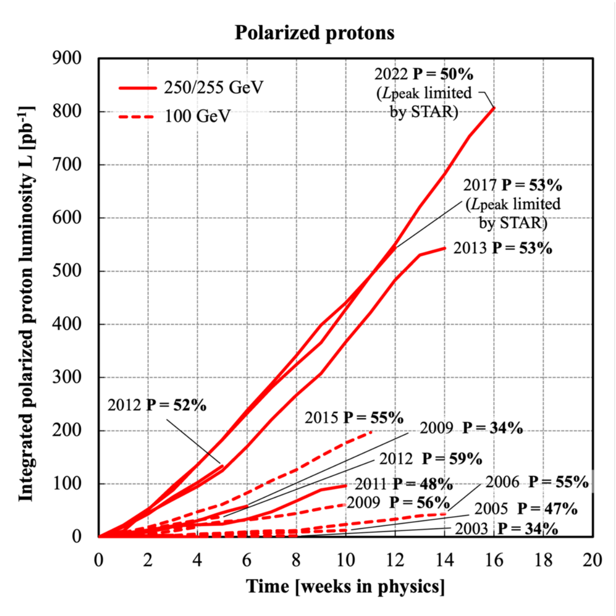


First beam September 10th, 2008, malfunction 9 days later no beam for experiments till 2010, March 19th, 2010 collisions at 7 TeV

Design Lumi was reached June 2016

13.6 TeV reached April 2022

RHIC



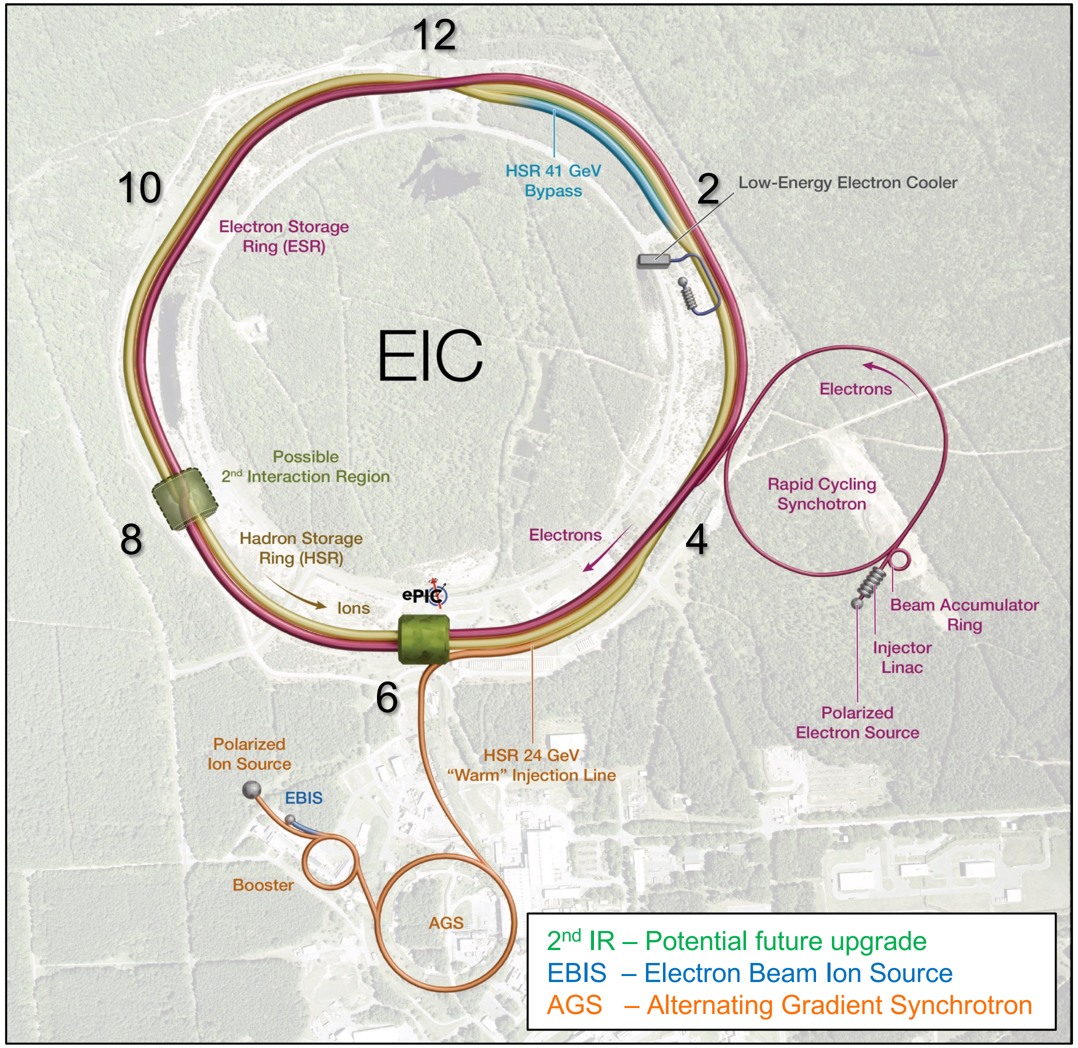
First Beam in 2000

Polarization and Luminosity often anti-corelated.

Took in 2015 in one year the integrated luminosity from all the years before at $\sqrt{s}$=100 GeV and for $\sqrt{s}$=250 GeV in 2017

Design

- Existing Relativistic Heavy Ion Collider (RHIC) tunnel ~3.8 km
- **Hadron Storage Ring (HSR)** *← Re-use one upgrade ring from RHIC*
  - Large range of ion species (H–U)
  - E_p = 41, 100–275 GeV
  - I_p = 0.38–1.0 A
- **Electron Storage Ring (ESR)** *← Build a new ring*
  - E_e = 5–18 GeV
  - I_e = 0.227–2.5 A
  - 1 Hz swap-out bunch replacement
- High polarization of ~70% for electron and light ion beams
- E_{CM} = 29–141 GeV
- $L = 10^{33}$–10^{34} $cm^{-2}s^{-1}$
- Crossing angle of 25 mrad with Crab Cavities
- **Start commissioning in the 2030s**



Electron-Proton/Ion Collider (ePIC) detector

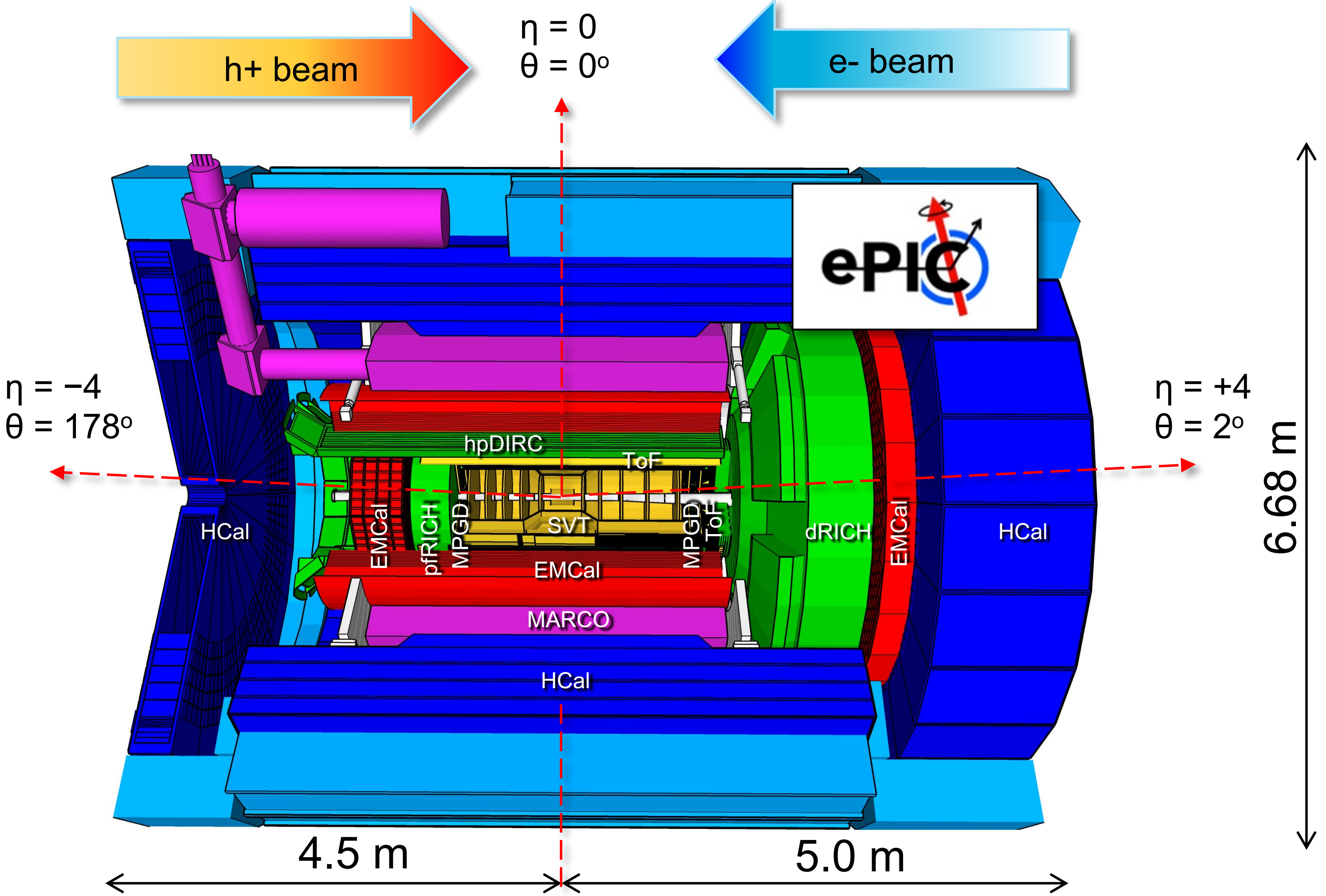
IP6 beam pipe:
- *0.76 mm thick* ***beryllium*** *pipe + 5 μm* ***gold*** *coating*
- *1.47 m long and 62 mm in diameter*

Tracking:
- *Primary and secondary vertexing*
- *High-precision low mass tracking*
  - 2 T Solenoid (MARCO)
  - Silicon Monolithic Active Pixel Sensors (MAPS) Tracker (SVT)
    - Vertex Barrels + Endcap Disks
  - Micro Pattern Gas Detectors (MPGDs)

Particle identification (PID):
- *High-performance single track PID for π, K, p separation*
  - Backward proximity focusing RICH (pfRICH)
  - Barrel high-performance (hpDIRC)
  - Forward dual-radiator RICH (dRICH)
  - Barrel & Forward ToF

Electromagnetic calorimetry (EMCal):
- *Photon measurements and electron identification*
  - Backward e-endcap, forward h-endcap, barrel

Hadron calorimetry (HCal):
- *Charged hadron, neutron, and K_L measurements*
  - Backward e-endcap, forward h-endcap, barrel

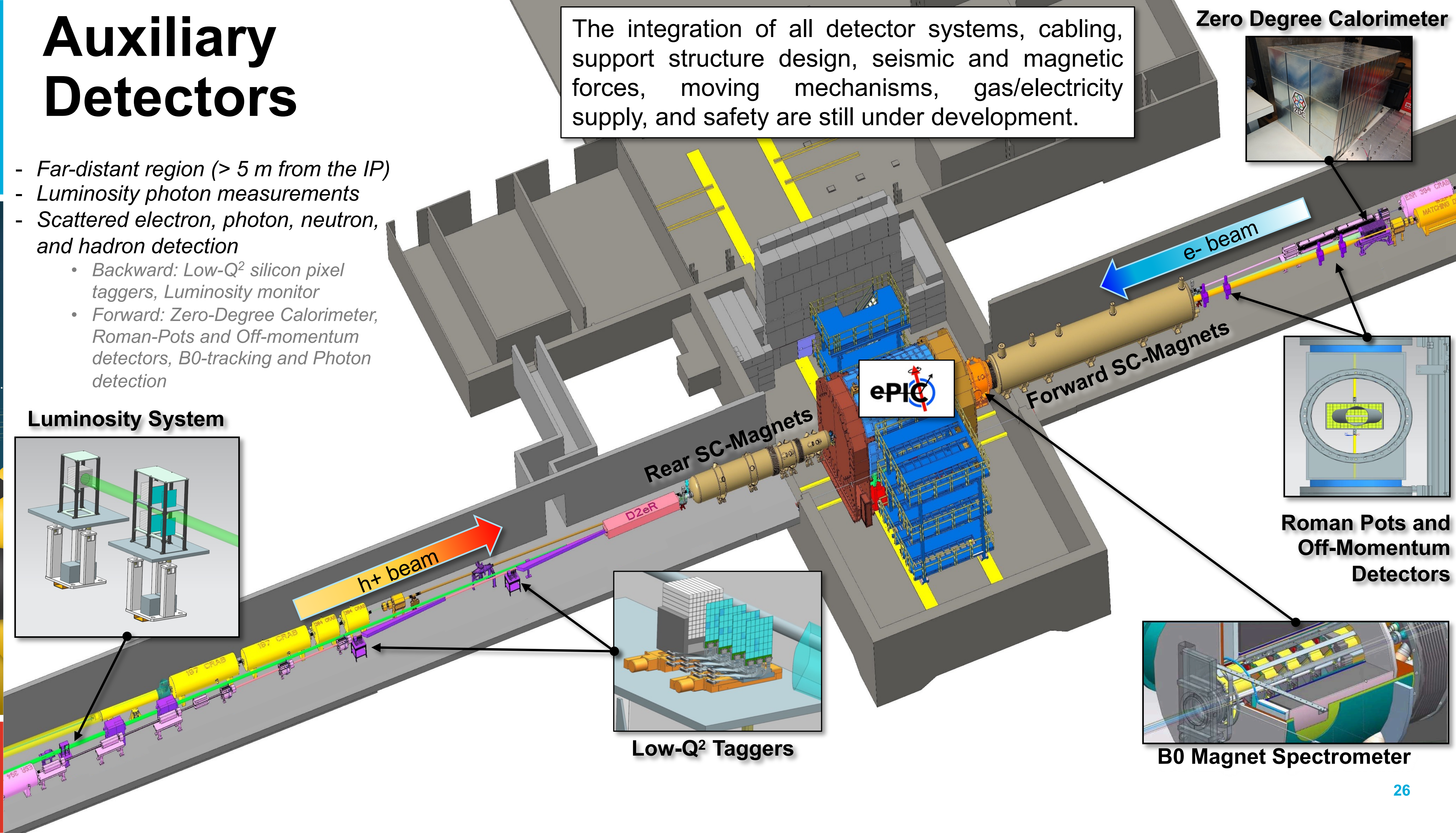


Schematic drawing of the ePIC detector.

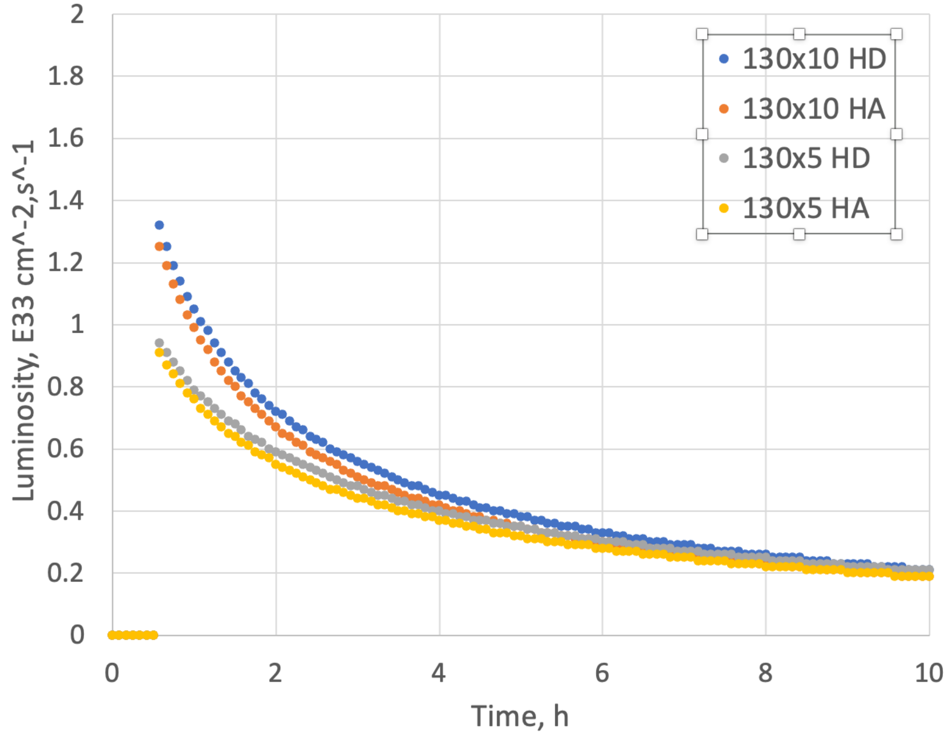
Auxiliary Detectors

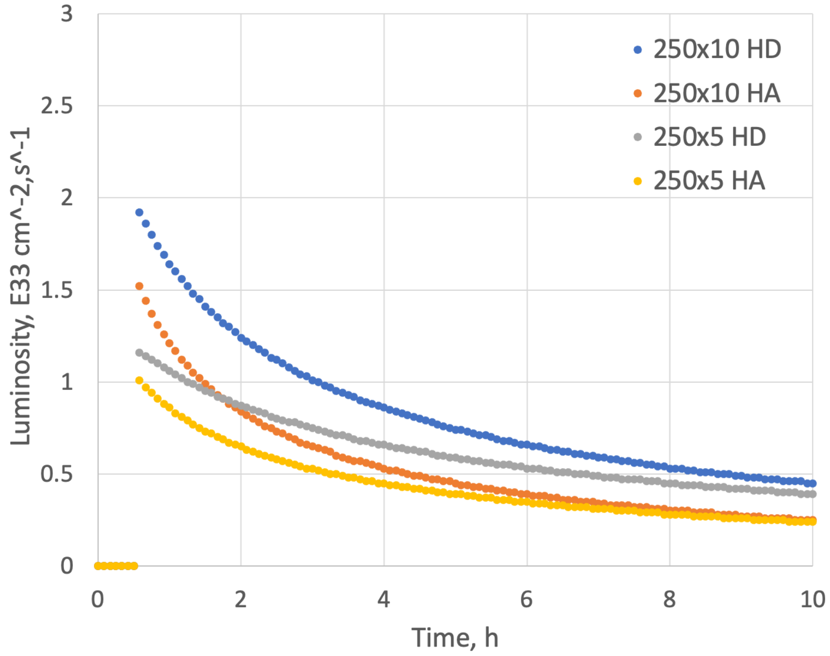
- *Far-distant region (> 5 m from the IP)*
- *Luminosity photon measurements*
- *Scattered electron, photon, neutron, and hadron detection*
  - *Backward: Low-Q^2 silicon pixel taggers, Luminosity monitor*
  - *Forward: Zero-Degree Calorimeter, Roman-Pots and Off-momentum detectors, B0-tracking and Photon detection*

The integration of all detector systems, cabling, support structure design, seismic and magnetic forces, moving mechanisms, gas/electricity supply, and safety are still under development.



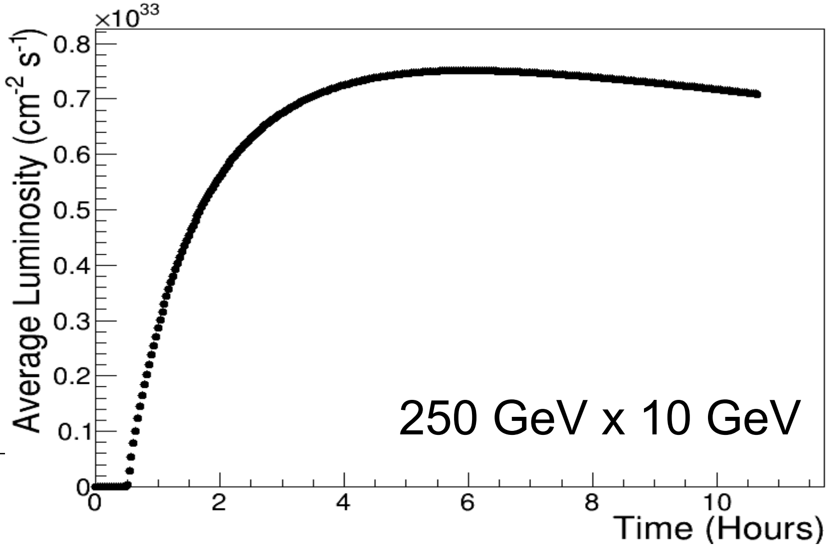
Luminosity ep for Phase-1





Compare to HERA peak luminosity of $5x10^{31}cm^{-2}sec^{-1}$

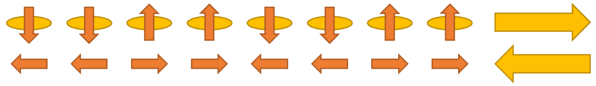
Max average luminosity without SHC: 0.8×10^{33} cm^{-2} s^{-1} with 5.9 hr store



Initial thoughts on the EIC Commissioning Strategy

Science Requirement for Polarisation:

- need high polarization (~70%) → experimental uncertainties proportional to $1/(P_e^2 P_A^2 L)$ or $1/(P_{e/A}^2 L)$ depending on measurements (single or double spin dependent observables)
- if electron polarization is required, it needs to be always longitudinal → requires ESR spin rotators
- to limit systematics → optimum would be to have arbitrary spin patters for both HSR and ESR



HSR: have trains of 4 bunches with the same spin direction
ESR: using RCS allows for arbitrary spin patters in the ESR through replacements

Running at 5 and 10 GeV electrons:

- we want polarization as early as possible,
- depolarization is small → max allowable replacement time for 10 GeV 360 mins (85% → 70%) for the preferred polarization state and 96 mins for opposite direction

→ proposal run only the preferred spin state per fill → backup to swap out option in case backgrounds at detector would be high

Consequence: need to flip the ESR spin rotators between fills to keep systematics small → possible; optics does not depend on spin rotator polarity and in the shadow of filling the HSR we change spin rotator polarity in ESR

Energy [GeV]	5	10	18
bunch charge [nC]	28	28	11
number of bunches	1160	1160	290
max. replacement time (up/down/total) [min]	150/232/182	96/359/151	4/11.5/6
equilibrium emittance (h/v) [nm]	20/1.8	20/1.2	24/2.0
RMS momentum spread	6×10^{-4}	6×10^{-4}	10×10^{-4}

Maximum replacement times (= max. allowable storage times in ESR) are based on 85% injected polarization and 70% time averaged polarization

Project timeline

- The ePIC Collaboration (177 Institutions, 26 countries), formed in July 2022, is dedicated to realizing the project detector.
- Jefferson Lab and DOE's Brookhaven National Laboratory are partners in building the EIC.