



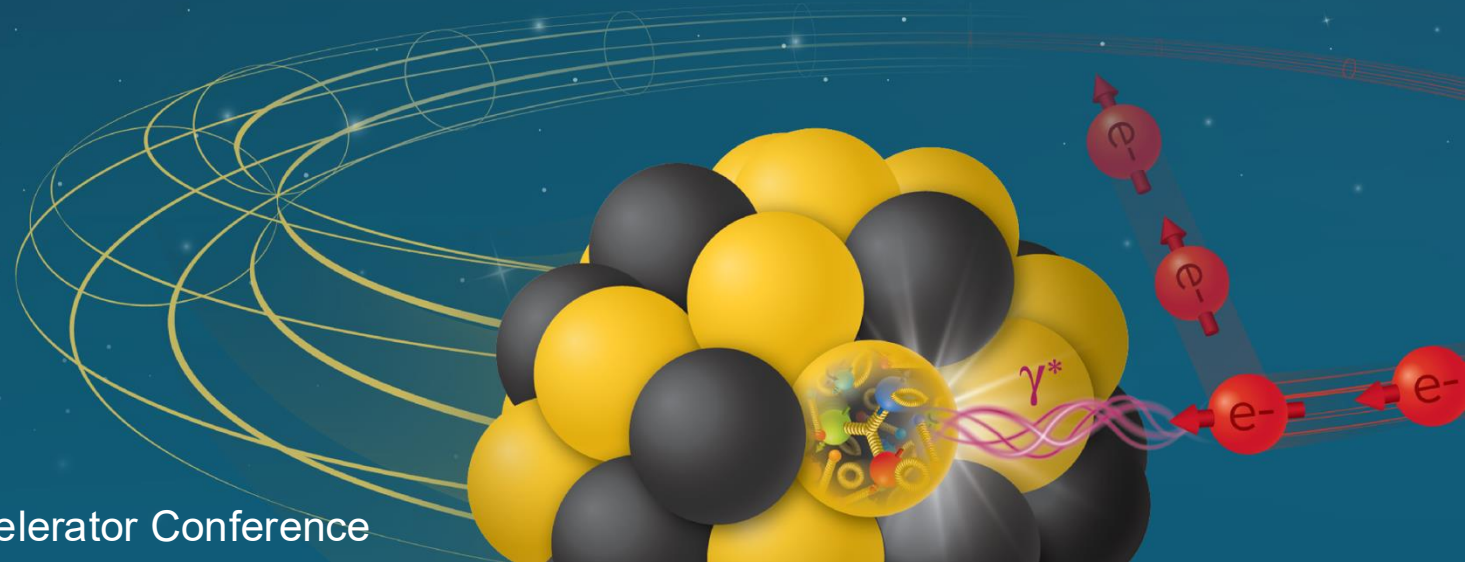
# Performance Strategy for the First Years of the EIC Science Program

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Pre-Operations Lead

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Electron-Ion Collider

IPAC'26 – the 17<sup>th</sup> International Particle Accelerator Conference



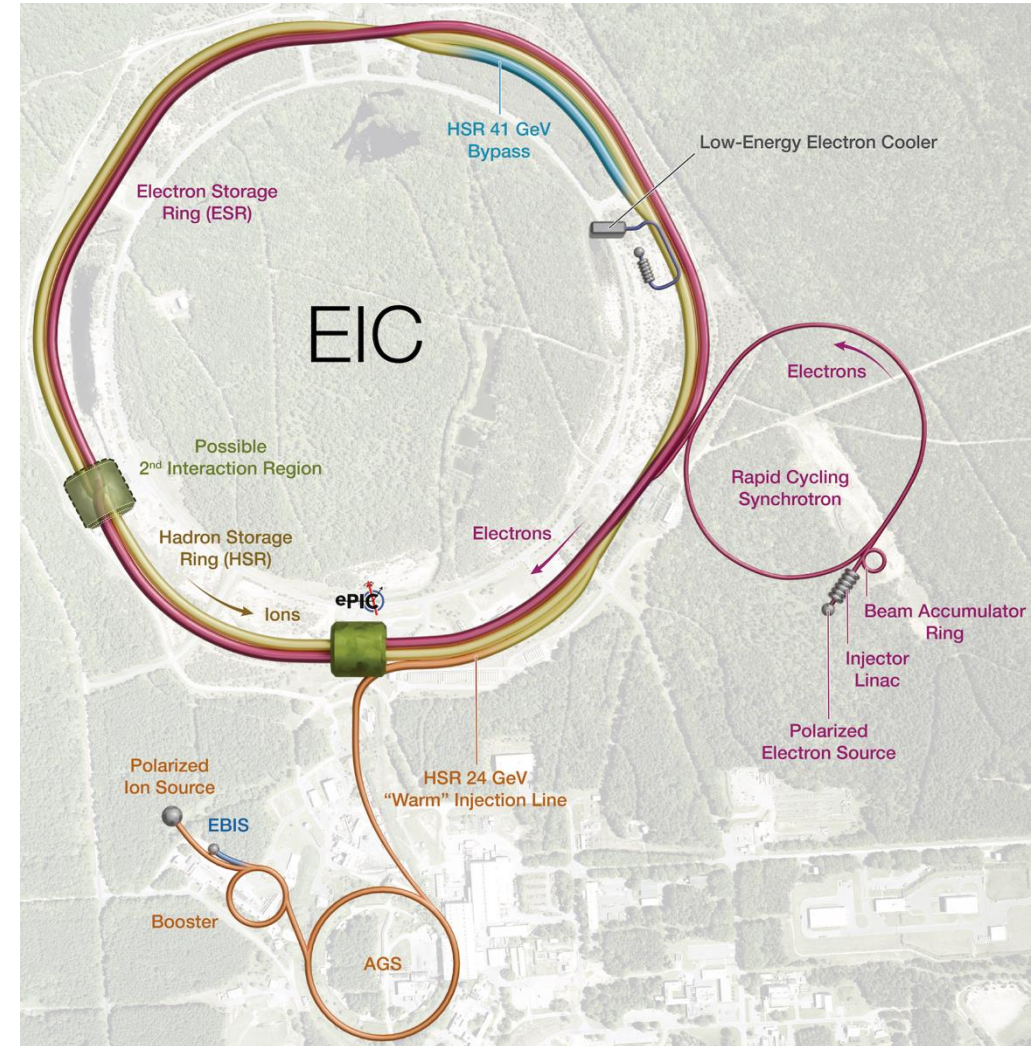
# Outline

- EIC Project Overview
- Early Operation Constraints
- Performance Strategy & Staged Commissioning
- Luminosity Evolution: Years 1-3
- Summary



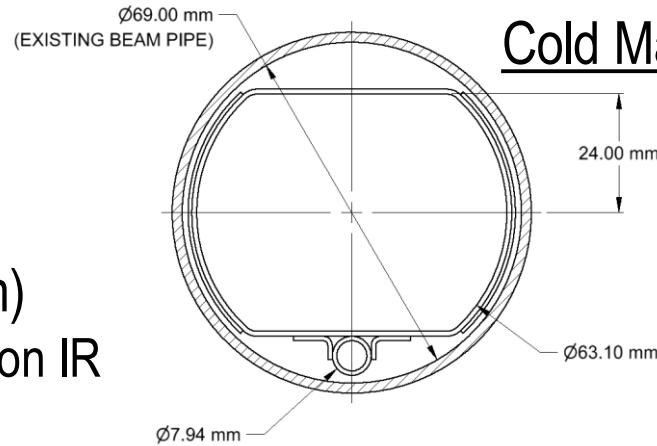
# EIC Project Overview

- **Electron Injection System**
  - DC Photoelectron Gun
    - 320 keV, ~85% polarization, 1.5 nC per bunch @ 30 Hz
  - S-band LINAC
    - 750 MeV, 30 Hz, normalized emittance: ~80  $\mu\text{m}$  (x), ~50  $\mu\text{m}$  (y)
- **Beam Accumulator Ring (BAR,  $C \approx 50$  m)**
  - 750 MeV energy, single-bunch accumulation: **28 nC per sec**
  - Design lead by the NSLS-II and ANL teams
- **Rapid Cycling Synchrotron (RCS,  $C \approx 1.5$  km)**
  - **0.750  $\rightarrow$  18 GeV** in 100 ms, 1 Hz
  - Spin-transparent lattice, **28 nC**, geometric  $\epsilon_{x,y}$ : 16-24 nm (x), 1.4-2.4 nm (y)
- **Electron Storage Ring (ESR,  $C \approx 3.8$  km)**
  - Beam energy: **5-18 GeV**, current : **up to 2.5 A**, SR power: up to 10 MW
  - **Polarized bunches**, swap-out injection @ one bunch per sec
- **Hadron Storage Ring (HSR,  $C \approx 3.8$  km)**
  - **Beam energy**: Injection at 23.8 GeV, accelerated to 41-275 GeV
  - **Beam current**: up to 1 A / 0.7 A with  $M = 1160 / 290$  bunches
  - **Crossing angle**: 25 mrad with crab cavities
  - **Spin rotators** (longitudinal) for p, d,  $\text{He}^3$
  - **Cooler**: low-energy electron at injection and stochastic cooling
  - **Luminosity**: up to  $10^{33}$ - $10^{34}$   $\text{cm}^{-2}\text{s}^{-1}$

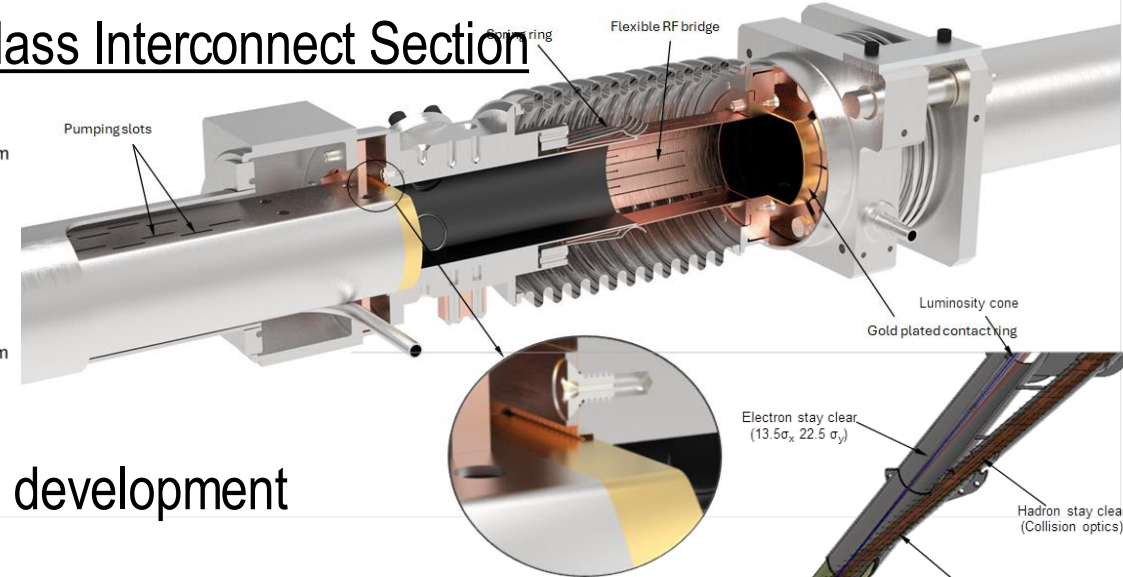


# HSR Vacuum System

- Arcs (L=2880 m)
  - $b_x = 32$  mm
  - $b_y = 24$  mm
- Straight Sections (L=953.9 m)
  - Apertures vary depending on IR
- HSR wakefield database for 4mm bunch length under active development



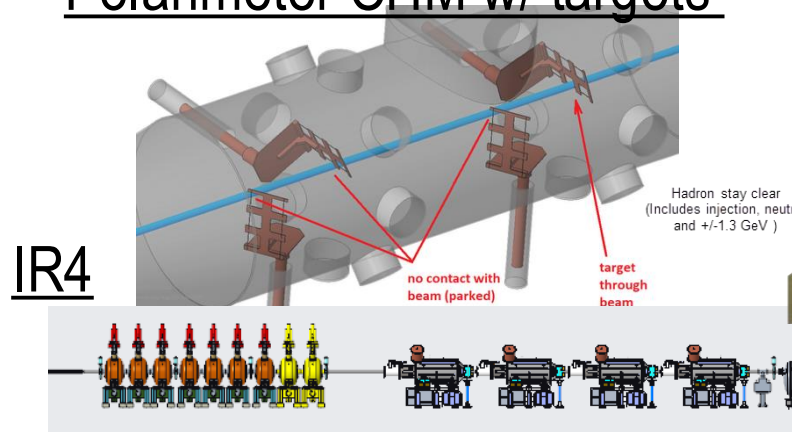
## Cold Mass Interconnect Section



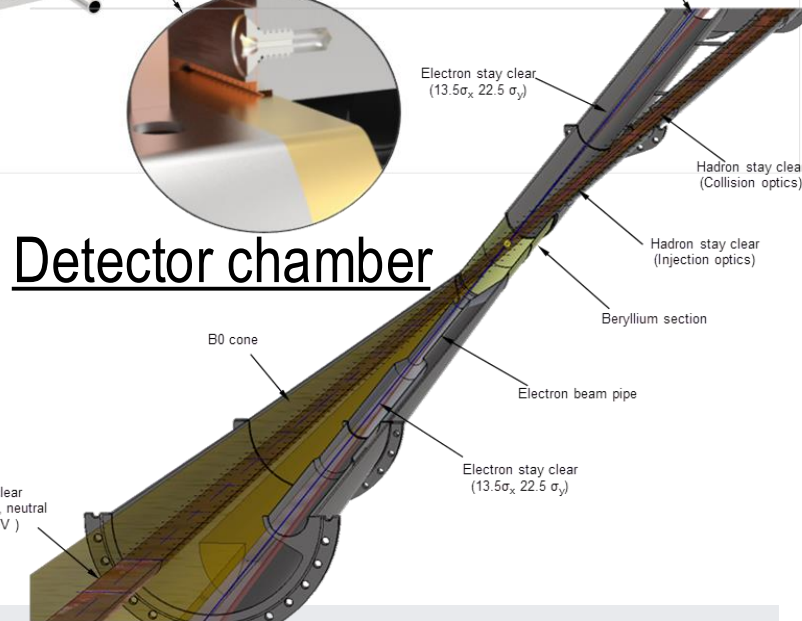
## Interaction Regions and Subsystems

- IR2 - Low Energy Cooling
- IR4 - NC RF & Stripline Kickers
- IR6 - ePIC Detector
- IR8 - SRF System
- IR10 - Empty
- IR12 - Second Detector

## Polarimeter CHM w/ targets



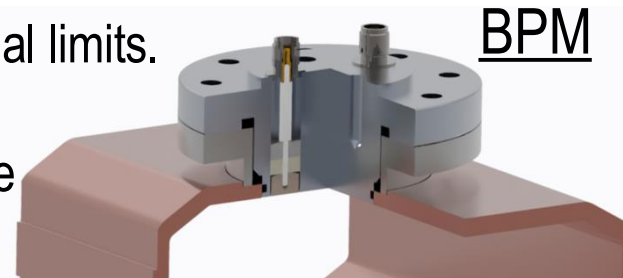
## Detector chamber



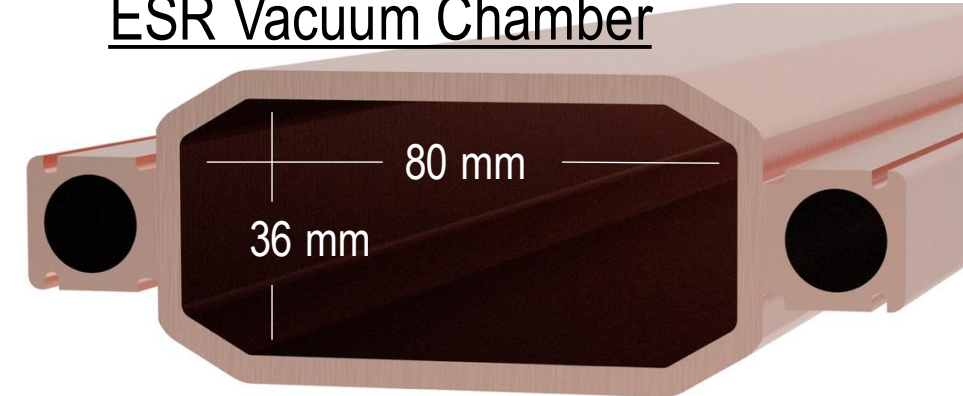
# ESR Beam Parameters and Vacuum Constraints

	5 GeV	9 GeV	18 GeV
Num. of electrons per bunch, $N$	1.72x10 <sup>11</sup>		6.25x10 <sup>10</sup>
Bunch Charge, $Ne$	28 nC		11 nC
Number of Bunches, $M$	1160		290
Single Bunch Current, $I_0 = \frac{Ne}{T_0}$	2.2 mA		0.8 mA
Bunch Length, $\sigma_\tau$	22.7 ps	25.4 ps	30 ps
Peak Bunch Current, $I_p = \frac{Ne}{\sqrt{2\pi}\sigma_\tau}$	484 A	433 A	155 A
Average Current, $I_{av}$	2.5 A	2.5 A	0.23 A

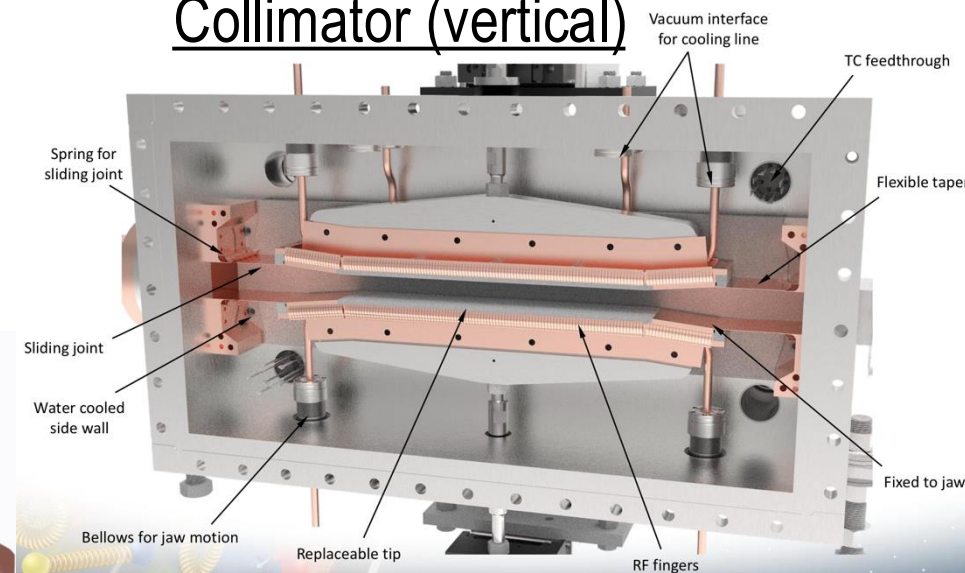
- High peak current sets wakefield and thermal limits.
- Sync. Rad. is the dominant heating source
- 18 GeV operation is part of a future upgrade
- $I_{av}=2.5$  A requires full RF configuration



ESR Vacuum Chamber



Collimator (vertical)



# Commissioning Constraints

## Commissioning Constraints

- Limited RF (2 cryomodules in ESR out of 6)
- No beam cooling (LEC/stochastic)
- No 394 MHz crab cavities in ESR & HSR
- Beam-beam limited intensity
- Conservative optics ( $\beta^*$ )

## Consequences for Luminosity

- RF  $\rightarrow$  limited beam current ( $I_e$ )
- No beam cooling  $\rightarrow$  larger emittance ( $\varepsilon$ )
- Optics  $\rightarrow$  larger  $\beta^*$
- Beam-beam parameters  $\rightarrow$  stability limit
- Reduced peak and average luminosity

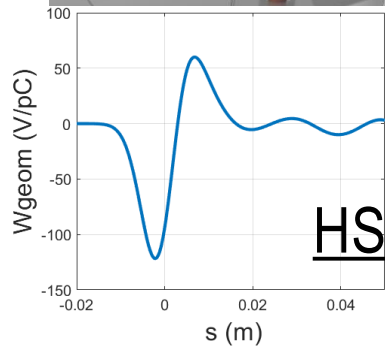
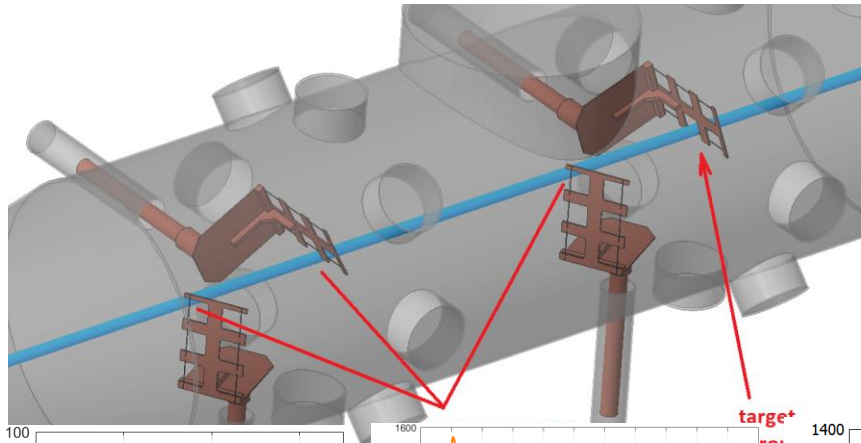
$$L \propto \frac{I_e I_h}{\varepsilon \beta^*} \cdot H$$

- Constraints are temporary and will be removed through staged RF, cooling and crab-cavity installation
- Design luminosity target:  $10^{33}$ - $10^{34}$   $\text{cm}^{-2}\text{s}^{-1}$  (full performance)

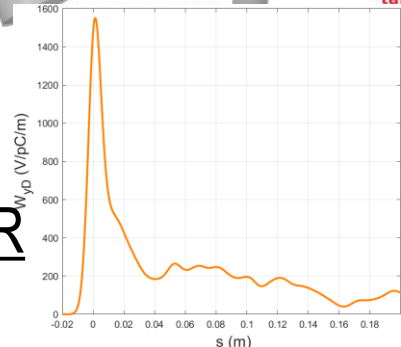
# Wakefields Constraints in Early EIC Operation

- Brand new vacuum system for RCS - ESR. Wakefields under evaluation
- HSR: reuse of RHIC StSt vacuum chambers with beam screens integrated
- Shorter HSR bunch length  $\rightarrow$  broader beam spectrum  $\rightarrow$  stronger wakefields

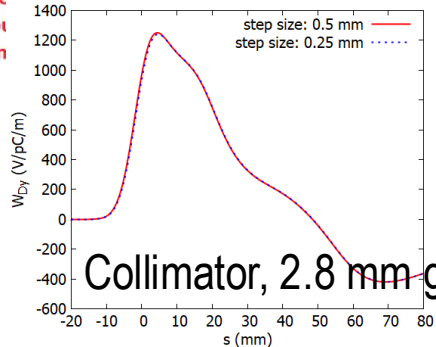
## HSR Polarimeter



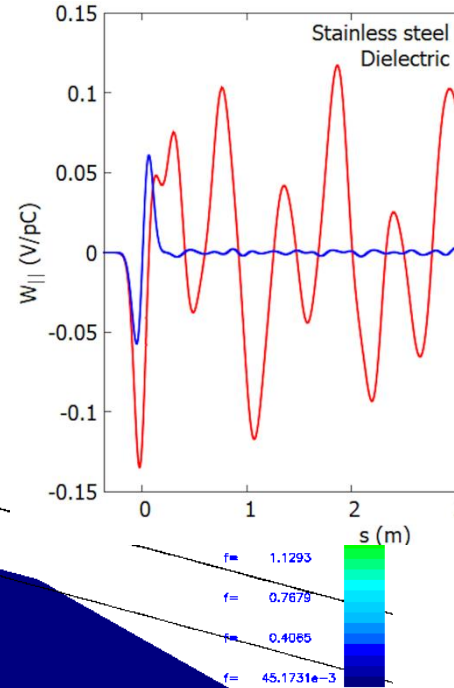
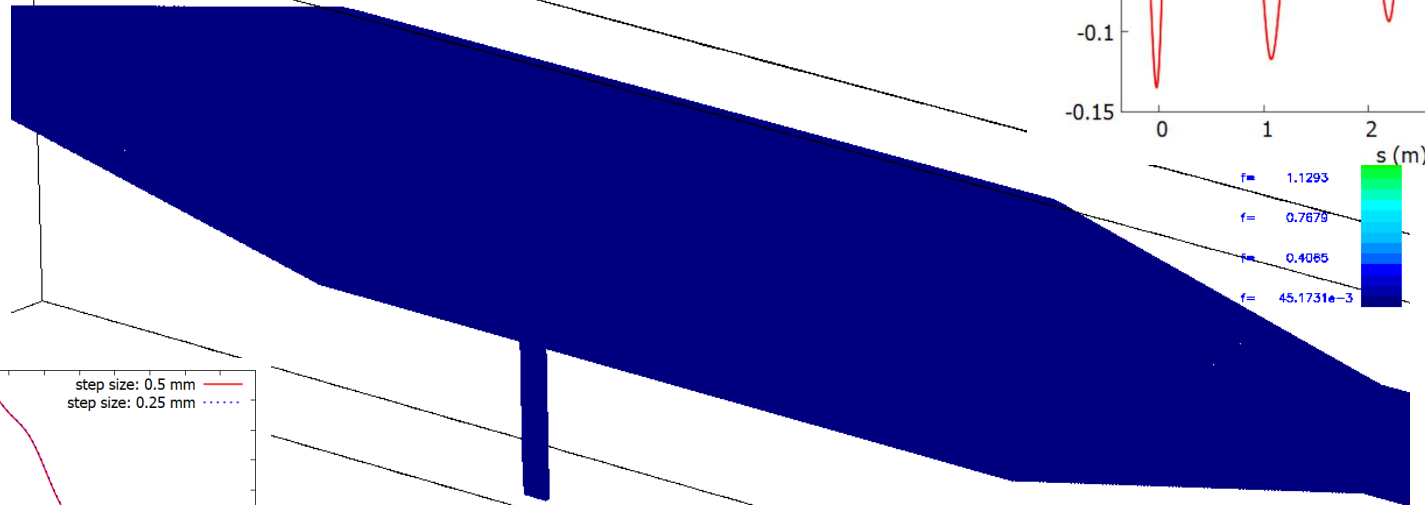
HSR



target  
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an



GdfidL, 3D Arrowplot  
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- Codes: GdfidL, ECHO 2D, ECHO 3D
- Wakefield effects are within acceptable limits

# Luminosity Scenarios: EIC Years 1-3

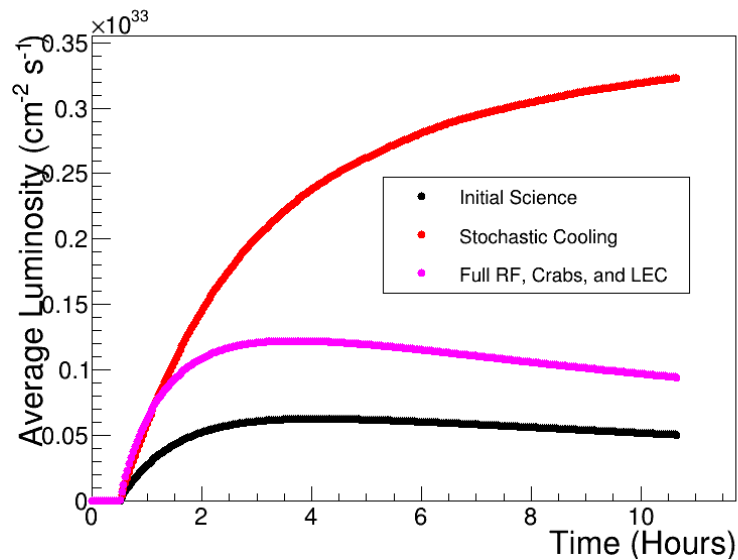
	Science Year 1	Science Year 2	Science Year 3
Species	Silver (Ag)	Deuterium (d)	Proton (p)
Energy, ESR x HSR	9 GeV e <sup>-</sup> x 118 GeV/u Ag	9 GeV e <sup>-</sup> x 130 GeV/u d	9 GeV e <sup>-</sup> x 130 GeV p
Integrated Luminosity	~0.9 fb <sup>-1</sup>	~3.9 fb <sup>-1</sup>	~1 fb <sup>-1</sup>
Average Luminosity	~6.2 × 10 <sup>31</sup> cm <sup>-2</sup> s <sup>-1</sup>	~2.7 × 10 <sup>32</sup> cm <sup>-2</sup> s <sup>-1</sup>	~6.8 × 10 <sup>31</sup> cm <sup>-2</sup> s <sup>-1</sup>
Polarization, e <sup>-</sup> / h	Commissioning only / No	Yes / No	Yes / Yes
Average Current, I <sub>e</sub> x I <sub>h</sub>	0.63 A x 0.07 A	0.9 A x 0.3 A	0.9 A x 0.3 A
Number of Bunches	290 x 290	1160 x 1160	1160 x 1160
Roman Pot	No	No	Yes

- **Electron injector:** 28 nC at 9 GeV      *HERA delivered ~0.5 fb<sup>-1</sup> luminosity → EIC starts above this level*
- **ESR:** 2 RF Cryo Modules (4 cavities); M=290 (28 nC) or M=1160 (~10nC) at 9 GeV
- **HSR:** w/o Beam Cooling and 394 MHz Crab Cavities, intensity limited by beam-beam effects
- **Assumptions:** 30 weeks/year with a 2.5-hour turnaround time and 80% facility availability

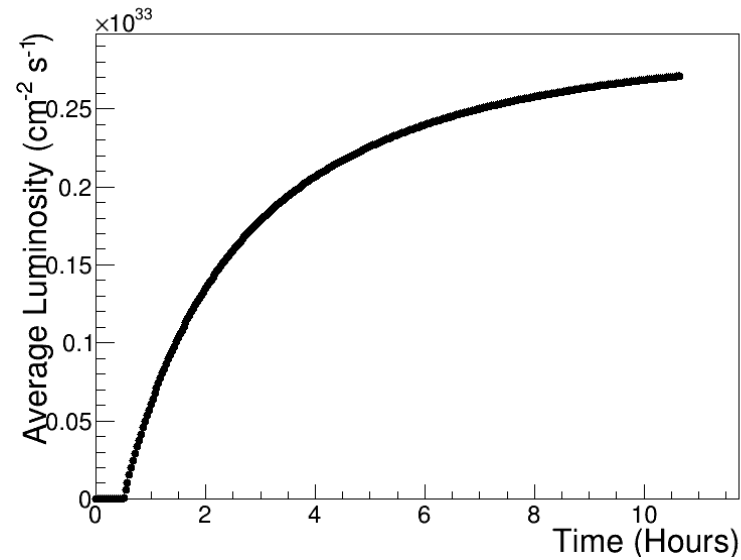
# Beam Cooling And Luminosity Performance

- The same beam parameters for p and d
- Luminosity higher for deuterium (d)
- Initial science: no cooling and partial RF/crab configuration → lower luminosity

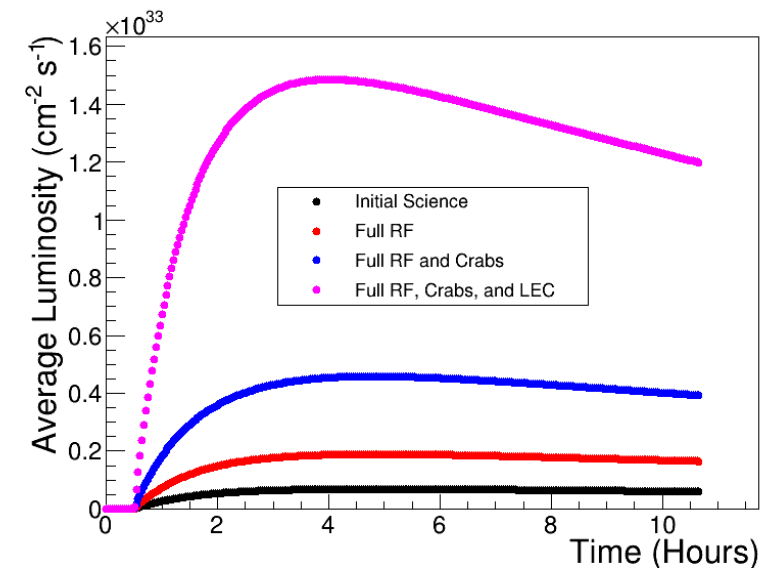
e-Ag (Year 1 assumptions)



e-d (Year 2 assumptions)



e-p (Year 3 assumptions)



# Commissioning Considerations for Early Operation

- **Collimation System**

- Coupling impedance and beam loss control
- Machine protection during intensity ramp-up

- **SRF System and HOM Damping**

- Control of HOM and heating
- Stability at increasing beam current

- **Interaction Region / Detector Integration**

- Roman Pots, polarimeters, detector chamber

- **Injection Beam Dynamics (HSR)**

- No low-energy cooling in early operation
- Larger hadron emittance
- Impacts beam-beam parameters and achievable luminosity
- Space-charge and Geom.+RW wakefield effects

- **Electron Injector / ESR Operation**

- High bunch charge ( $\sim 28$  nC) in the BAR

- **Crab Cavities (Staged Configuration)**

- 197 MHz system available for early operation
- 394 MHz system implemented in later stage
- Full configuration required for optimal luminosity

- **Beam-Beam and Spin Dynamics**

- Beam-Beam interaction and stability
- Polarization preservation in collisions

- *Early performance is achieved through staged commissioning, with luminosity increasing as RF, cooling, and crab systems are progressively implemented.*

# Staged Commissioning

## Staged Commissioning

- Stage 0: First beam / subsystems checkout
- Stage 1: Early collisions (low current)
- Stage 2: Optics tuning, beam-beam, MPS validation
- Stage 3: Beam intensity ramp-up

## Staged System Installation

- RF: 2 → 6 cryomodules
- Beam cooling: none → LEC/stochastic
- Crab cavities: 197 MHz → 394 MHz
- Optics: conservative →  $\beta^*$  squeeze
- HSR 41 GeV bypass

- Luminosity increases stepwise with staged commissioning and subsystem installation

## Physics Impact

- $I_e \uparrow$
- $\varepsilon \downarrow$
- $\beta^* \downarrow$
- Beam-beam limit  $\uparrow$

# Summary

- **Early EIC performance is not design-limited, but constraint-driven, dominated by RF availability, transverse diffusion, and beam-beam limits.**
- **A staged commissioning strategy defines the achievable operating envelope and enables a progressive increase in beam current and performance.**
- **Realistic early operation scenarios yield average luminosities in the  $10^{31} - 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  range, with stepwise improvement toward the ultimate EIC performance,  $10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ .**
- **Beam cooling and the complete RF and crab-cavity configuration are the key performance drivers for reaching design luminosity and maximizing forward acceptance (i.e., detection of small-angle particles in the forward region).**
- **Unique science questions will be addressed at initial luminosities as EIC performance ramps up to its full capability.**

# EIC Team Poster Contributions

Conversion of 28 MHz Cavities to 24.6 MHz Cavities for the EIC Hadron Storage Ring	(TUP7309)
High Power BLA Test Update and Path Forward for the EIC BLA	(WEP1320)
High Power FPC Progress for EIC ESR Cavities	(WEP1321)
Nickel-Zinc Ferrite Fast Tuner of the 24.6 MHz Accelerating Cavity for Transition Crossing	(WEP1333)
Progress of the RF Systems for the Electron-Ion Collider	(WEP1318)
Progress on the Normal-Conducting RF Cavities for the EIC Hadron Storage Ring	(TUP7307)
RF Design of the 49 and 98 MHz Normal-Conducting Cavities for Bunch Splitting in the EIC HSR	(TUP7310)
RF Design Progress of the 197 MHz Crab Cavity for EIC	(TUP7308)
Design and Recent Developments of the Electron Storage Ring for the Electron-Ion Collider	(WEP1332)
High-Average-Current, High-Brightness HVDC Electron Gun development for EIC Hadron Cooling	(WEP1352)
Space Charge Effects on Spin Polarization in a High-Intensity Preinjector	(WEP1353)
Preinjector Design Update for the EIC	(WEP1354)
SciBmad: A differentiable and GPU-parallelized software library for particle accelerator design, nonlinear analysis, and machine learning	(THP5325)
Injection Requirements for Electron Swap-Out in the EIC-ESR	(WEP1357)
Two-System RF Ramping for the EIC Rapid Cycling Synchrotron	(WEP1314)
Status of the Rapid Cycling Synchrotron Optics	(MOP1302)
Electron-Ion Collider (EIC) Project: An Overview on Recent Progress	(WEP1319)