



The 70th ICFA Advanced Beam Dynamics
Workshop on High Luminosity Circular
e⁺e⁻ Colliders (eeFACT 2025)



Recent Advances in Beam-Related Background Studies at the Electron-Ion Collider

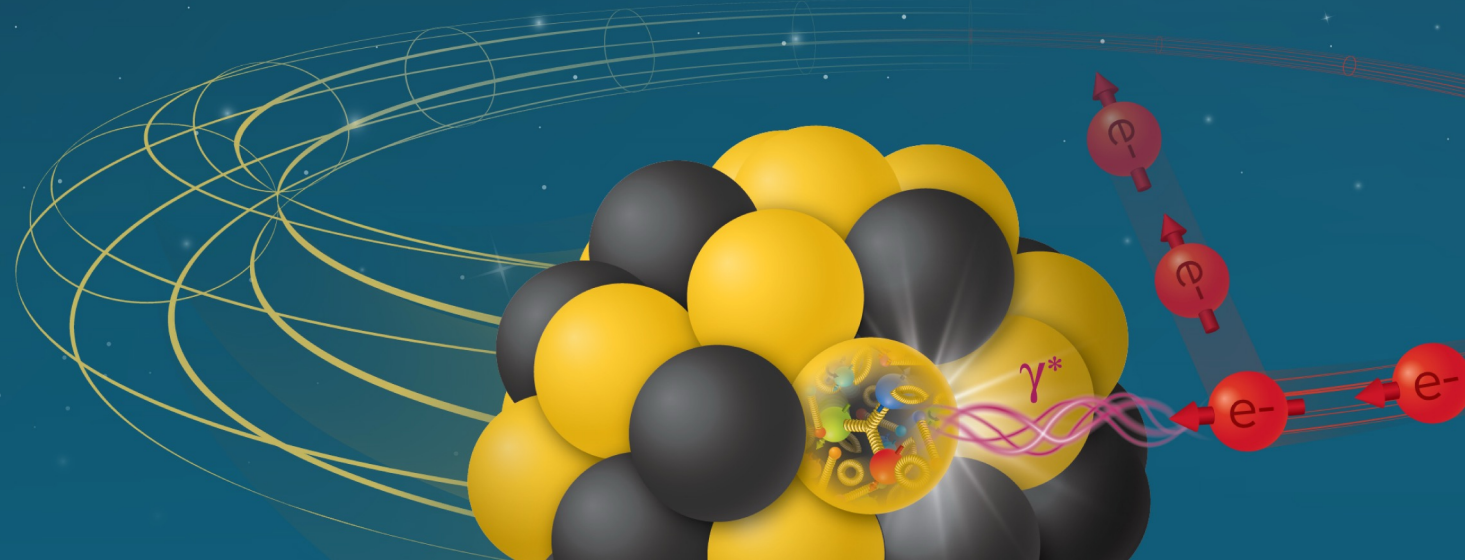
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Tsukuba, JAPAN

March 3-7, 2025

Electron-Ion Collider



Outline

- **Science Highlights**
- **Experiment Design**
 - Collider
 - Detectors
- **MDI**
 - Beam Backgrounds
 - Estimated Rates
 - Synchrotron Radiation
 - Multi-turn Particle Tracking
- **Prospects**
- **Summary**



Science Highlights



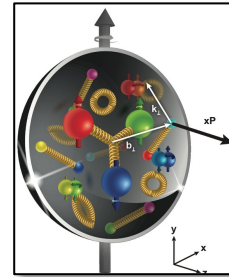
Spin is one of the fundamental properties of matter.

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?

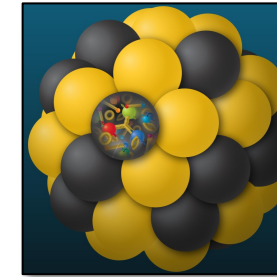
The EIC will determine an important term contributing to the proton mass.



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

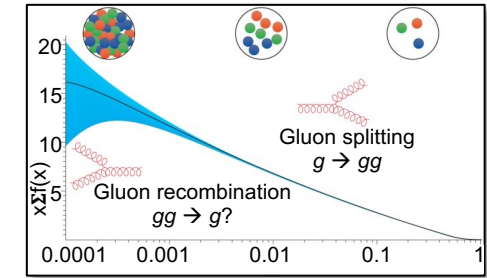
How do the **nucleon properties** emerge from them and their interactions?
How can we understand their **dynamical origin in QCD**?

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**?



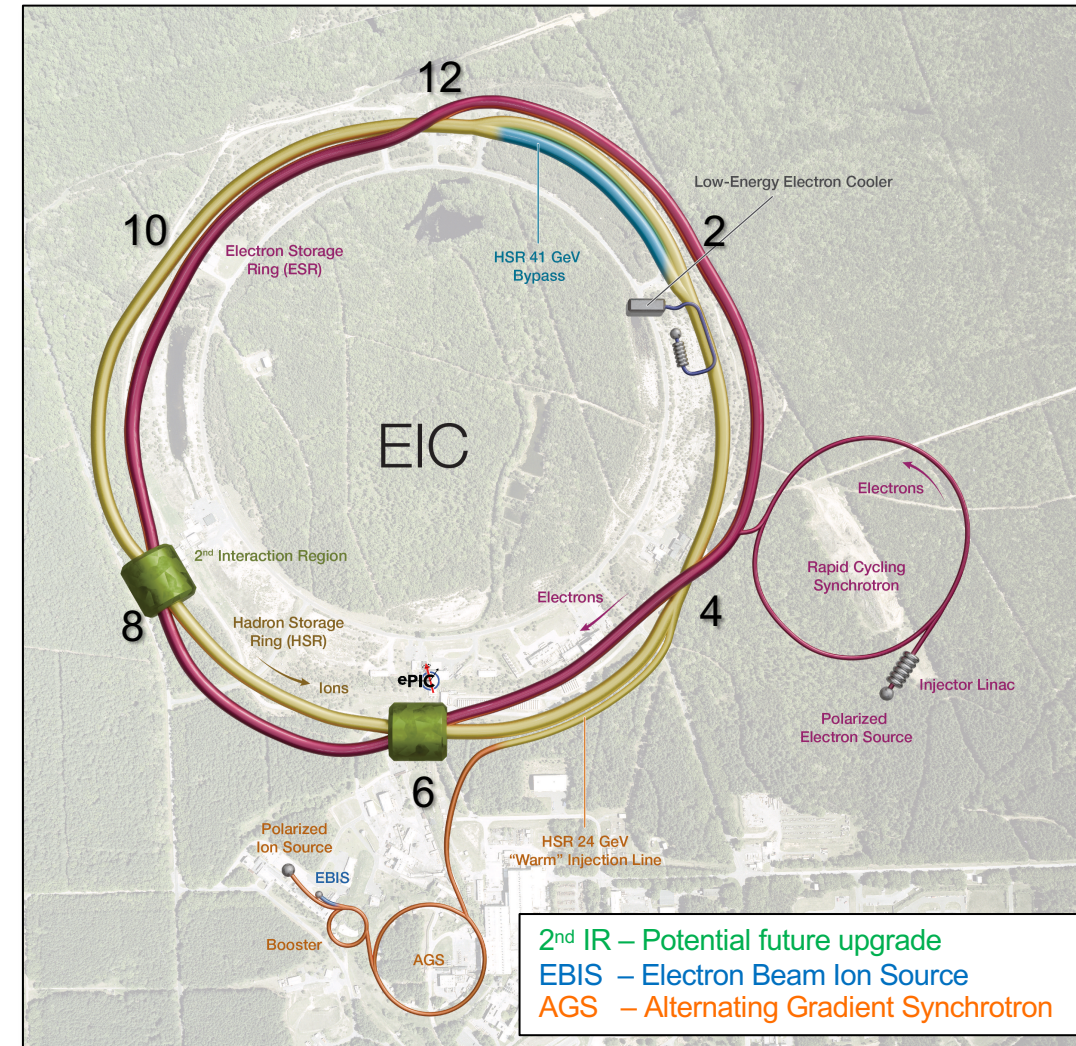
How many **gluons** can fit in a proton?

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**?

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)
 - $E_p = 41, 100\text{--}275\text{ GeV}$
 - $I_p = 0.38\text{--}1.0\text{ A}$
- Electron Storage Ring (ESR)** ← *Build a new ring*
 - $E_e = 5\text{--}18\text{ GeV}$
 - $I_e = 0.227\text{--}2.5\text{ A}$
 - 1 Hz swap-out bunch replacement
- High polarization of ~70% for electron and light ion beams
- $E_{\text{CM}} = 29\text{--}141\text{ GeV}$
- $L = 10^{33}\text{--}10^{34}\text{ cm}^{-2}\text{s}^{-1}$
- 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):

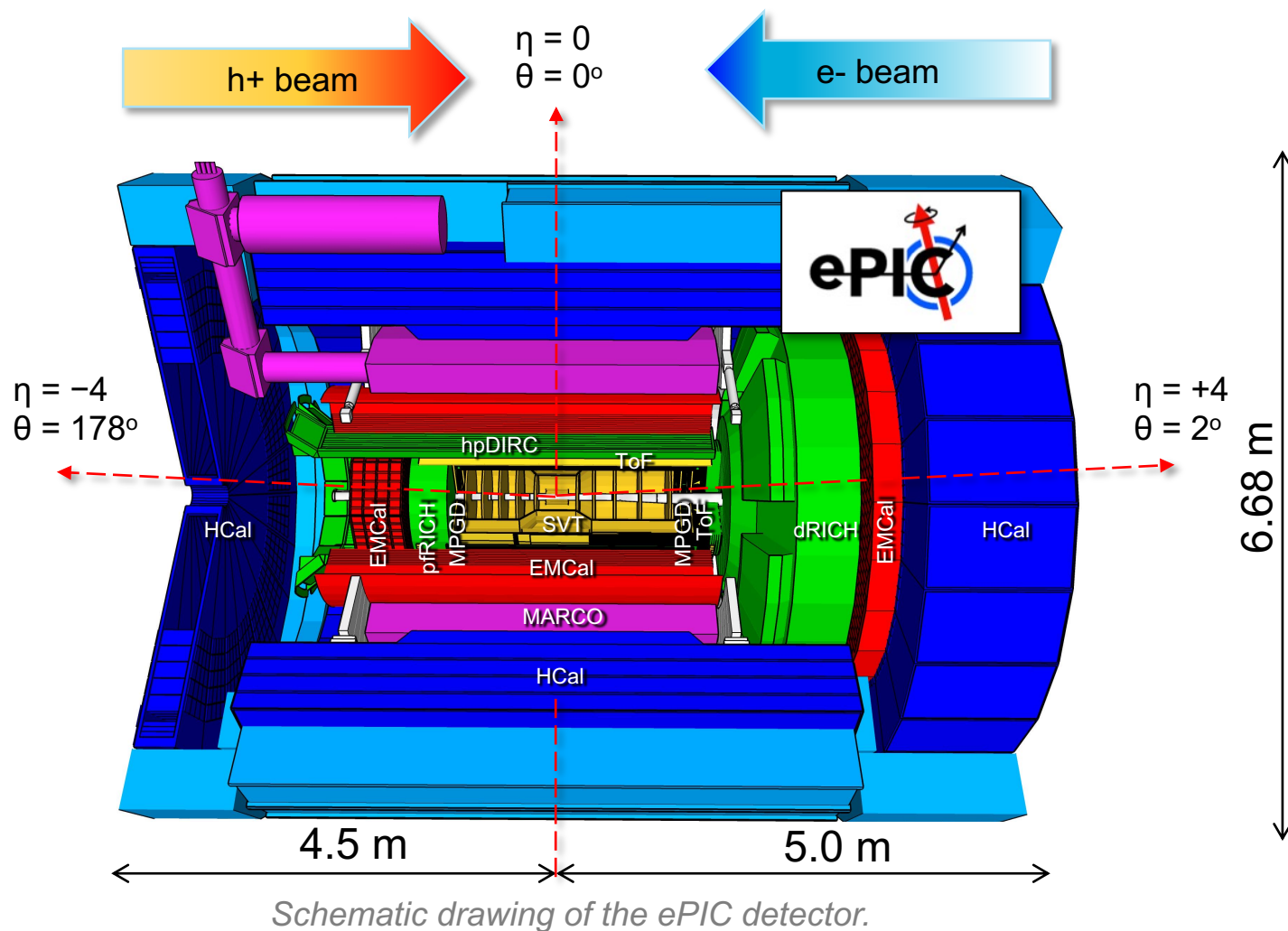
- High-performance single track PID for π , K , p separation
 - Backward proximity focusing RICH (pfRICH)
 - Barrel high-performance (hpDIRC)
 - Forward dual-radiator RICH (dRICH)
 - Barrel & Forward ToF

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

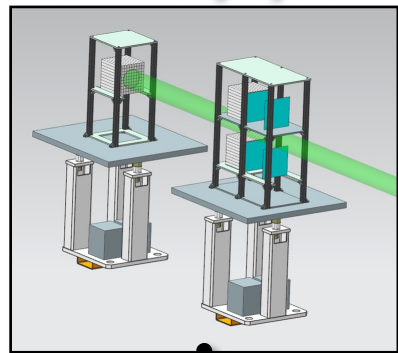


Auxiliary Detectors

- Far-distant region (> 5 m from the IP)
- Luminosity photon measurements
- Scattered electron, photon, neutron, and hadron detection

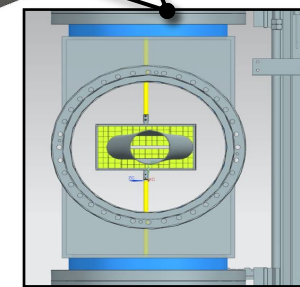
- Backward: Low- Q^2 silicon pixel taggers, Luminosity monitor
- Forward: Zero-Degree Calorimeter, Roman-Pots and Off-momentum detectors, B0-tracking and Photon detection

Luminosity System

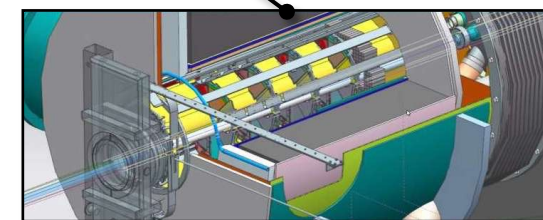


The integration of all detector systems, cabling, support structure design, seismic and magnetic forces, moving mechanisms, gas/electricity supply, and safety are still under development.

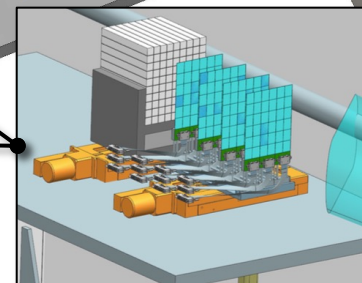
Zero Degree Calorimeter



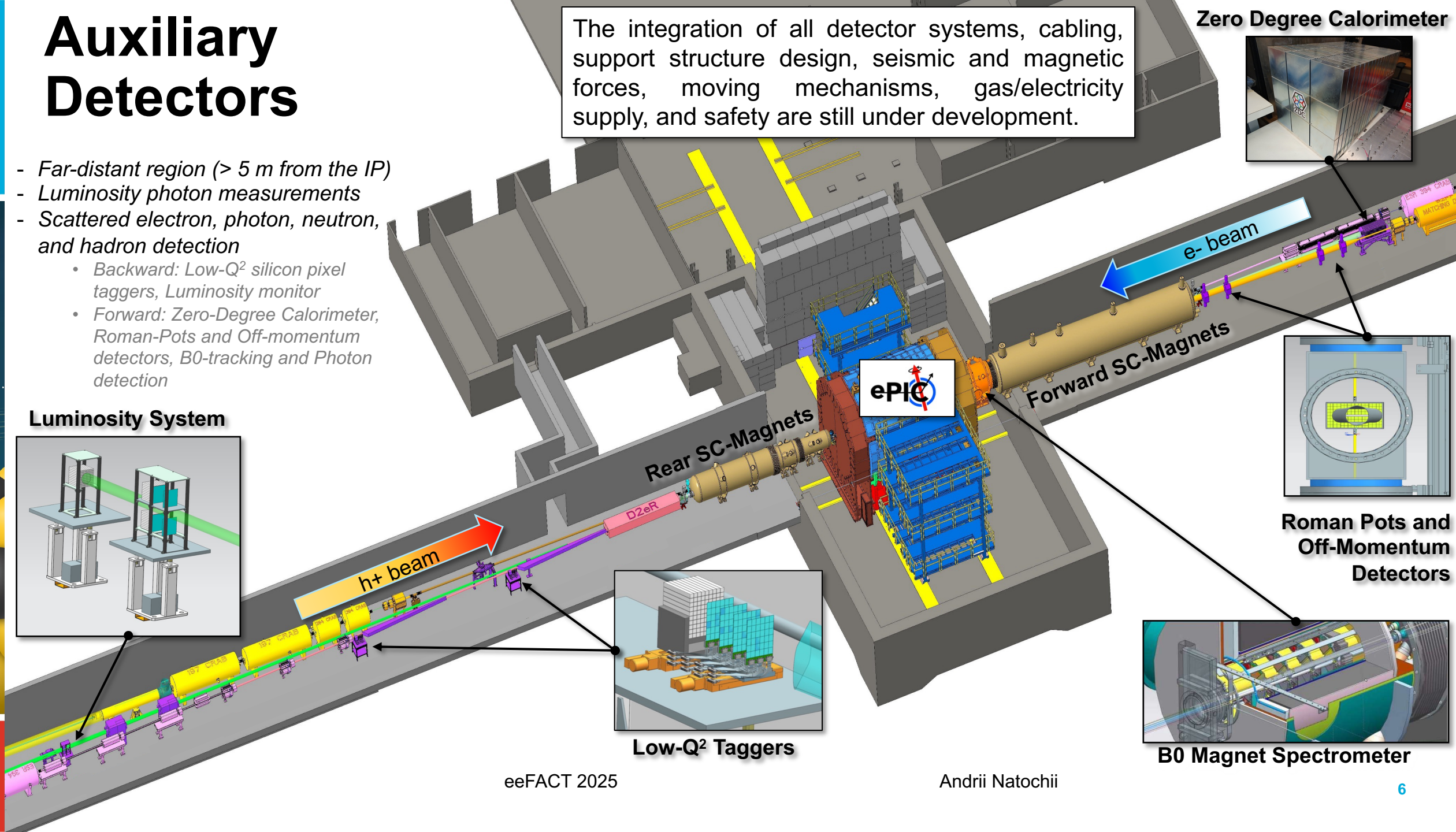
Roman Pots and Off-Momentum Detectors



B0 Magnet Spectrometer

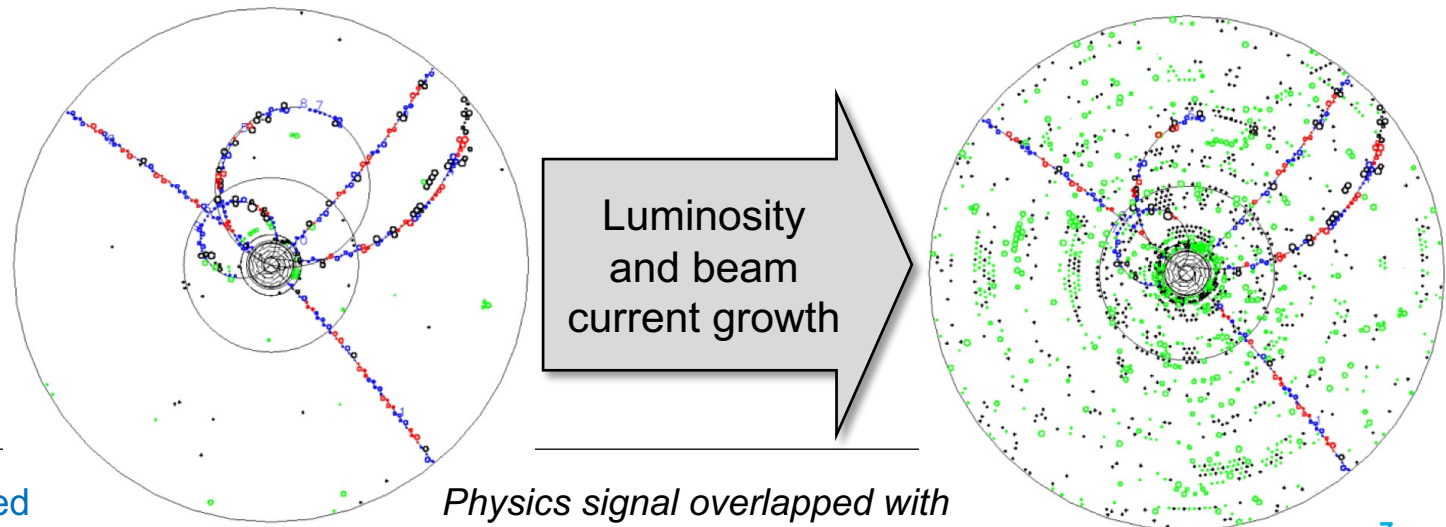
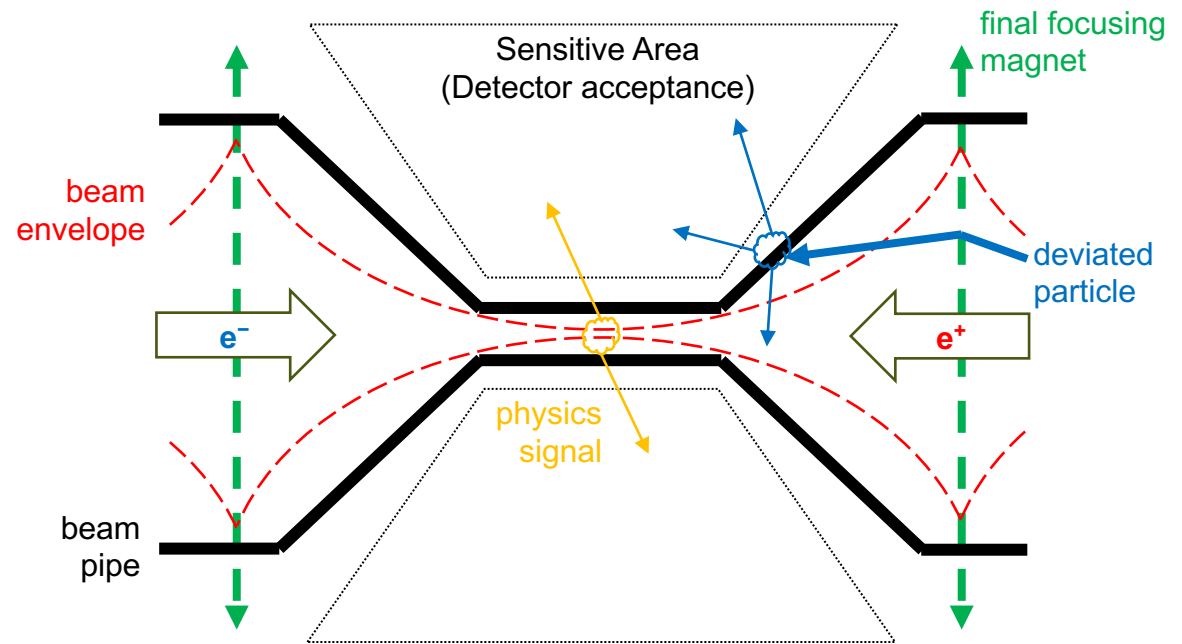


Low- Q^2 Taggers



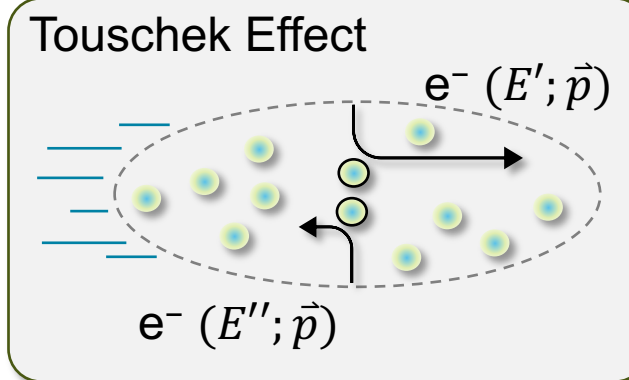
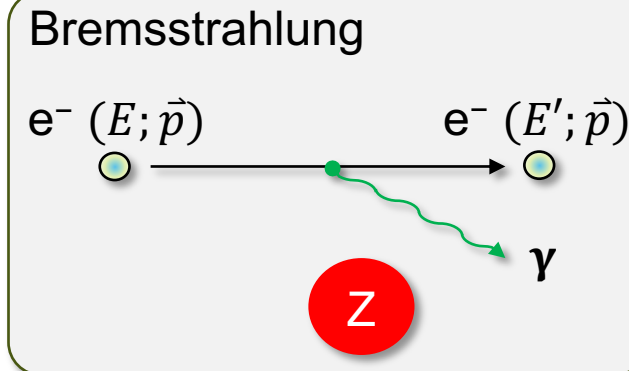
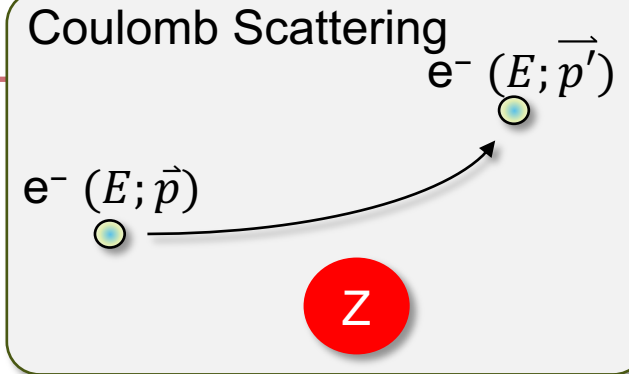
Detector Background

- Beam particles that **deviate from the nominal orbit** are eventually lost by **hitting the beam pipe's** inner wall or other machine apparatus.
- If the loss position is close to the detector, generated **shower particles** might reach the detector and increase its dose and hit rate.
- This increase is referred to as **beam-induced background** and is one of the most difficult challenges at the collider.
- It is **crucial to understand** all main sources of beam losses affecting machine and detector components' longevity and causing detector performance degradation.



Background Sources

- Lessons learned from HERA (e/p) and SuperKEKB (e+/e-) have been considered.
- Main mechanisms causing detector BGs from stored beams:
 - **Electron beam:**
 - **Beam-gas scattering** through Coulomb and Bremsstrahlung (Bethe-Heitler) processes:
 - Elastic and inelastic beam particle scatterings on residual gas molecules and a hadron beam.
 - **Touschek effect:**
 - Incoherent scattering of the particles in the same beam bunch.
 - **Synchrotron radiation (SR)**
 - Generated by nearby dipole magnets (X-ray reflections) and final focusing magnets (direct X-rays).
 - **Hadron beam:**
 - **Beam-gas scattering** through Coulomb process.
 - **Inelastic beam-gas interaction** (producing showers of secondaries in the IR).
- Detector BGs from the **injected beam**:
 - The hadron beam is planned to be refilled once in 5-10 hours.
 - The electron beam will be refilled every ~20 minutes.



Background Mitigation

- Lessons learned from HERA (e/p) and SuperKEKB (e+/e-) have been considered.
- Main mechanisms causing detector BGs from stored beams:

- **Electron beam:**

- **Beam-gas scattering** through Coulomb and Bremsstrahlung (Bethe-Heitler) processes:

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Vacuum scrubbing

- **Touschek effect:**

- Incoherent scattering of the particles in the same beam bunch

Collimation

- **Synchrotron radiation (SR)**

- Generated by nearby dipole magnets (X-ray reflections) and final focusing magnets (direct X-rays).

SR masking & Optics Tuning

- **Hadron beam:**

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Collimation

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Vacuum scrubbing

- Detector BGs from the **injected beam**:

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- The electron beam **On-energy/axis injection within the machine aperture**

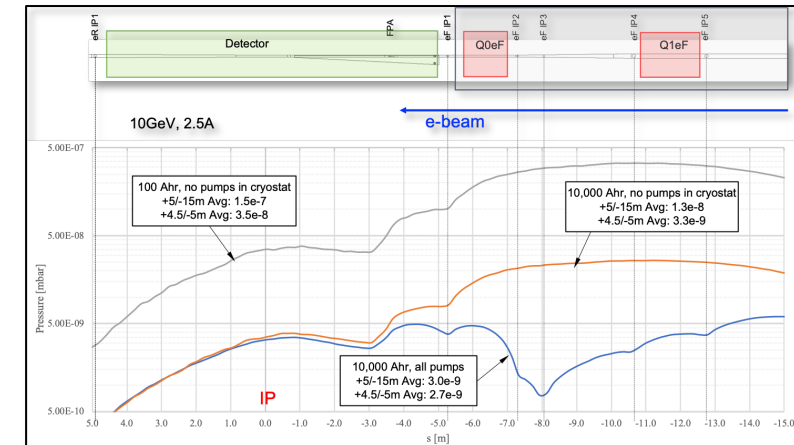
Estimated Beam-gas Rates in the IR

- The physics signal has a much lower cross-section (< 0.1 mb) compared to the electron and hadron beam-gas events (~ 1000 mb and ~ 100 mb, respectively).
 - The beam-gas BG dominates the physics signal unless proper mitigation strategies are developed, including but not limited to triggering, shielding, and collimation.
- Moreover, a good vacuum is critical to keep beam-gas related BGs under control.

rates in kHz	5x41 GeV	5x100 GeV	10x100 GeV	10x275 GeV	18x275 GeV	Vacuum
Total ep	12.5 kHz	129 kHz	184 kHz	500 kHz	83 kHz	
hadron beam gas	12.2kHz	22.0kHz	31.9kHz	32.6kHz	22.5kHz	10000Ahr
	131.1kHz	236.4kHz	342.8kHz	350.3kHz	241.8kHz	100Ahr
electron beam gas	2181.97 kHz	2826.38 kHz	3177.25 kHz	3177.25 kHz	316.94 kHz	10000Ahr

Collision and beam-gas rates in the detector region Ref.[1].

vacuum scrubbing



Estimated vacuum pressure profile in the IR.

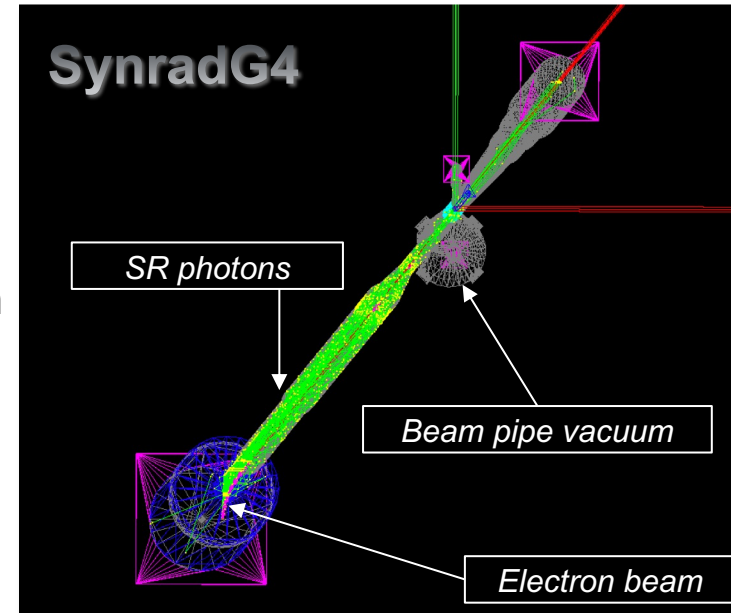
For the proper beam halo collimation and SR masking, we recently started two Monte-Carlo campaigns with **SR simulations** and **multi-turn particle tracking** discussed on the next slides.

A New Framework for SR Studies – SynradG4

Developed on Geant4 to address the limitations of widely used frameworks – [Synrad+](#) and [Synrad3D](#).

- **Features:**

- Precise particle tracking using Geant4 libraries with complex 3D geometries imported from CAD files.
- Same X-ray reflection models as Synrad+.
- Multiprocessing support (runs on personal computers and large-scale computer farms).



Preprint and **open-source** code:
A. Natochii (2024)
<https://arxiv.org/abs/2408.11709>

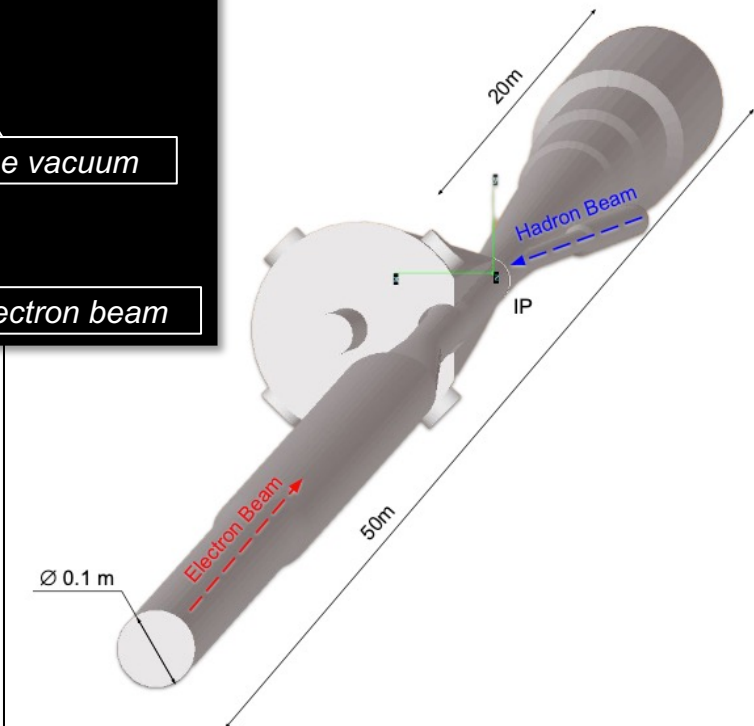


Figure 3: A drawing of the IR beam pipe vacuum around the IP.

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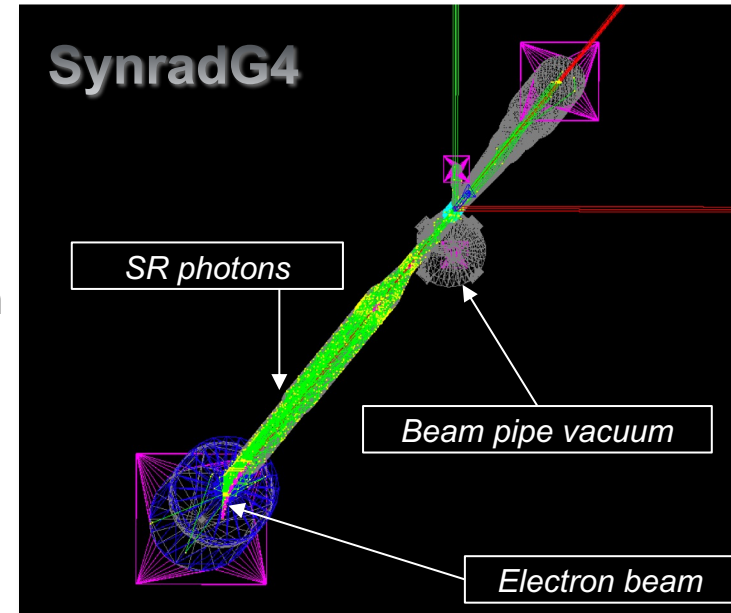
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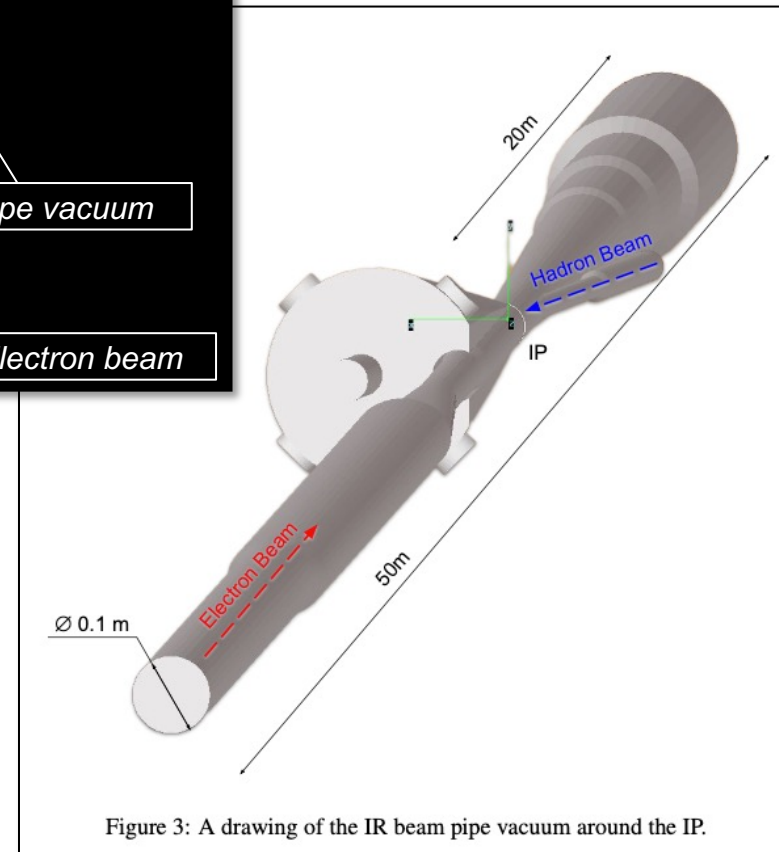
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- **Outputs:**

- Absorbed SR photons exportable as ROOT/HepMC3 for DD4hep ePIC detector model integration.
- Benchmarked against Synrad3D, Synrad+, and Geant4.



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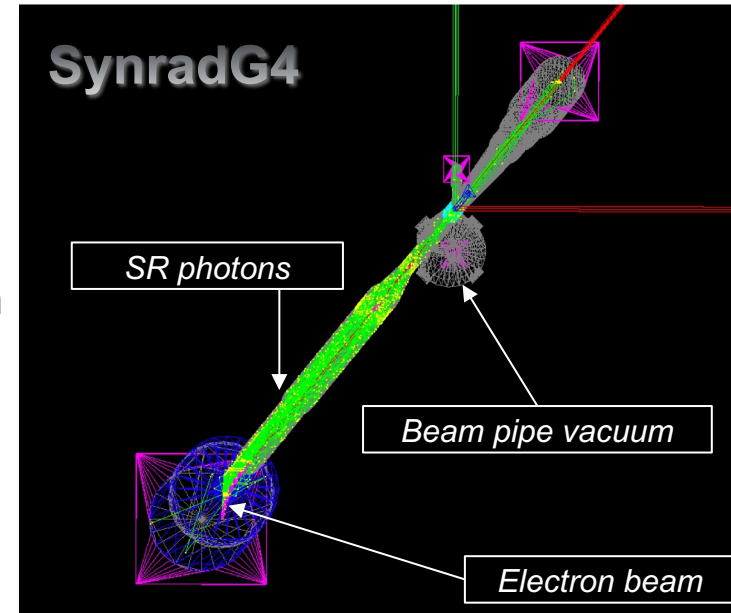
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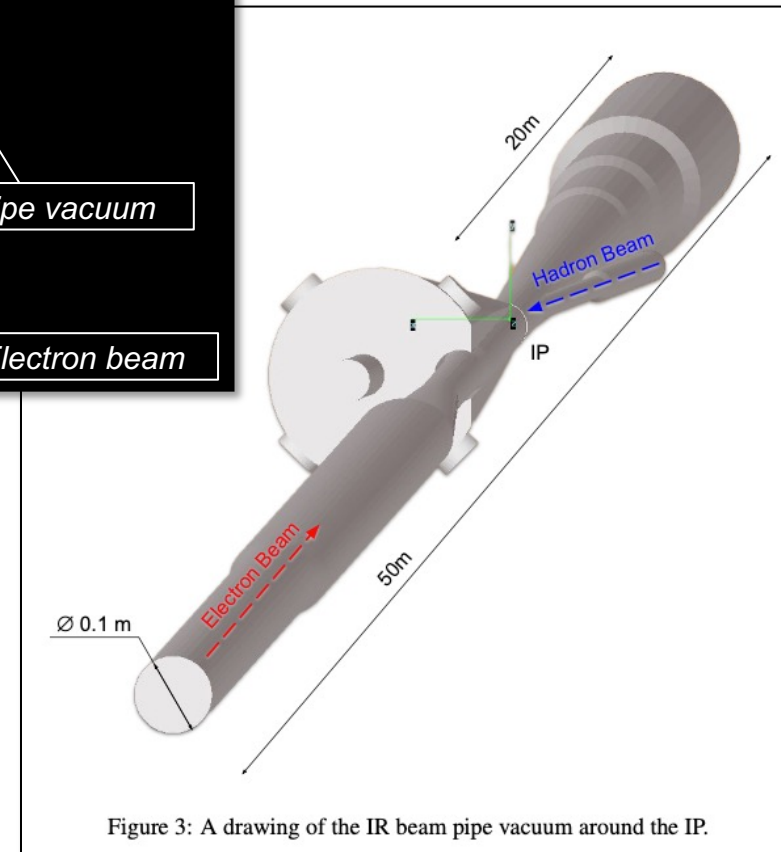
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- **Impact:**

- SynradG4 enhances SR background simulations, ensuring precision for ePIC detector studies.



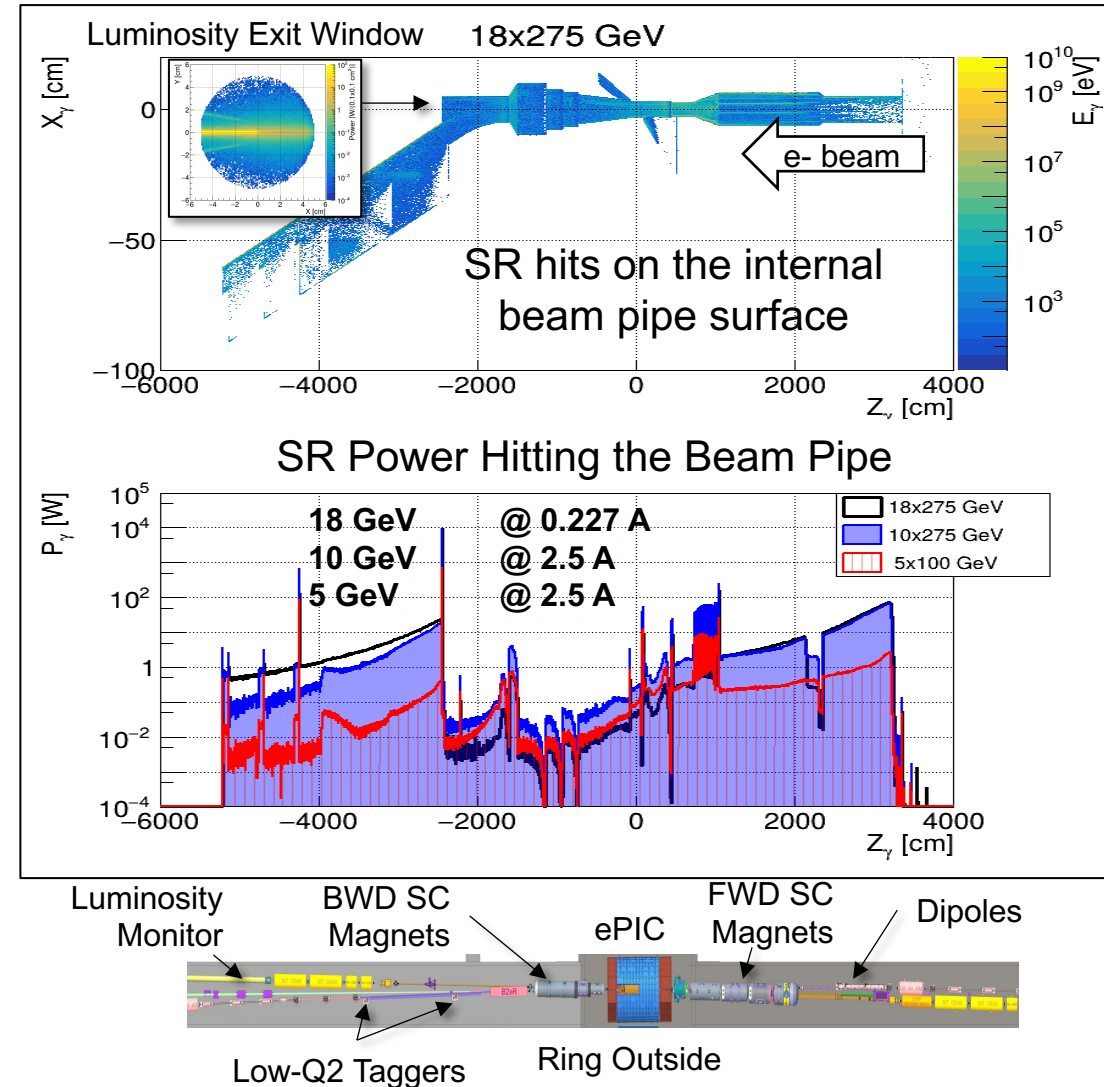
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Advancements in SR Studies with the New Code

- **SR Simulation Capabilities:**

- Enables detailed SR studies in the ESR across varying machine and detector configurations



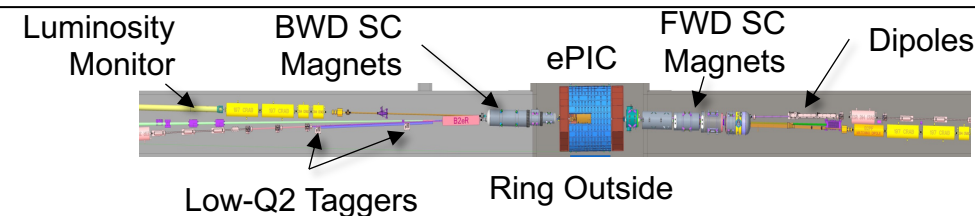
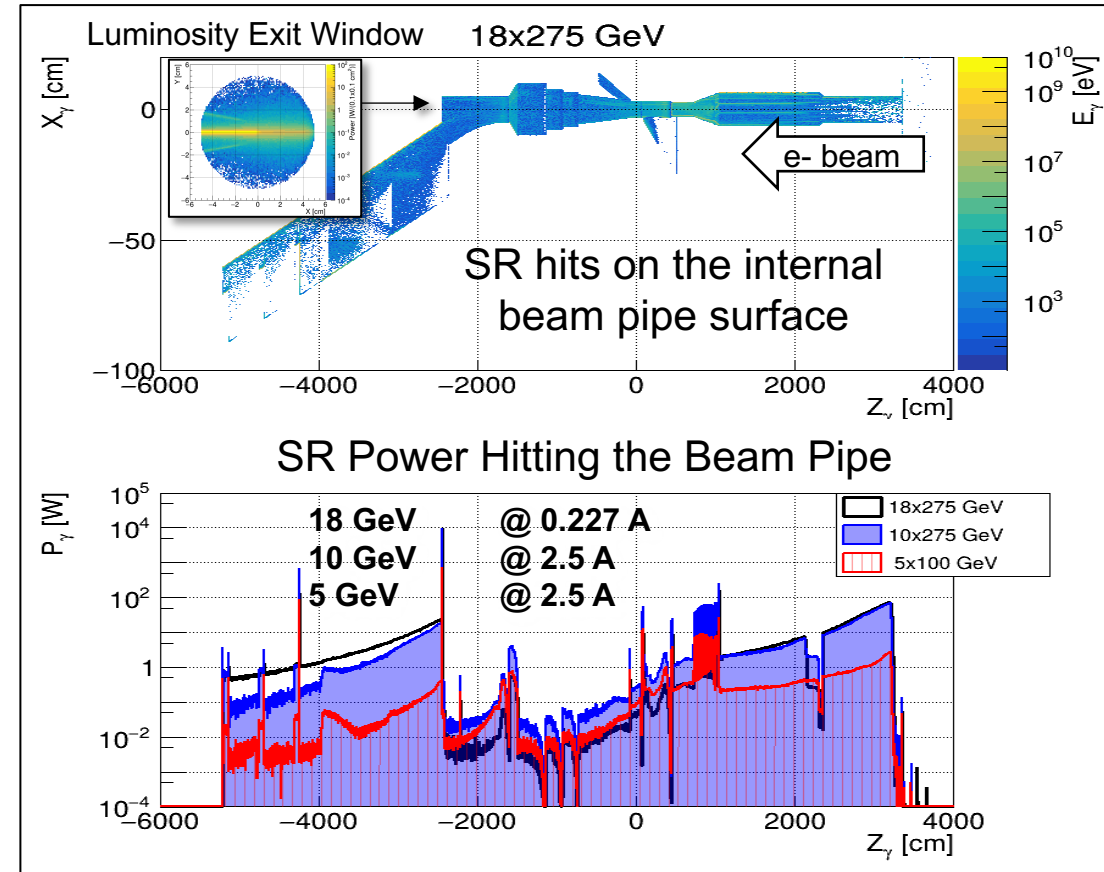
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- **Key Findings:**

- Highest SR load of **~ 0.1 kW** and **~ 0.1 W** on the superconducting (SC) quad cold mass is at 18 GeV (0.2 A) and 10 GeV (2.5 A), respectively
- The ePIC detector SR background rates are **~ 1 THz** at 18 GeV (0.2 A)
- High SR power on the Lumi Window of max. **~ 100 W/mm²**



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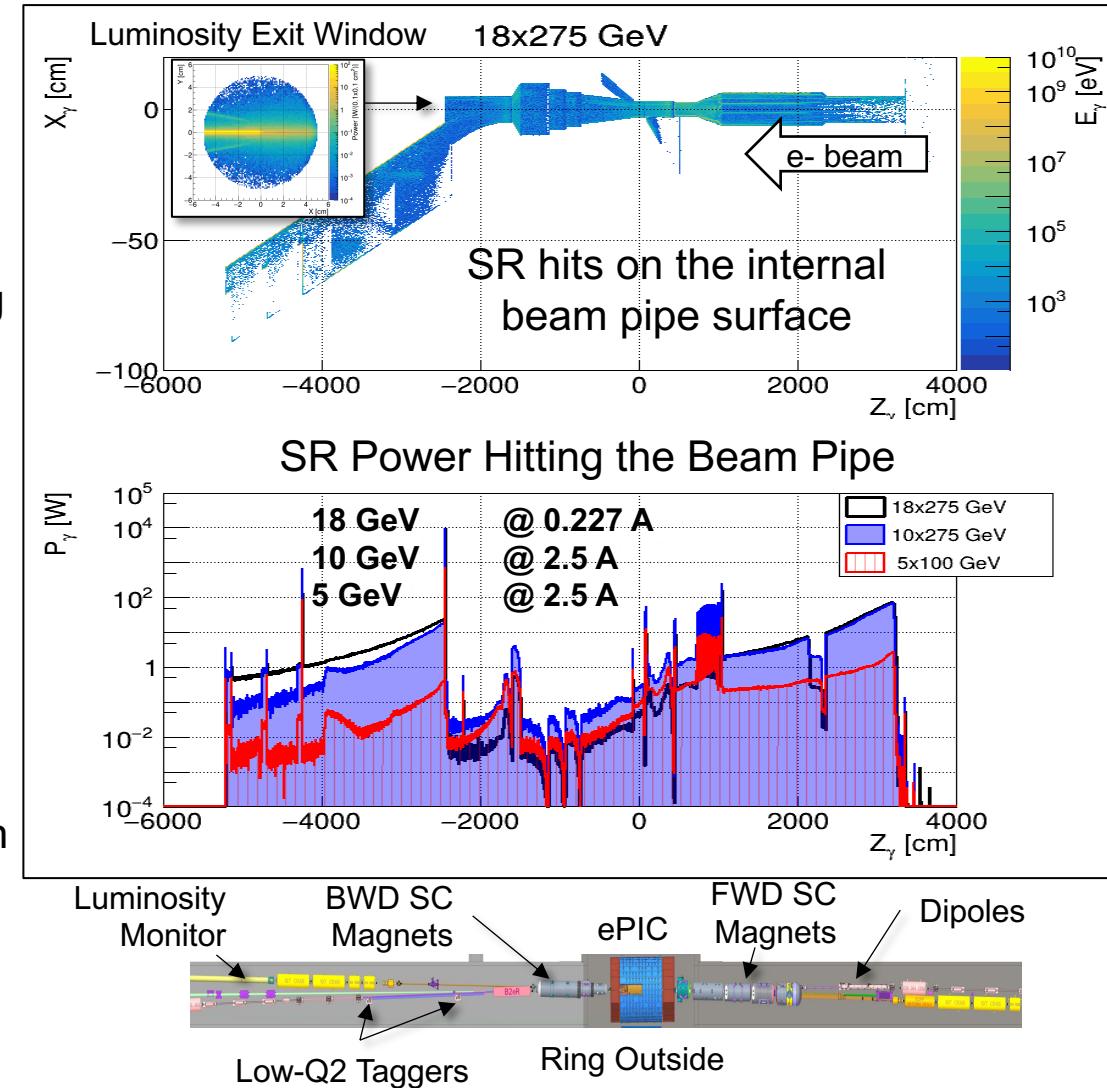
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- **Countermeasures:**

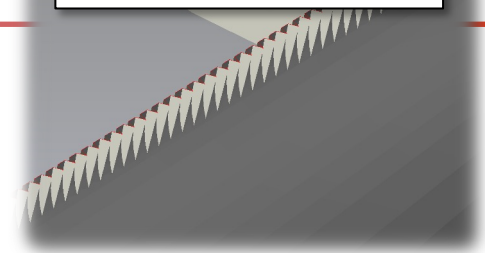
- High-Z shielding can reduce the load on SC quads by a few orders of magnitude **below the safety limit**
- Dedicated SR masking significantly reduces detector rates down to **~ 0.1 GHz**
 - *Contributions from upstream dipoles and final focusing quadrupoles are nearly equivalent*
- Adjust the dipole in front of the Lumi Window to **reduce SR**



SR Tracks Hitting the IP

- By placing a so-called “saw-tooth” mask (2 mm height, 20 mm step) along the upstream beam pipe the SR hitting the IP beam pipe can be reduced by a factor of ~ 1000 .
- X-ray reflection is essential for the accurate SR estimation along the beamline.

SR mask prototype



A. Natochii (2024) <https://arxiv.org/abs/2408.11709>

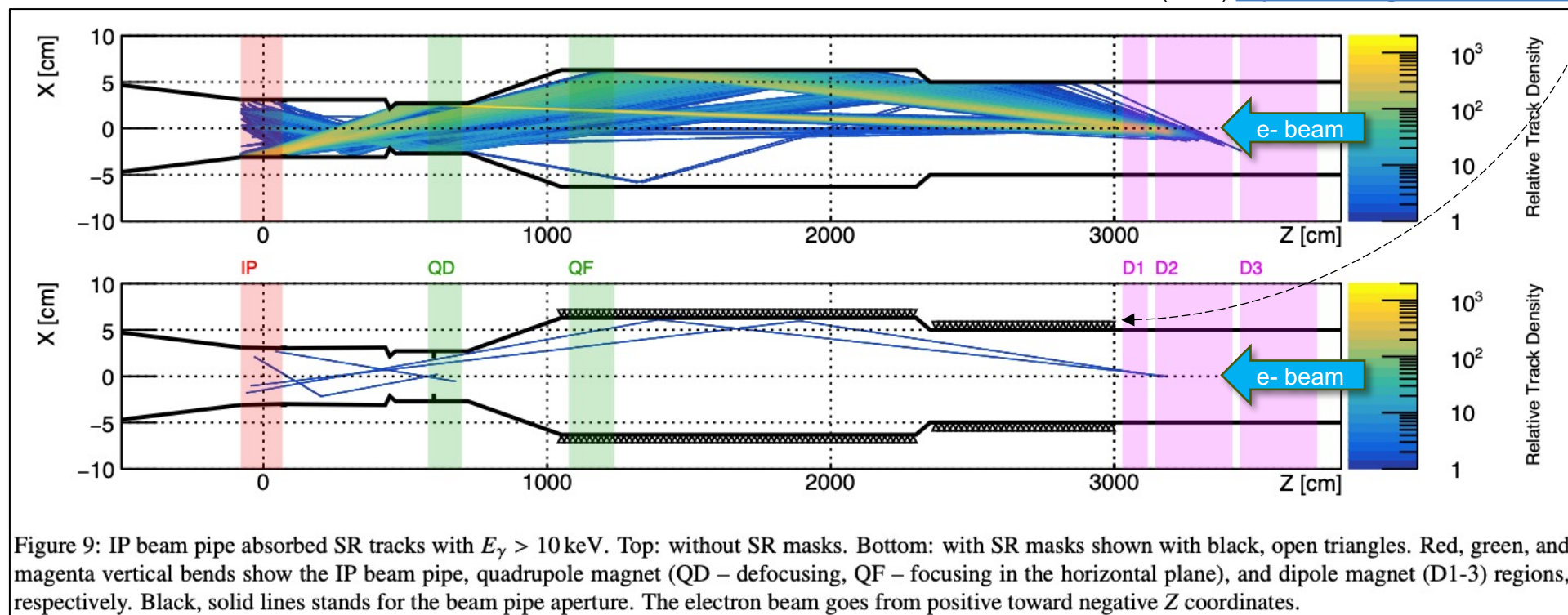


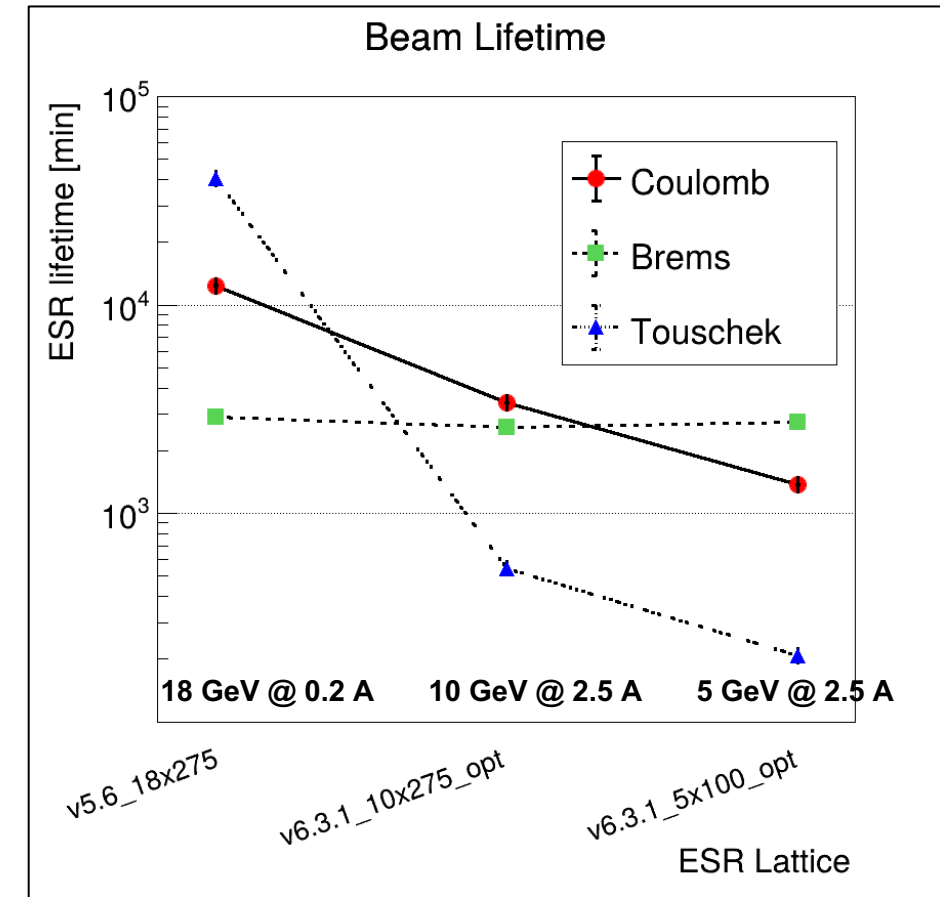
Figure 9: IP beam pipe absorbed SR tracks with $E_\gamma > 10$ keV. Top: without SR masks. Bottom: with SR masks shown with black, open triangles. Red, green, and magenta vertical bands show the IP beam pipe, quadrupole magnet (QD – defocusing, QF – focusing in the horizontal plane), and dipole magnet (D1-3) regions, respectively. Black, solid lines stands for the beam pipe aperture. The electron beam goes from positive toward negative Z coordinates.

Multi-turn Particle Tracking in the ESR

Developed a code based on the Xsuite framework [1] to study multi-turn electron beam losses

- **Features:**

- **Dynamic Aperture** study for the machine acceptance estimation
- Beam-gas and Touschek **scattering processes** following the SuperKEKB approach; see Ref. [2,3]



- Uniform vacuum gas pressure is 1 nTorr (CO, $Z_{eff} = 7$)
- Simulation without collimators
- Realistic beam pipe profile in the ring

Multi-turn Particle Tracking in the ESR

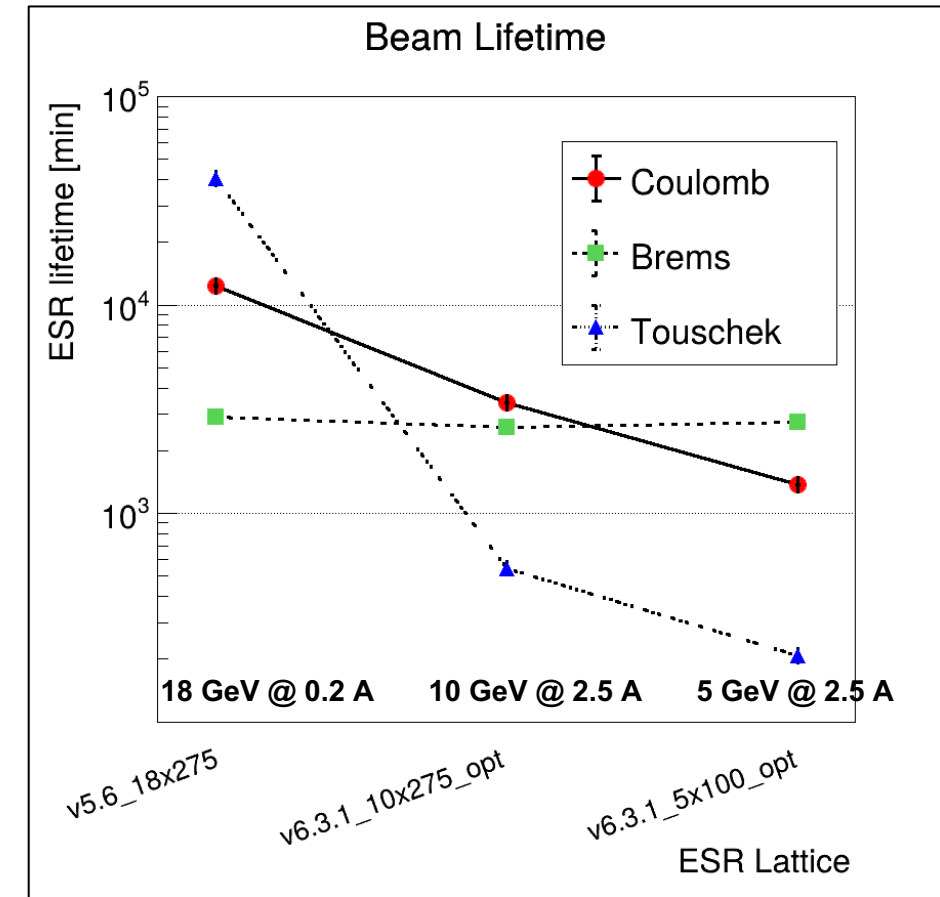
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- **Benchmark:**

- The Touschek lifetime estimation based on the Monte-Carlo approach for multi-turn tracking in Xsuite **agreed** with independent analytical calculations (BNL) and Bmad simulations (Cornell Univ.)



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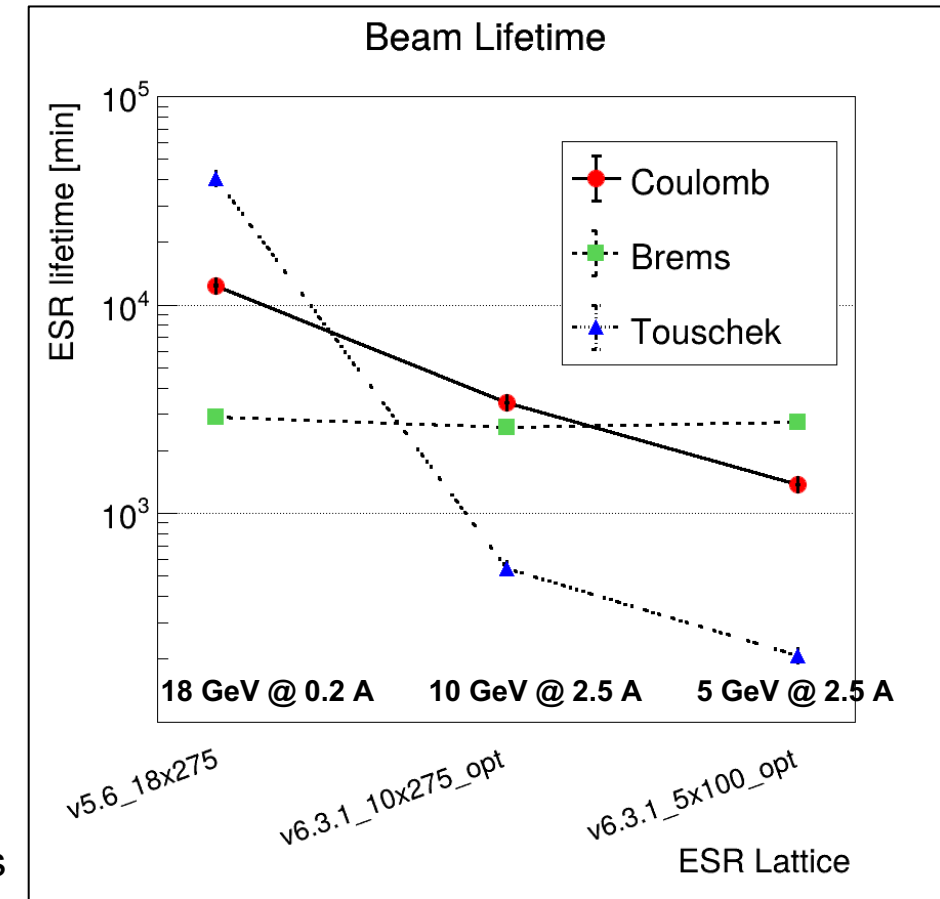
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- **Findings:**

- The hours-long beam lifetime **does not degrade the luminosity** with the ESR swap-out injection scheme
- Simulated losses (< 1 MHz) **do not exceed the rates** for various sources of particle production (0.1-1 MHz) in the same central detector region
- Beam loss power on SC quads is **below 1 W** at 10 GeV (2.5 A)



- Uniform vacuum gas pressure is 1 nTorr (CO, $Z_{\text{eff}} = 7$)
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Prospects

Synchrotron Radiation

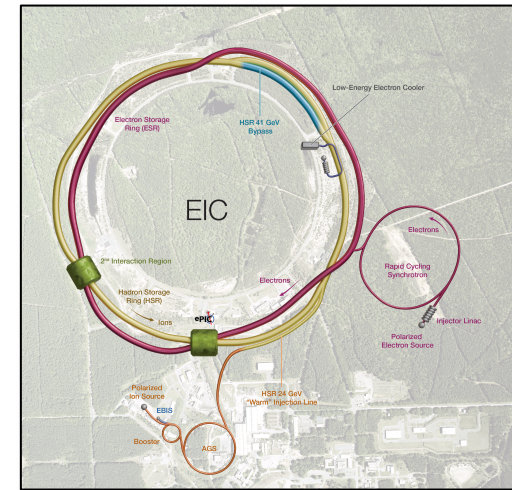
- Enhance the beam pipe design to minimize SR background in detectors, focusing on contributions from final focusing quads and nearby dipoles.
- Design and optimize radiation shielding within SC cryostats to reduce SR heat load on the magnet's cold mass.

Particle Losses

- Finalize the ESR and HSR lattice designs (see [C. Montag's talk](#) – *EIC beam dynamics*). Implement collimators and radiation shielding for effective mitigation of beam losses.
- Refine the IR beam pipe modeling in DD4hep for detailed detector performance studies.
- Incorporate a realistic vacuum pressure profile around the ring.
- Analyze the impact of the swap-out injection scheme on IR beam losses.
- Investigate abnormal beam operation scenarios, focusing on sudden beam loss events as seen at SuperKEKB (see [K. Ohmi's talk](#) – *SuperKEKB instabilities*).

Machine-Detector Protection

- Establish requirements for abort and radiation monitoring systems at the EIC.
- Develop dedicated protection and monitoring systems (seeking international collaboration).
- Design and implement collimators, abort kickers, and associated protection systems.



Summary

- The **EIC is a cutting-edge research facility** under construction at BNL, designed to **explore the fundamental structure of nucleons** by colliding high-energy polarized electron and ion beams.
- We work hard to **ensure the optimal integration and interaction between the machine and the detectors**.
- The **dominant detector background rates** are estimated to originate from the **electron beam losses**.
- To study the beam loss processes in the electron ring with further mitigation strategy implementation, we **developed dedicated simulation frameworks**.
- Further developments are planned for **SR and beam loss mitigation in the IR**.

Acknowledgements

Many thanks to the EIC accelerator, optics, and vacuum groups for their dedicated work on developing this unique machine; to the BNL and JLab computational teams for on-site support; and to our colleagues at ePIC for their contributions to the detector design and development of the DD4hep model.

Special thanks go to:

BNL:	E.-C. Aschenauer, W. Bergan, K. Hamdi, C. Hetzel, D. Marx, and M. Valette
Cornell:	G.H. Hoffstaetter, D. Sagan, and J. Unger
SLAC:	Y. Cai and M.K. Sullivan
CERN:	M. Ady and G. Broggi

We acknowledge support from the U.S. Department of Energy under contract number DE-SC0012704.

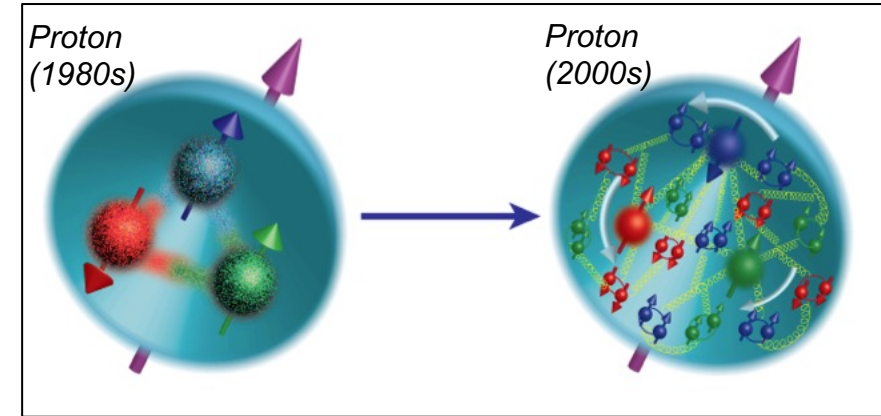
Backup

EIC: The Next QCD Frontier

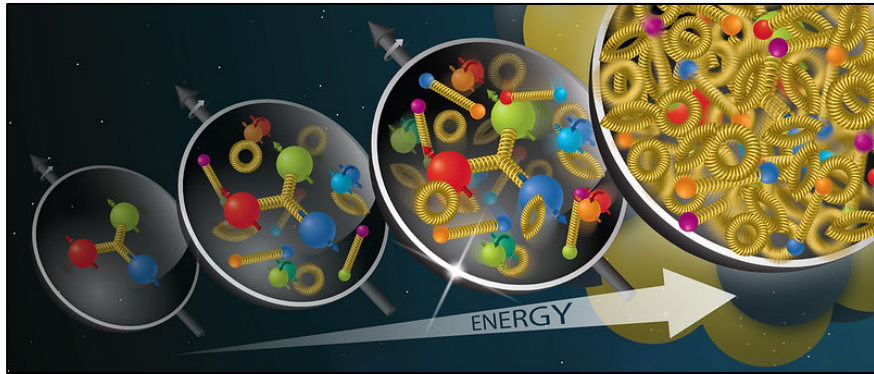
Nucleon Spin and Mass

Q: How do partons share the nucleon's spin and build up other nucleon intrinsic properties, such as its mass and magnetic moment?

A: The EIC is designed to yield much greater insight into the nucleon structure.



Evolution of our understanding of nucleon spin structure



Gluon density grow with energy.

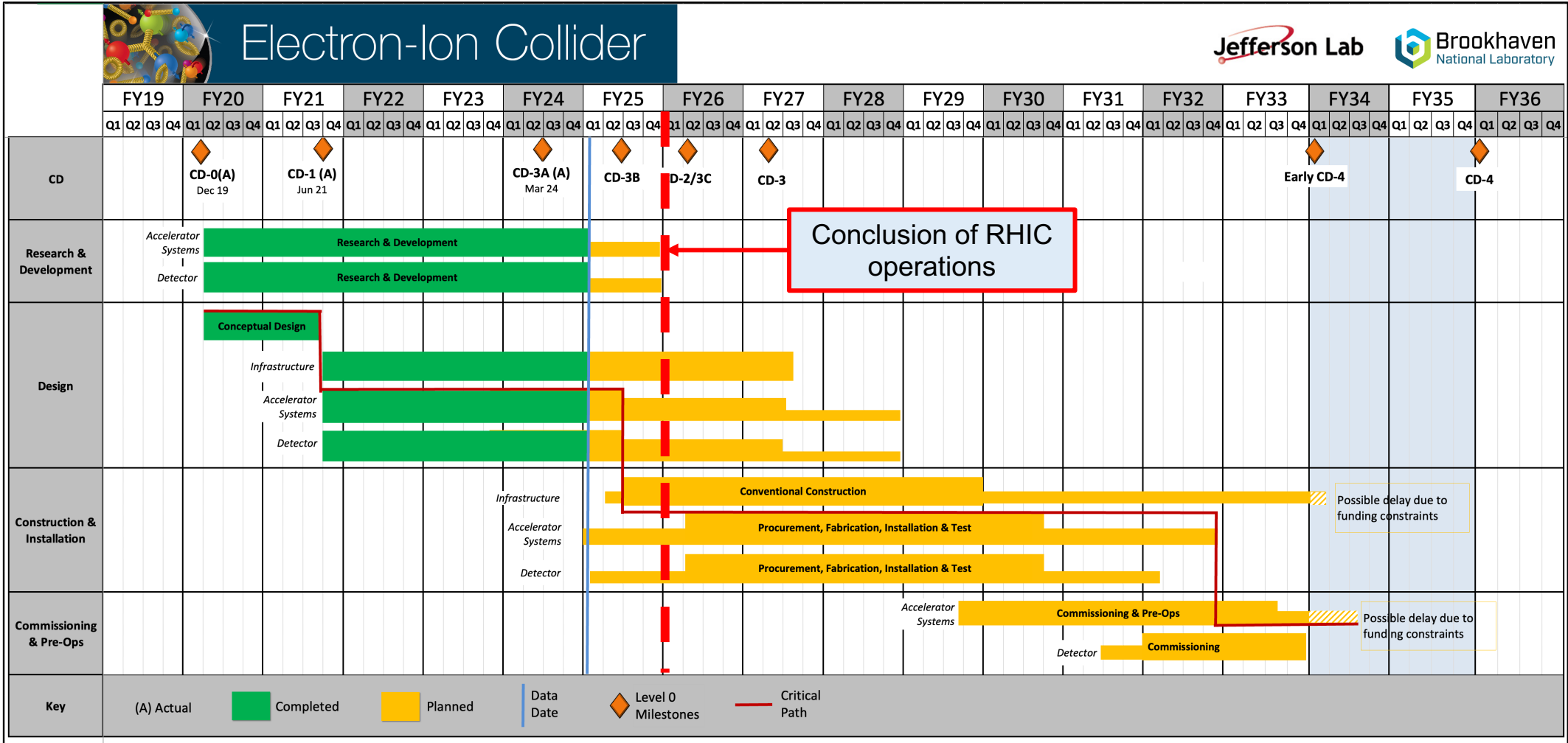
Gluon saturation

Q: Is there a saturation of the gluon density in nuclei at high energies?

A: The EIC would provide the first unambiguous evidence for the novel QCD matter of saturated gluons.

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.



MDI Goals

Ensure the optimal integration and interaction between the machine and the detectors.

1. Beam Background (BG) Mitigation

Reducing the unwanted beam-induced BG noise in the detectors.

2. Beam Pipe and Interaction Region (IR) Design

Designing the beam pipe and IR to minimize BGs while maximizing detector acceptance.

3. Synchronization

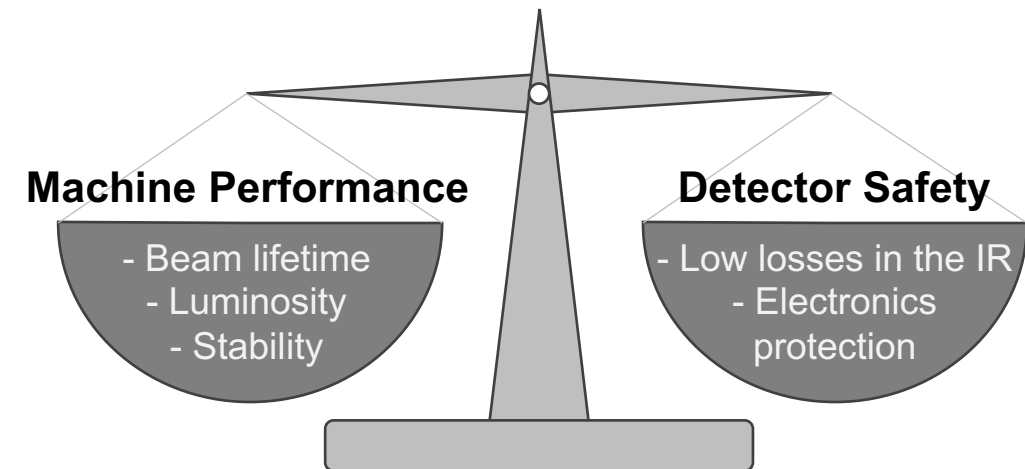
Ensuring precise timing synchronization between the beam and the detectors to allow for accurate event reconstruction.

4. Radiation Protection

Implementing measures to protect the detectors and electronics from radiation damage through shielding and collimation.

5. Integration

Coordinating the integration of accelerator components with the detector infrastructure.



Machine Parameters

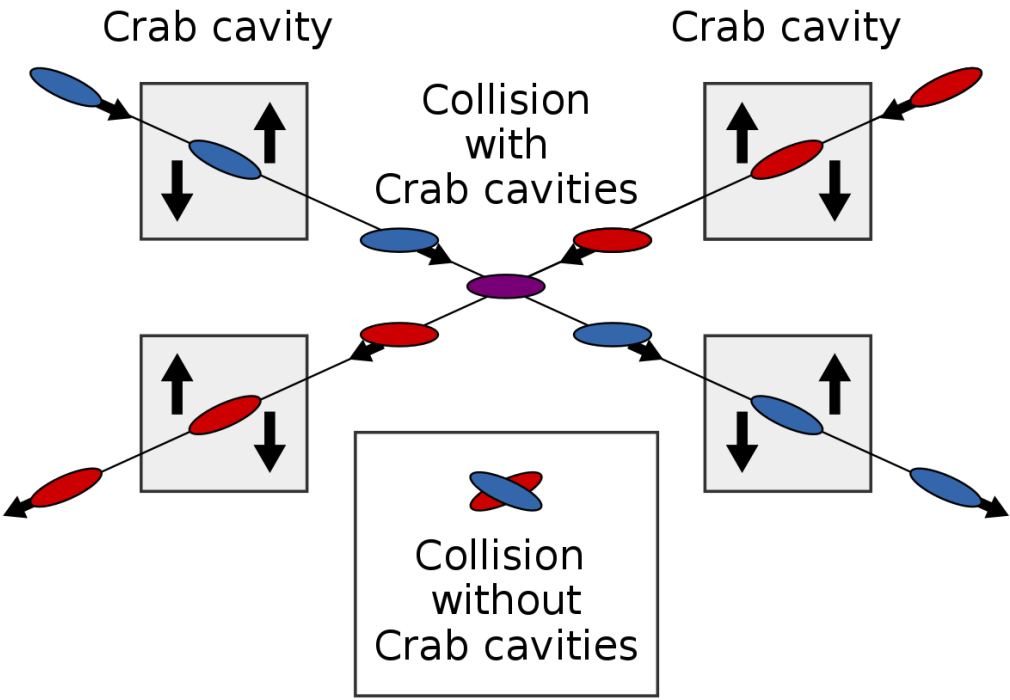


Table 2 Main parameters for the electron-proton operation in high acceptance operation mode.

Parameter		Units	p+	e-	p+	e-	p+	e-	p+	e-	p+	e-
Energy		GeV	275	18	275	10	100	10	100	5	41	5
CM energy		GeV	141		105		63.2		44.7		28.6	
Bunch intensity		10^{10}	18.9	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
Number 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 normalized emittance	H	μm	5.2	845	3.3	391	3.2	391	2.7	196	1.9	196
	V		0.46	70	0.3	26	0.29	26	0.25	18	0.45	34
RMS emittance	H	nm	17.6	24.0	11	20	30	20	26	20	44	20
	V		1.6	2.0	1.0	1.3	2.7	1.3	2.3	1.8	10	3.5
Beta	H	cm	417	306	265	149	94	143	80	103	90	196
	V		38	30	24	19	8.5	18	7.2	9.2	7.1	21
IP RMS beam size	H	μm	271		172		169		143		198	
	V		24		16		15		13		27	
Kx		-	11		11		11		11		7.3	
RMS divergence	H	μrad	65	89	65	116	180	118	180	140	220	101
	V		65	82	65	84	180	86	180	140	380	129
BB parameter	H	10^{-3}	3	92	12	72	12	72	14	100	15	53
	V		3	100	12	100	12	100	14	100	9	42
RMS longitudinal emittance		$10^{-3} \text{ eV}\cdot\text{s}$	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 fractional momentum spread		10^{-4}	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Maximum space charge		-	0.007	Neg	0.004	Neg	0.026	Neg	0.021	Neg	0.05	Neg
Piwinski angle		rad	2.8	0.9	4.3	1.4	5.2	1.5	6.1	1.7	4.2	1.1
Longitudinal IBS time		hrs	2		3.2		2.5		3.1		3.8	
Transverse IBS time	H	hrs	2		2		2.0		2.0		3.4	
	V		Lrg		Lrg		4.0		4.0		2.1	
Hourglass factor H		-	1		1		0.9		0.9		0.9	
Luminosity		$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	0.3		3.1		3.1		2.9		0.4	

Simulation Improvements

Synrad-based approach constraints:

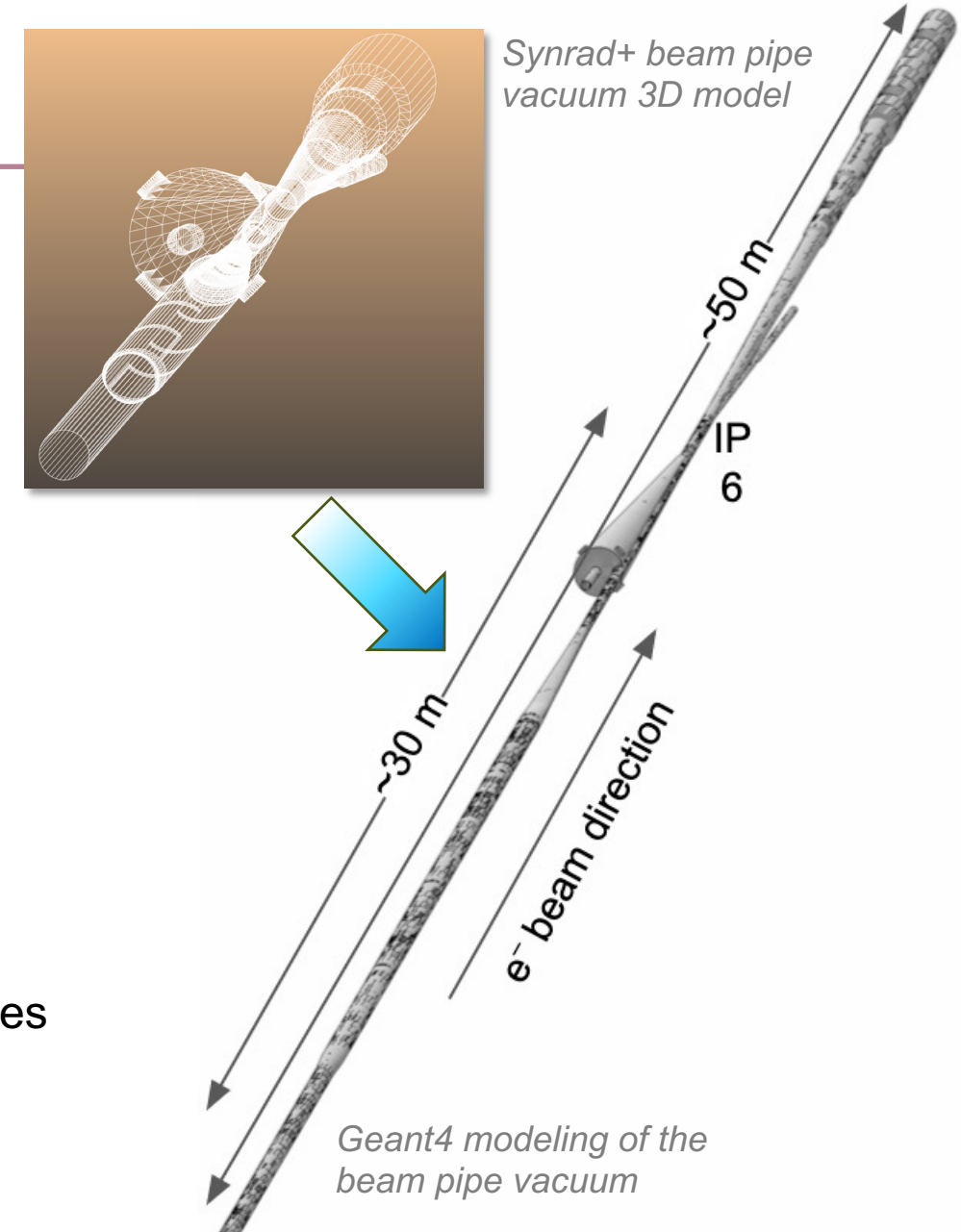
- Limitations for detailed SR background studies

Solution:

- Geant4-based model for SR simulation
+ photon reflection physics

Benefits:

- No weighting
 - Realistic SR photon tracking in the vacuum
 - Accurate SR mask development
 - Full information about SR photon trajectories
- Effective photon coordinate logging
- Ease and accurate implementation of any geometry changes



X-ray Reflection Physics in Geant4

Availability:

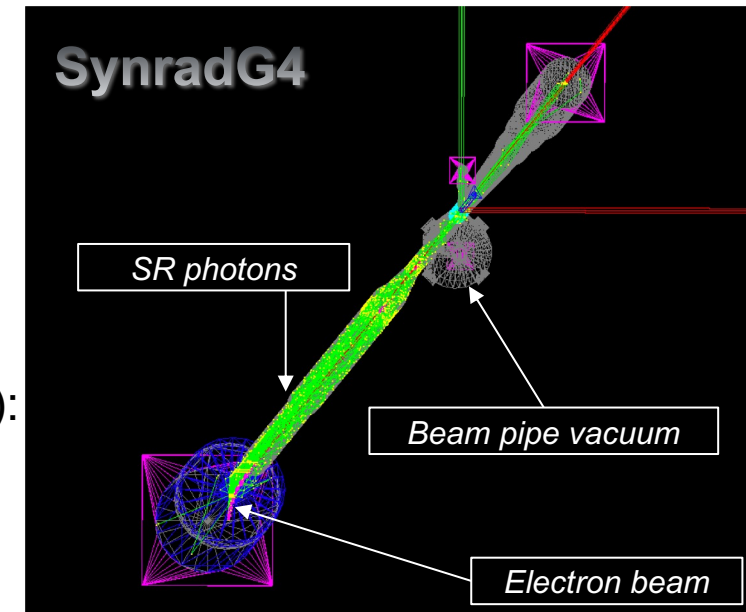
- X-ray reflection was missing in Geant4
 - Recent (Dec. 2023 [1]) implementation ← so-called *geant4-release*
 - Specular (mirror-like) reflection + attenuation factor for roughness

Solution:

- Develop a **custom-built** model for specular and diffuse X-ray reflection in Geant4 (same as in Synrad+) so-called **SynradG4**.

Benchmark (same material reflect. data prepared by B.L. Henke et al. (1993) [2]):

1. **Synrad+** (with bugfixes [3]) – diffuse reflection
 - a) Old reflection model based on Synrad (1993) [4]
 - b) New reflection model based on Synrad3D (2013) [5]
2. **Geant4-release** – specular reflection
3. **SynradG4**
 - a) Same as geant4-release – specular reflection
 - b) Same as the old model in Synrad+ – diffuse reflection
 - c) Same as the new model in Synrad+ – diffuse reflection

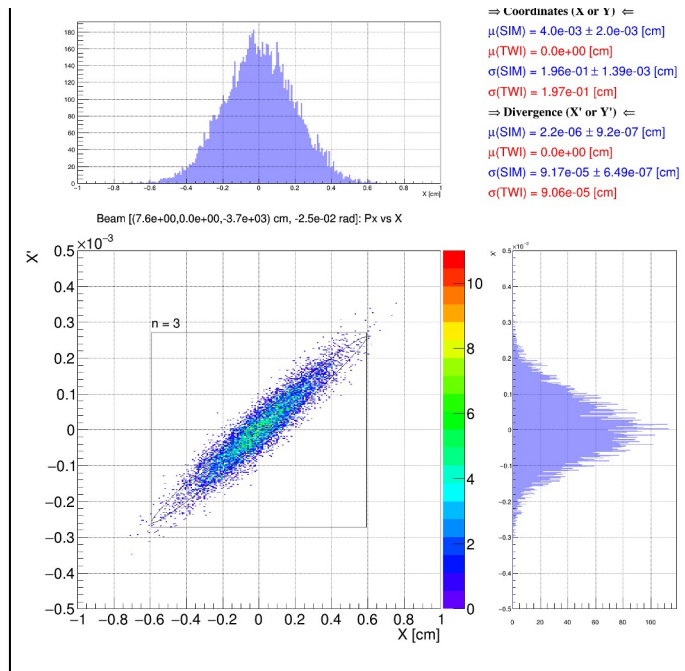


Geant4 geometry

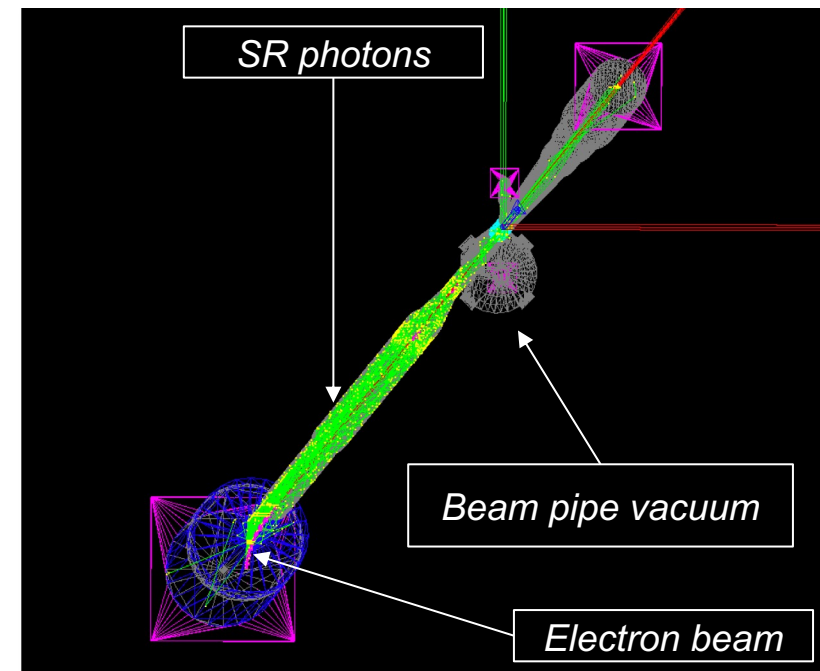
Geant4 modeling of the EIC interaction region (IR)

The code **propagates an electron beam through IR magnets** (3 upstream bends, 2 upstream quads, IP solenoid, 2 downstream quads, and 1 downstream bend) with the **SR production and custom-built reflection** (diffuse, new) processes.

- The beam profile at each magnet was successfully verified using Courant-Snyder parameters.
- The absorbed SR photons are collected and **transferred to EIC-Shell/DD4Hep for the detector response simulation.**



Initial distribution of the electron beam at the entrance of the IR

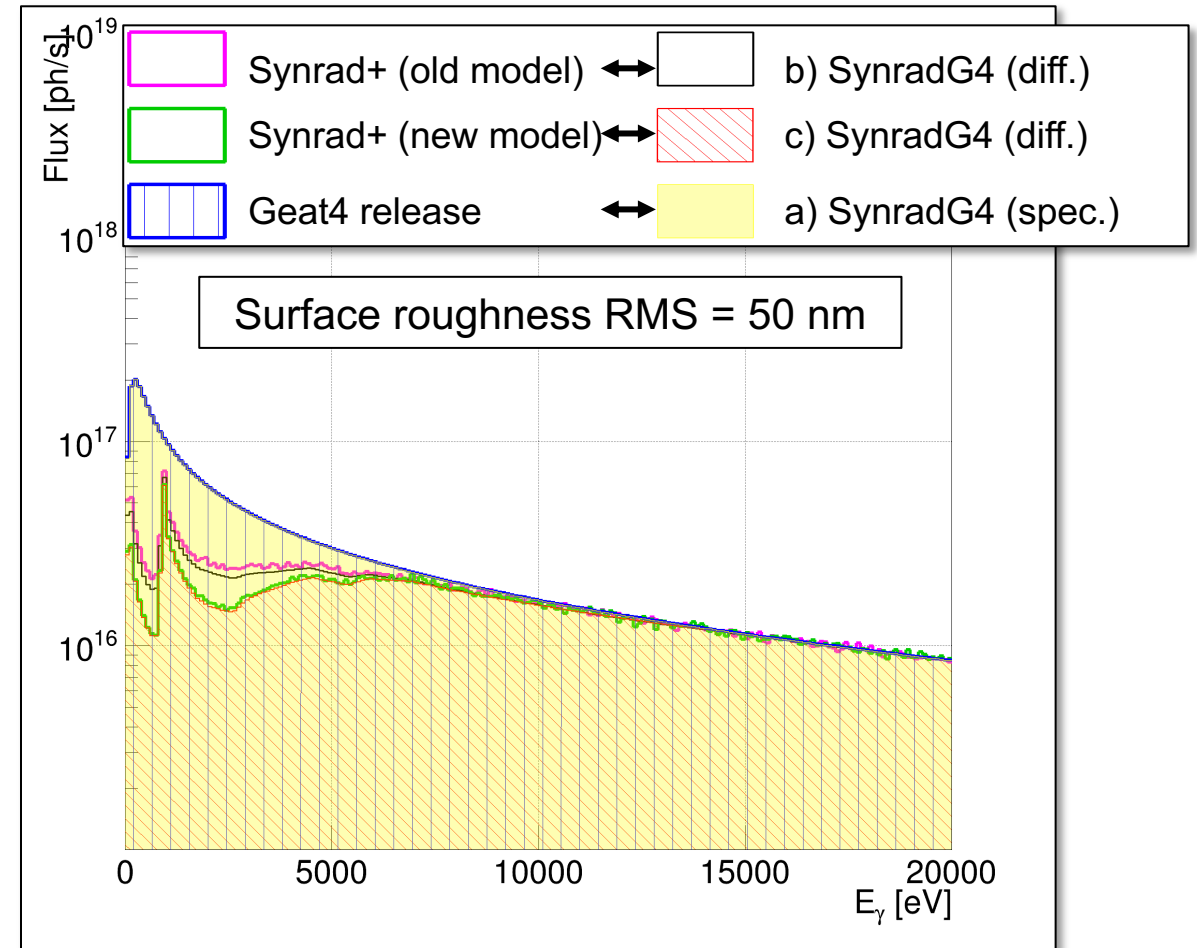


Geant4 geometry

Benchmark

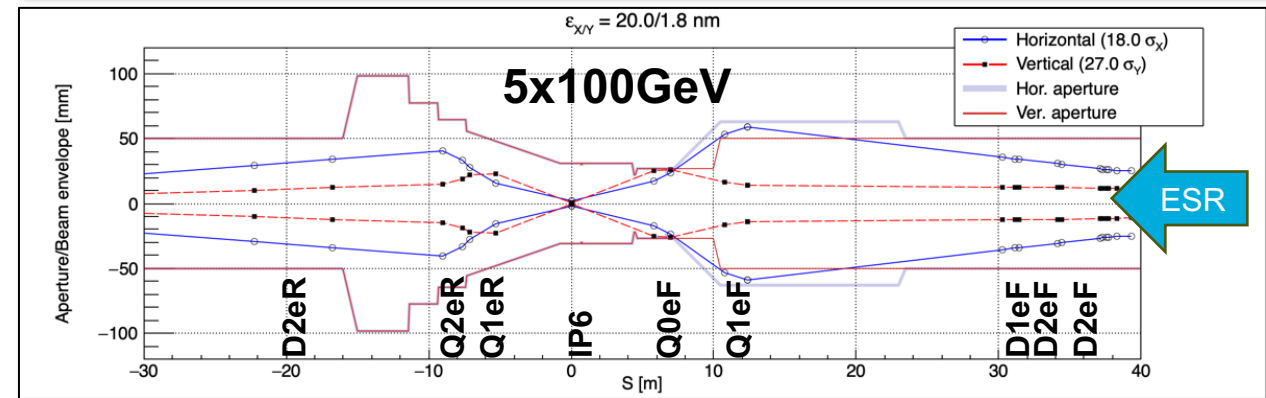
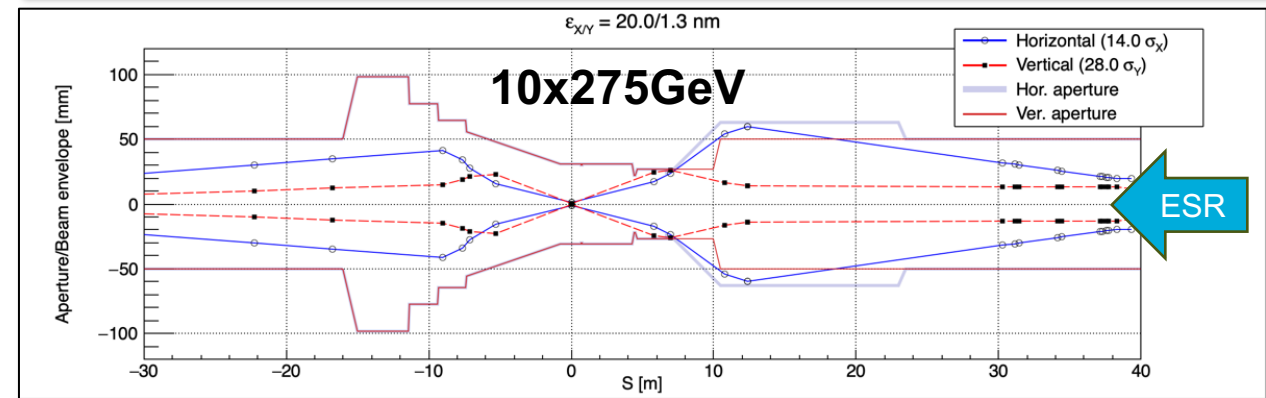
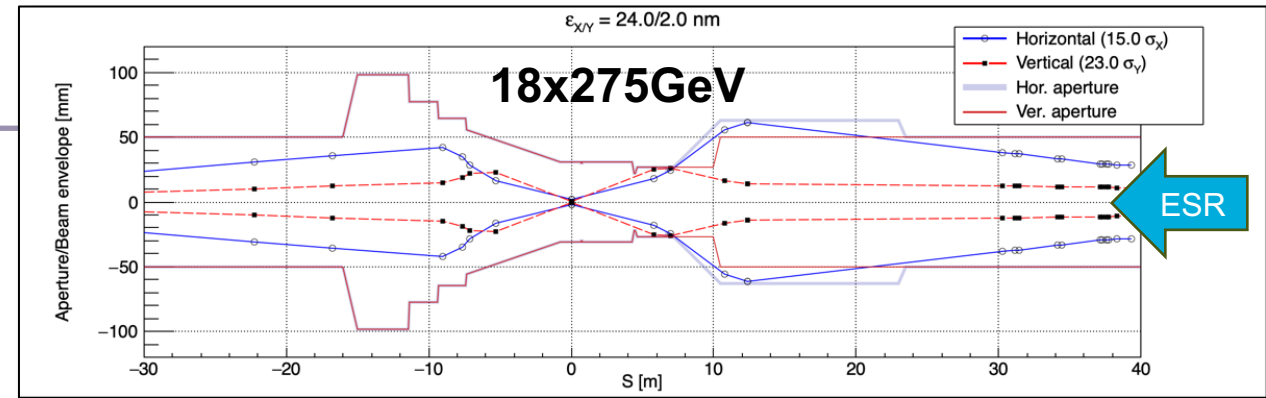
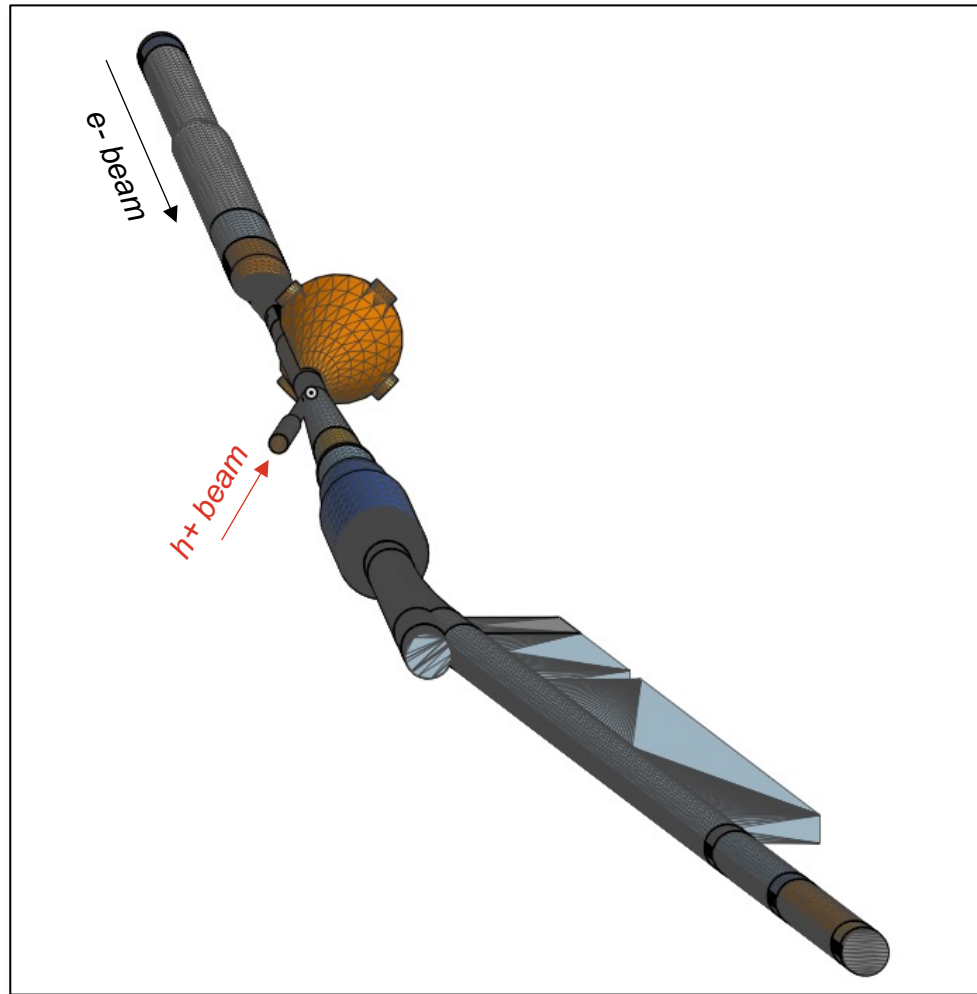
- There is a **good agreement** between SynradG4 and Synrad+/G4-release
 - It **confirms the correct implementation** of X-ray reflection into the new custom-built code.
- The absorbed **SR photons can be transferred to DD4Hep.**
- Recently **more benchmarks** (including the Synrad3D framework [1]) were conducted and reported in Ref.[2]; see backup slides.

The tool is ready for the SR background simulation !



Absorbed SR photon spectrum on the arbitrary beam pipe vacuum facet

Beam Envelope & IR Aperture



SynradG4 Applications: SR Rates in the IR

Although one 18 GeV electron generates more SR photons, the highest SR is expected for the 10 GeV electron beam at 2.5 A.

Critical photon energy:

$$\varepsilon_c \sim \frac{\gamma^3}{\rho}$$

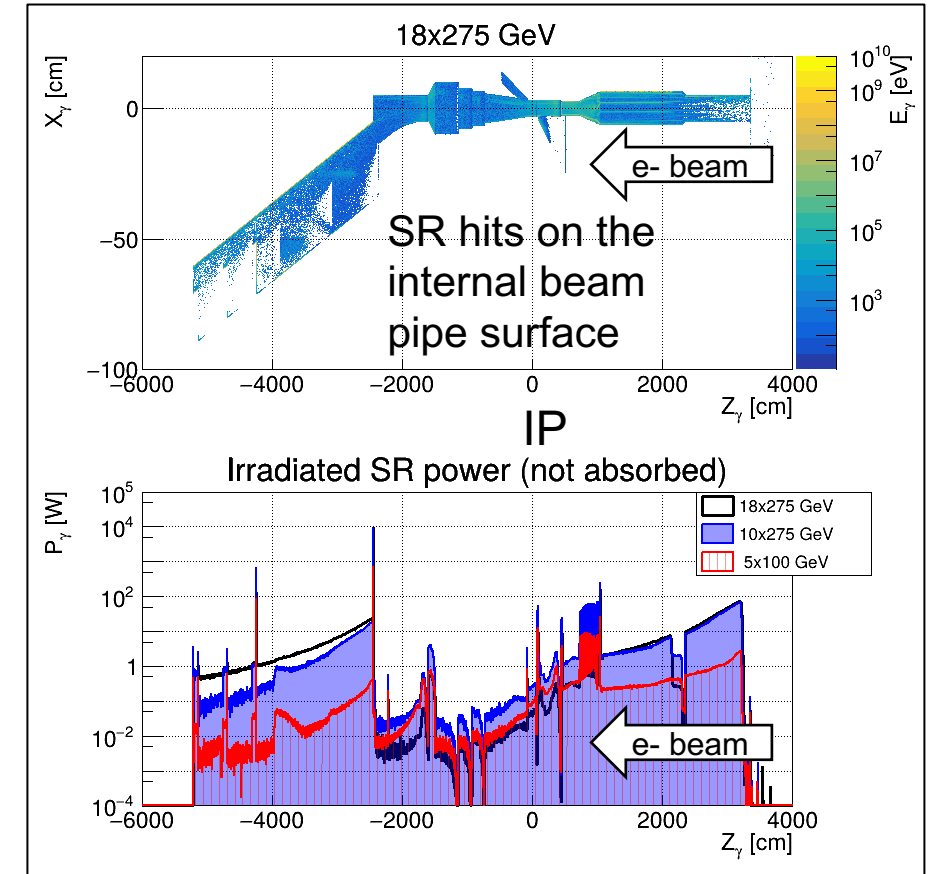
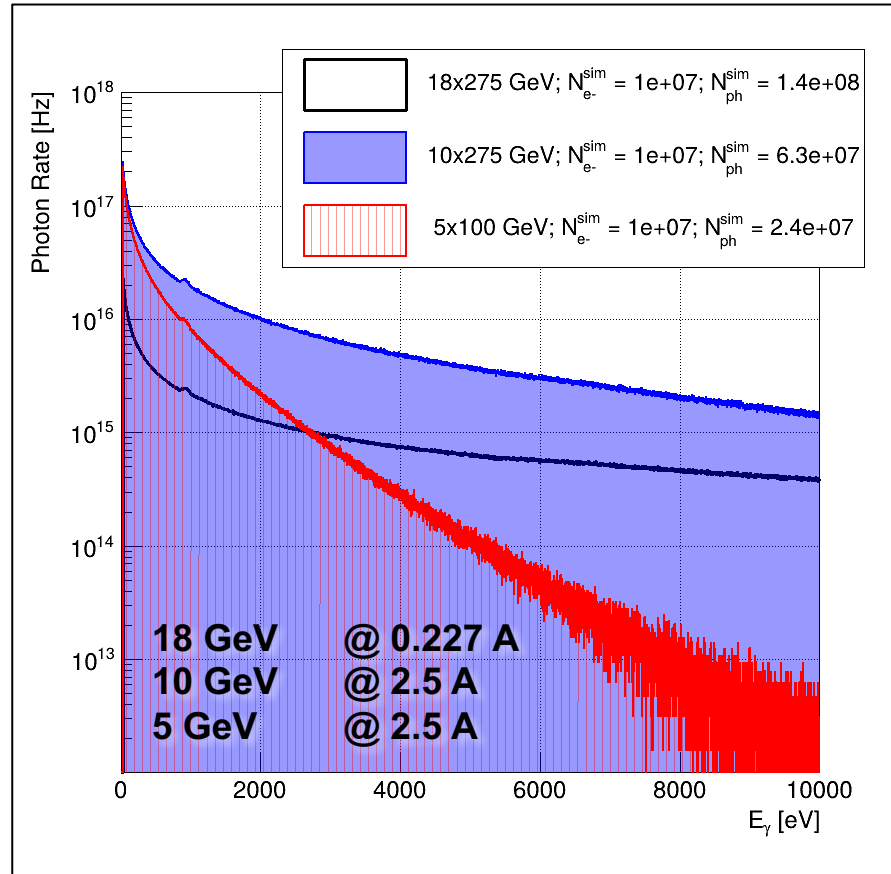
SR power:

$$P_\gamma \sim \frac{\gamma^4}{\rho^2}$$

SR photon rate:

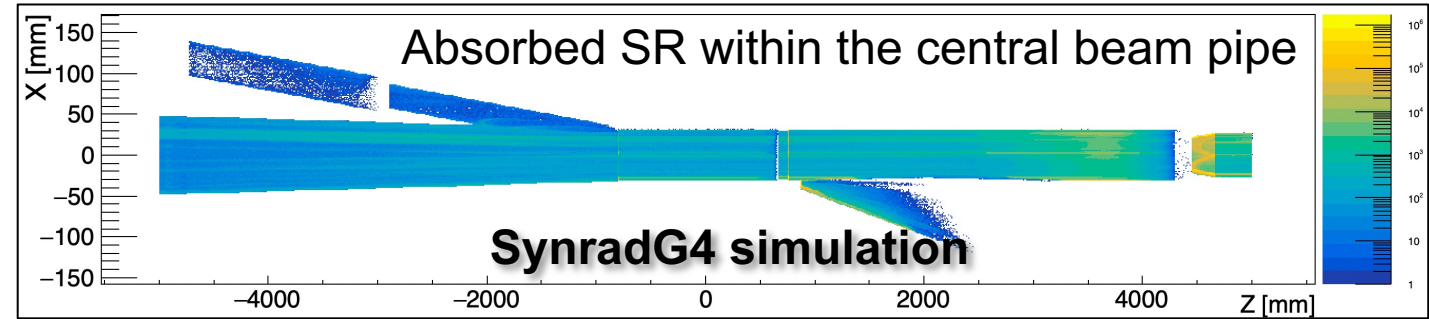
$$\dot{N}_{ph} \sim \frac{P_\gamma}{\varepsilon_c}$$

where γ and ρ are the Lorentz factor and curvature radius.

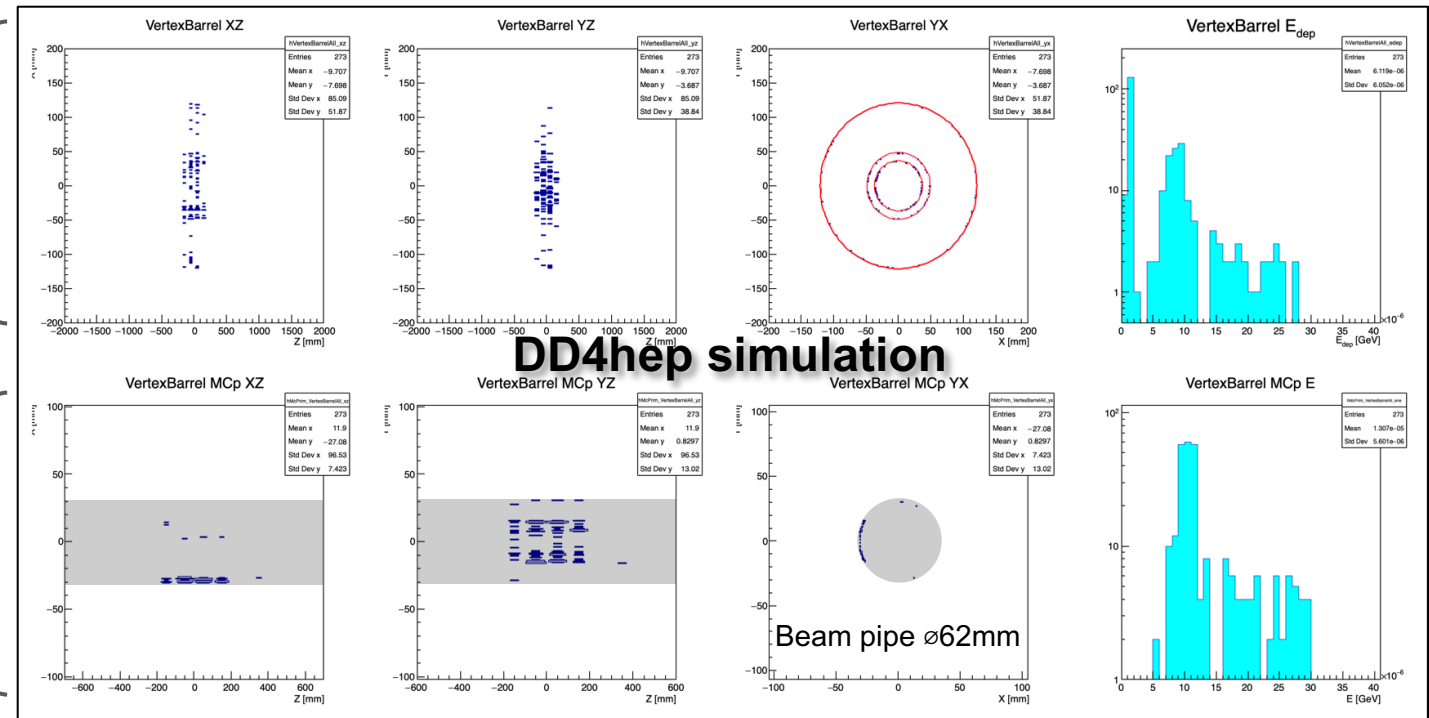


Detector Hits (18 GeV, w/o SR masks)

- Most of the SR will be absorbed by thick cryostat beam pipe walls.
- The tracking system sees SR photons primarily from the IP beam pipe.

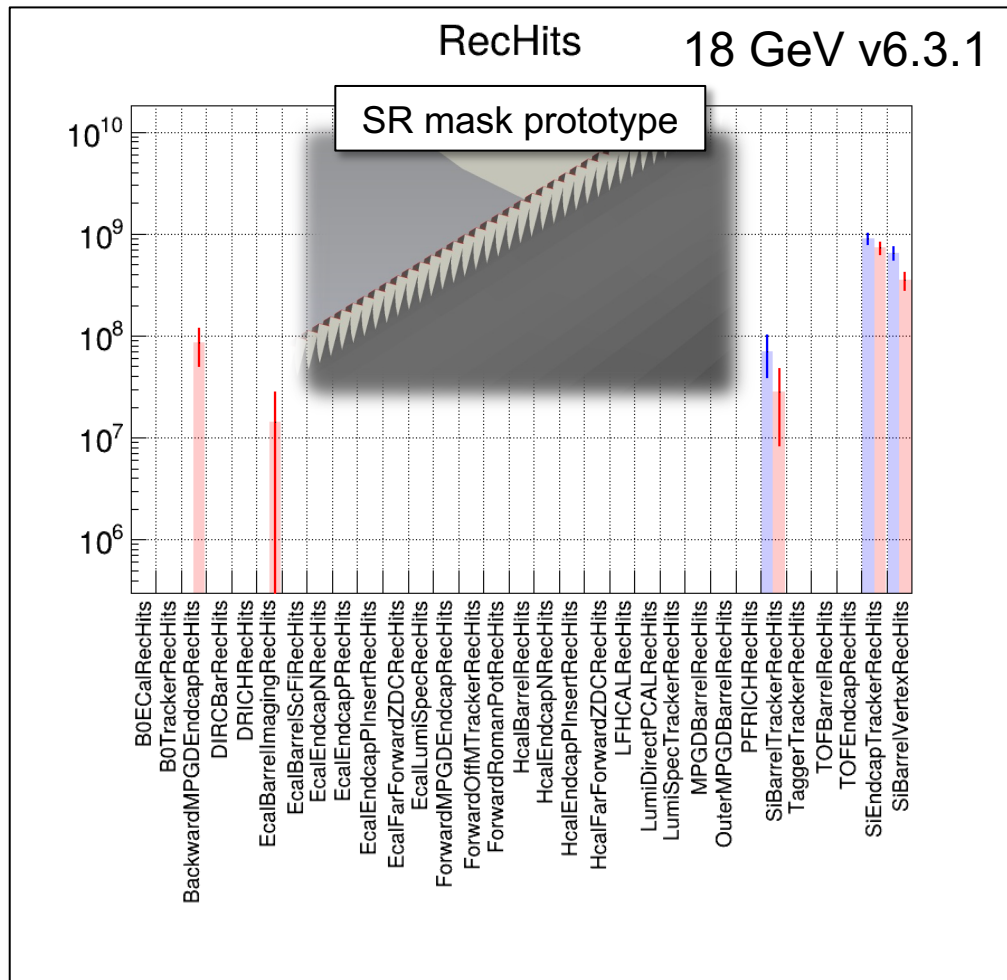


- Only the SR photons with $E_\gamma > 5$ keV produce hits in the detector.

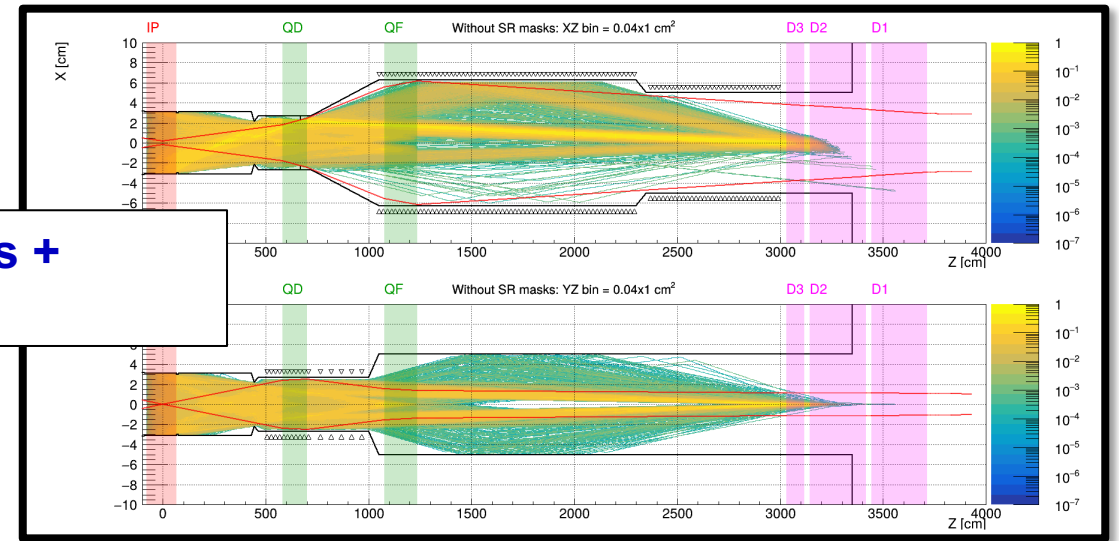


- Let's study background rates in ePIC using the SR from the IP beam pipe region only.

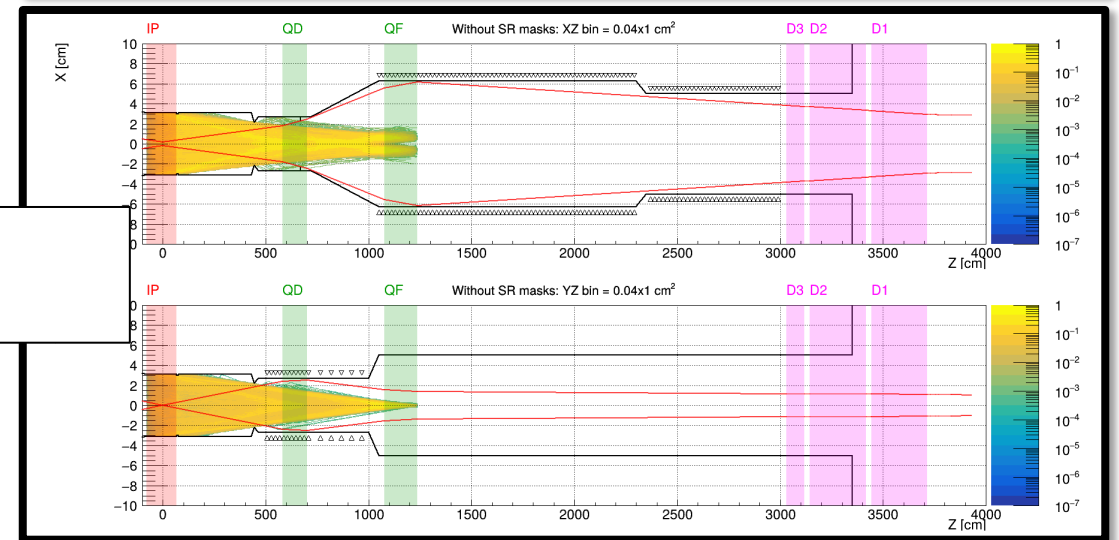
ePIC Detector SR Background Rates



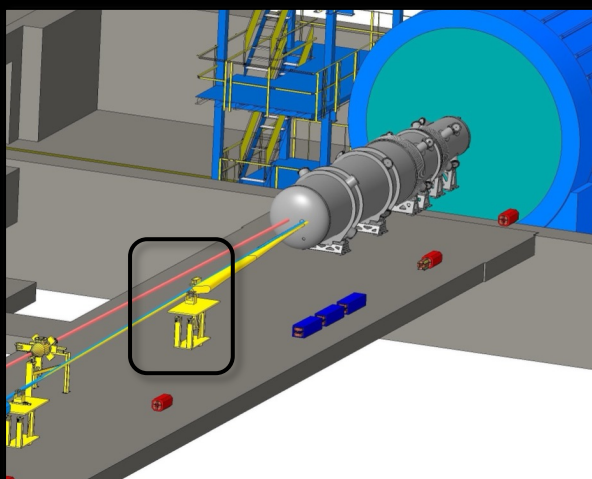
Dipoles + Quads



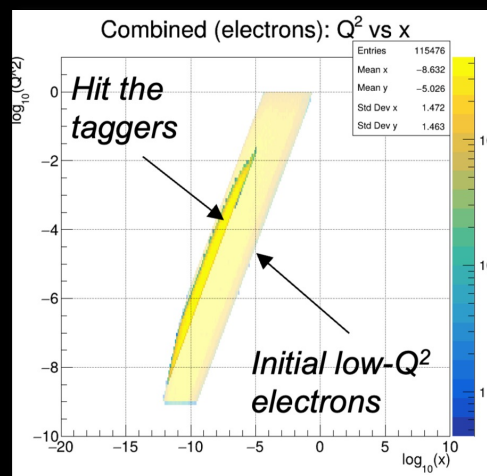
Quads ONLY



SynradG4 Applications: Low- Q^2 Taggers

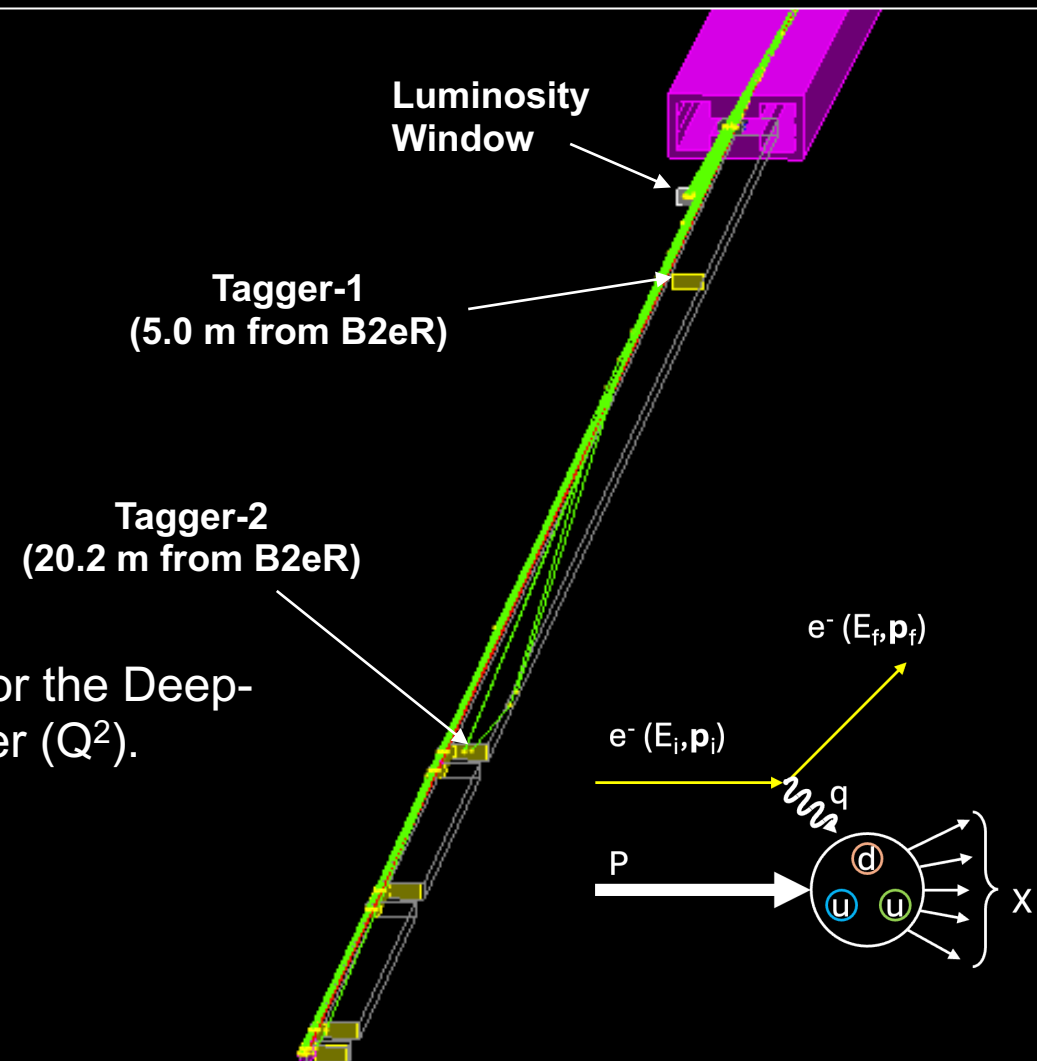


Far-backward setup



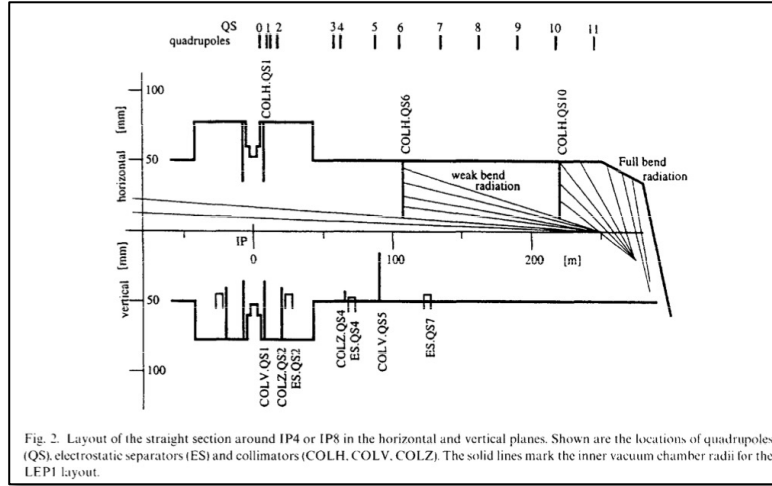
Momentum transfer (Q^2) vs Bjorken variable (x)

- SynradG4, helps us optimize the far-backward experimental setup for the Deep-Inelastic Scattering (DIS) measurements at a low momentum transfer (Q^2).
- Currently, only **12%** low- Q^2 electrons are detected by the taggers.
 - A big part of the electrons ($\sim 65\%$) goes through the quads.
- Further tunings of optics and tagger's configuration are ongoing.



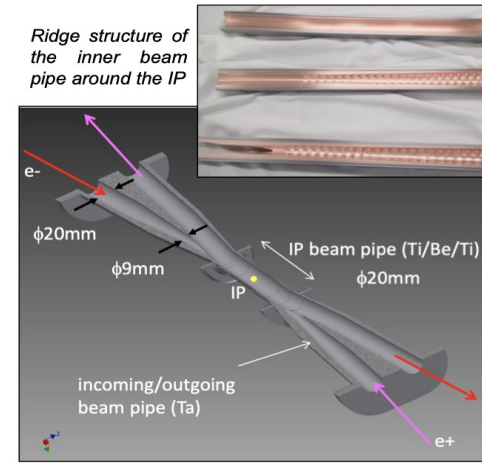
Challenges of Using Conventional SR Masks

LEP

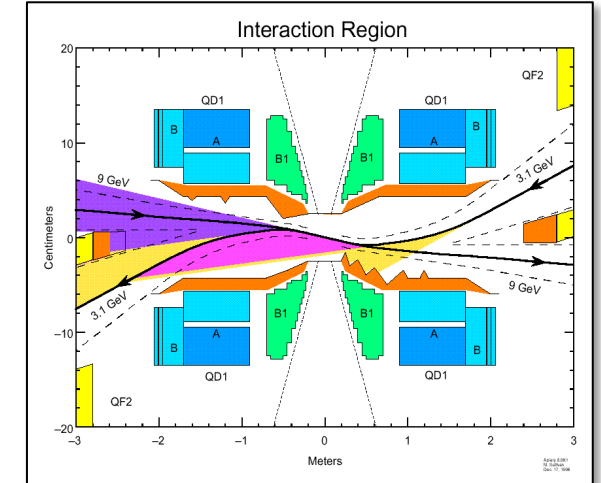


SuperKEKB

Beryllium beam pipe coated with a gold layer
+ ridge surface
+ variable incoming pipe radius

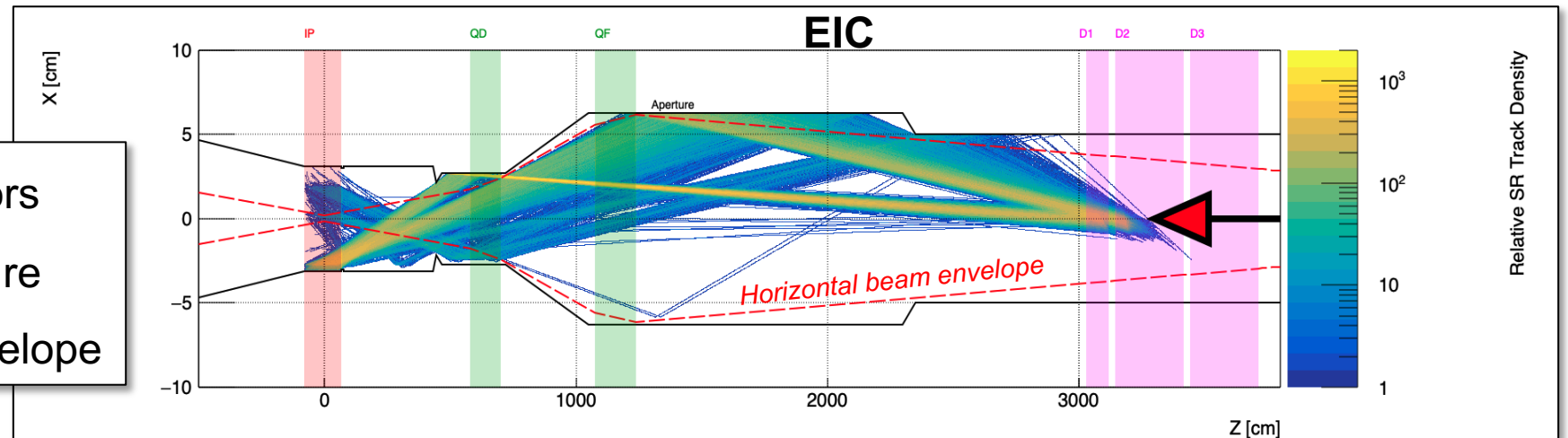


PEP-II



- Limited space for collimators
- Large IP beam pipe aperture
- Large upstream beam envelope

EIC



- For diffuse reflection with a rough surface (Setup- 3), the Synrad3D spectrum diverges from the Synrad+ and SynradG4 distributions for SR photons above 1 keV.
 - This discrepancy is likely due to the differing methods of calculating reflection angles across the frameworks.
- Although Synrad3D employs the full expression for diffusely scattered power, which involves an infinite sum, the approximated reflection model in SynradG4/Synrad+ still performs satisfactorily.
 - It strikes a good balance between computational speed and reflection accuracy, which is critical for high-statistics SR background studies at the EIC.

Framework	Setup-1	Setup-2	Setup-3
Synrad3D	SRO = TRUE	N/A	$\sigma_{\text{RMS}} = 50$, $T = 10$
Synrad+	RSS = OFF	N/A	$\sigma_{\text{RMS}} = 50$, $T = 10$
SynradG4	$\sigma_{\text{RMS}} = 0$ (spec.)	$\sigma_{\text{RMS}} = 50$ (spec.)	$\sigma_{\text{RMS}} = 50$, $T = 10$ (diff.)
G4-11.2.0	$\sigma_{\text{RMS}} = 0$	$\sigma_{\text{RMS}} = 50$	N/A

Table 2: Simulation setups for the SynradG4 benchmark. Surface roughness σ_{RMS} and autocorrelation length T are given in nanometers and micrometres, respectively.

Specular reflection: the code employs the Debye-Waller attenuation factor.

$$P_{\text{spec}} = e^{-2k_{\perp}^2 \sigma^2}$$

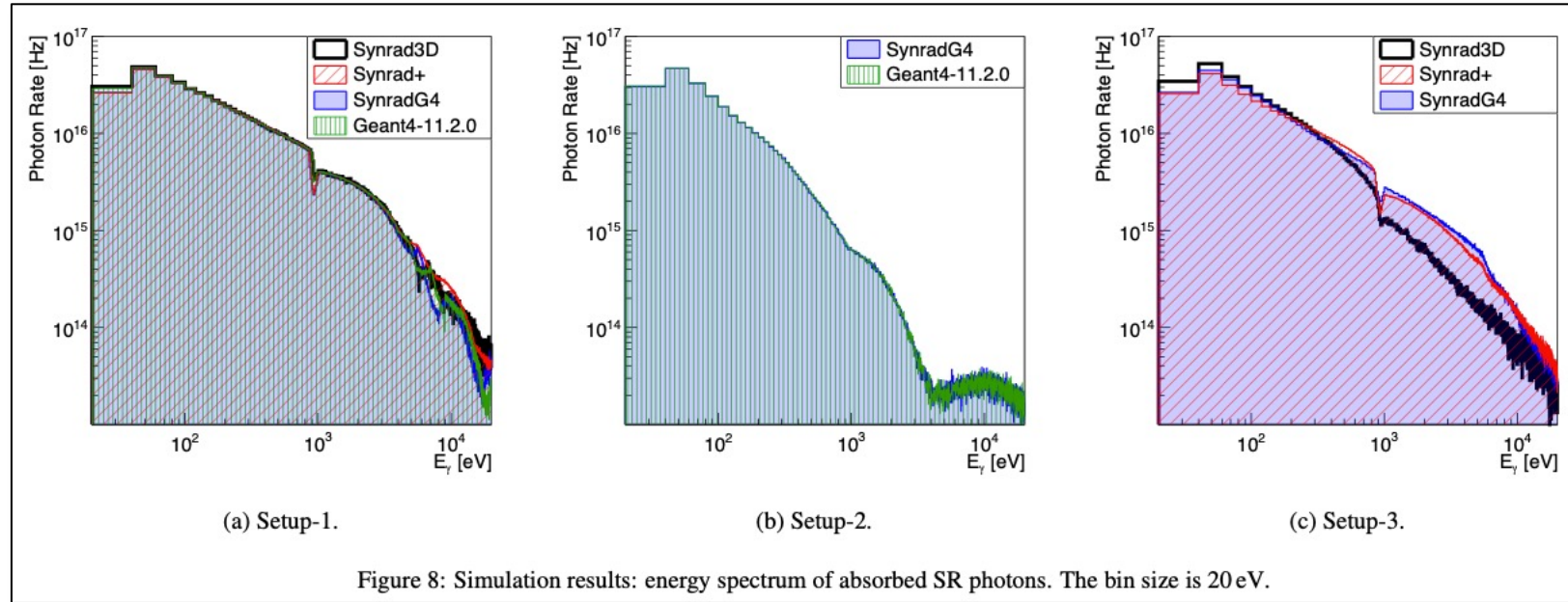
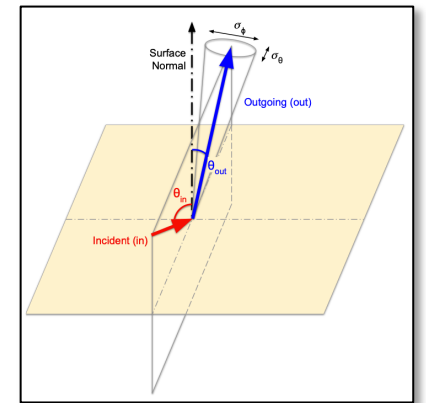
$\swarrow$ surface roughness
 $\nwarrow$ wave vector

Diffuse reflection: the reflected photon's polar (θ) and azimuthal (ϕ) angles are randomly smeared following a Gaussian distribution.

$$\sigma_{\theta} = \frac{2.9267}{\tau},$$

$$\sigma_{\phi} = \frac{1}{\tau} (2.80657 \theta_{\text{in}}^{-1.00238} - 1.00293 \theta_{\text{in}}^{1.2266})$$

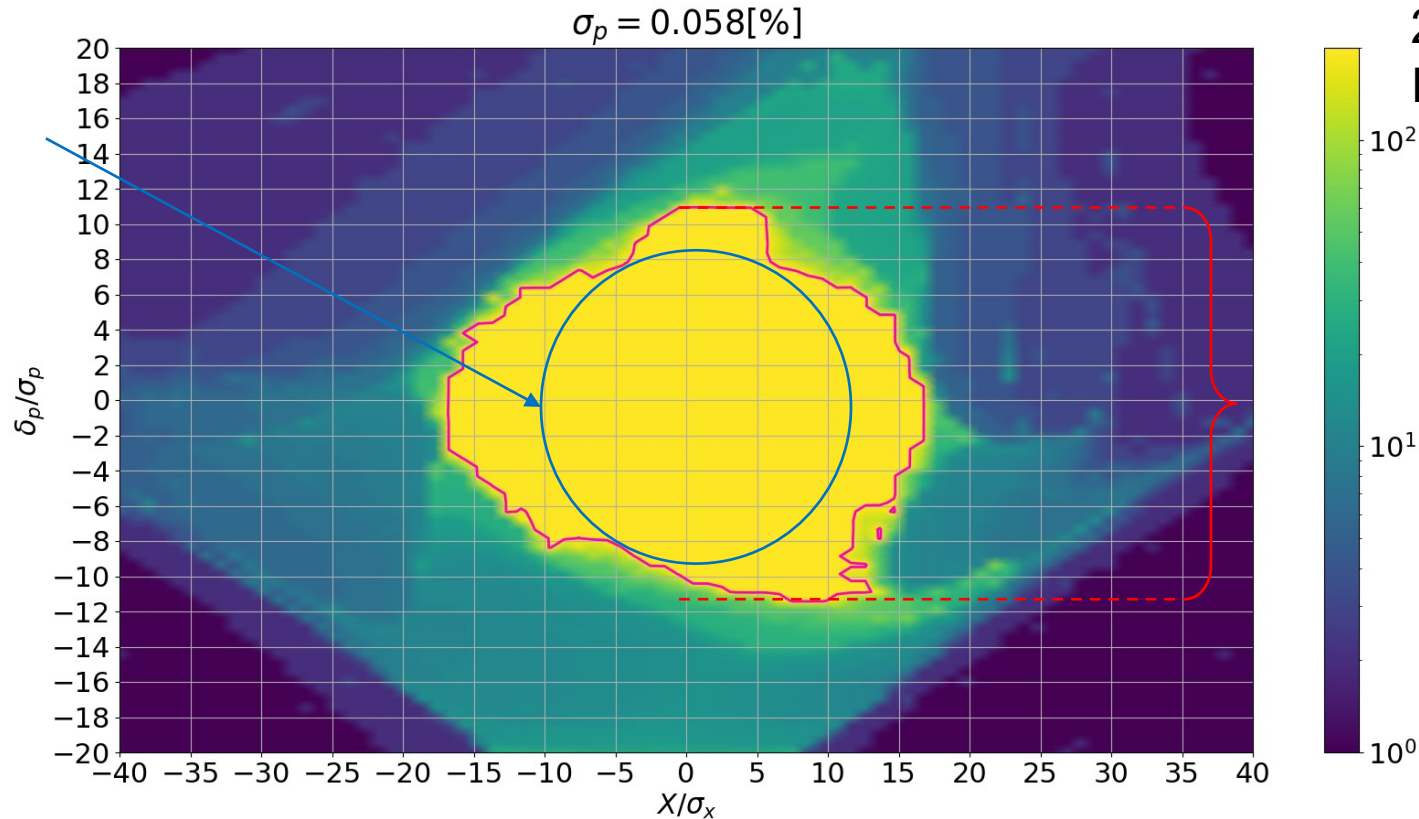
Here, $\tau = T/\sigma$, T is the autocorrelation length and σ is the surface roughness RMS.



10x275 GeV – v6.3.1

New lattice, optimized

The maximum possible ellipse that fits inside the aperture contour and centers at (0;0)



SR ON, RF ON (phase adjust.)

Without Physical Aperture

Without Machine Errors

200 revolutions

IP6 - starting tracking point

Mom. Acceptance:

Max.: $\pm 11\sigma_p \rightarrow \delta_p \approx \pm 0.64\%$

Ellipse: $\pm 9\sigma_p \rightarrow \delta_p \approx \pm 0.52\%$

ESR Touschek Lifetime

$$\tau_T \approx \frac{48 \gamma^2 \pi \sigma_x \sigma_y \sigma_z}{N r_0^2 c} \left(\frac{\widehat{\Delta p}}{p} \right)^3$$

Eq. 4.166 in S. Y. Lee “Accelerator Physics”
(4th edition), World Scientific (2019).

There is good agreement between analytical calculations and tracking simulations done by different people independently.

Systematic uncertainty (how accurately we can define the momentum acceptance)

Lattice E _e x E _p	γ	<β _{x/y} > [m]	ε _{x/y} [nm]	σ _z [cm]	N x10 ¹⁰	< $\frac{\Delta p}{p}$ > $^{+0.05}_{-0.05}$ [%]			τ _T [hours]				
	Lattice	Lattice	Design	Design	Design	From DA+PA	From DA	Design (10σ _δ)	Analytical			Xsuite Tracking W/ SR	Bmad Tracking W/o SR
									From DA+PA	From DA	Design (10σ _δ)		
V5.6 18x275	34924. 3	46.2/68.2	24.0/2.0	0.9	6.2	0.71	0.82	1.1	434 ⁵³² ₃₄₈	668 ⁷⁹⁸ ₅₅₃	1590	674.7	130 (459 w/ SR)
V5.6 10x275	19402. 4	62.0/73.5	20.0/1.3	0.7	17.2	0.55	0.55	0.6	15.4 ^{20.0} _{11.6}	15.4 ^{20.0} _{11.6}	20	14.9	20
V5.6 6x100	11641.4	40.1/62.5	20.0/1.8	0.7	17.2	0.41	0.44	0.7	2.0 ^{2.8} _{1.4}	2.5 ^{3.4} _{1.7}	10	2.6	2.7

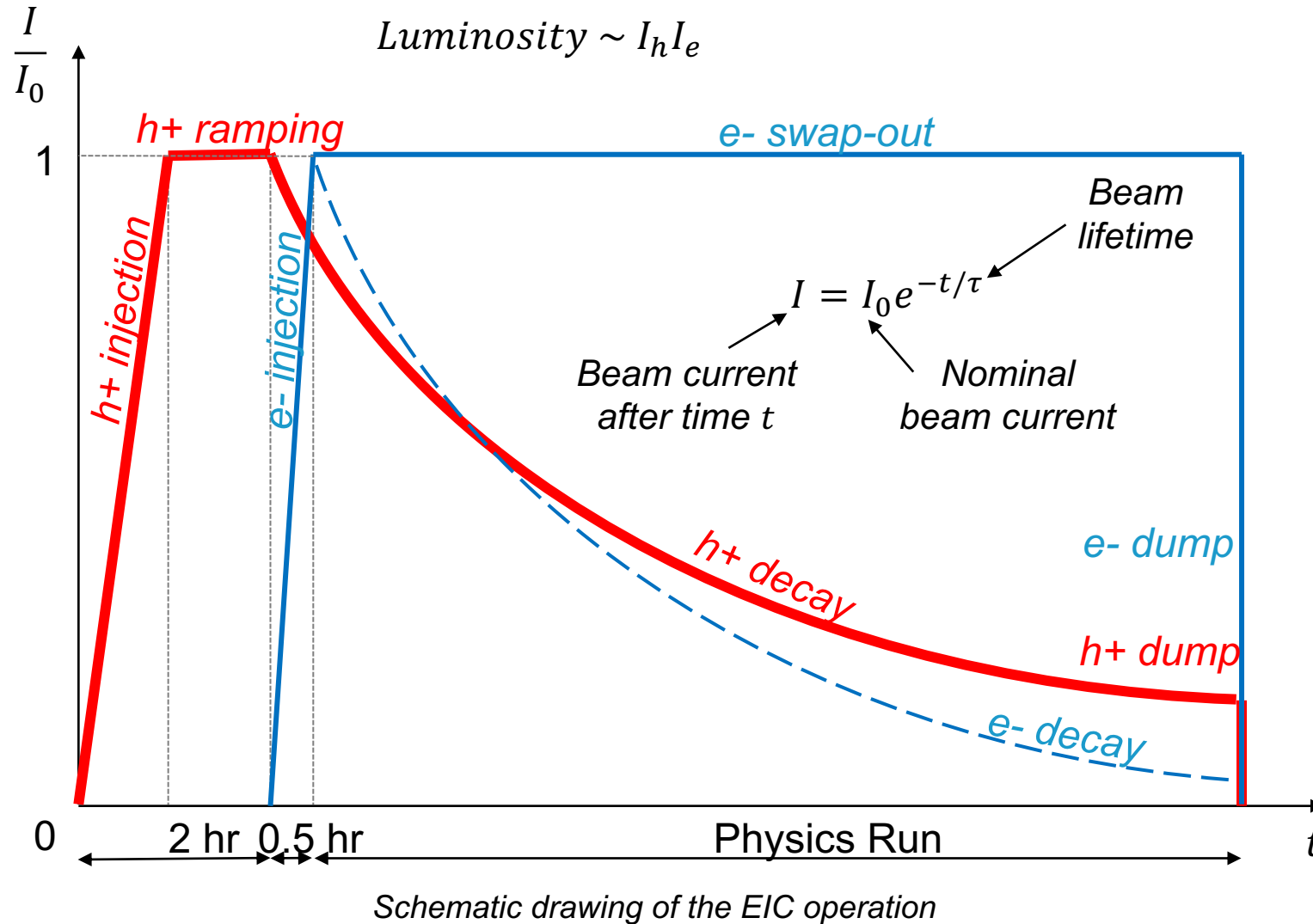
DA = Dynamic Aperture

PA = Physical Aperture (beam pipe)

Electron-Ion Collider

EIC Operation Scheme

EIC CDR-CD1 (2021) - Baseline



Option-1:

- RCS is in the main ring tunnel
- **Swap-out** bunch replacement at 1 Hz rate $\rightarrow$ full beam replacement < 20 min
- **The impact of the ESR lifetime > 1 hour is negligible**

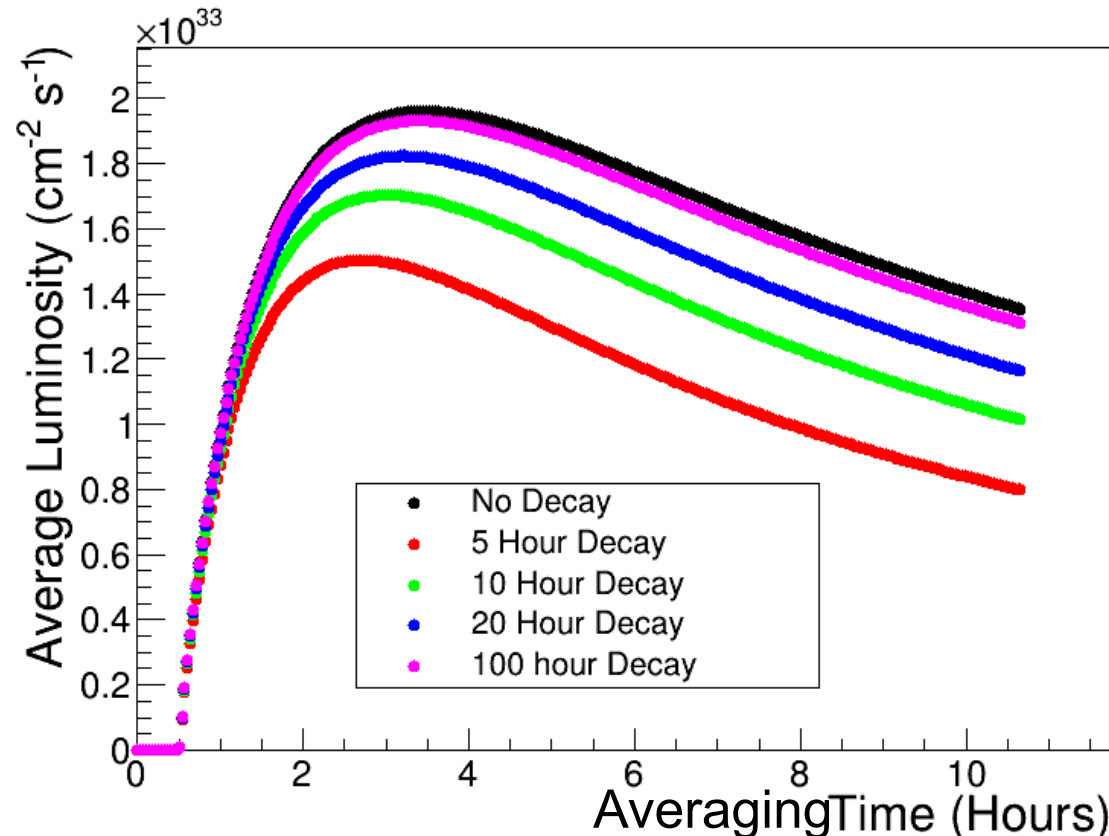
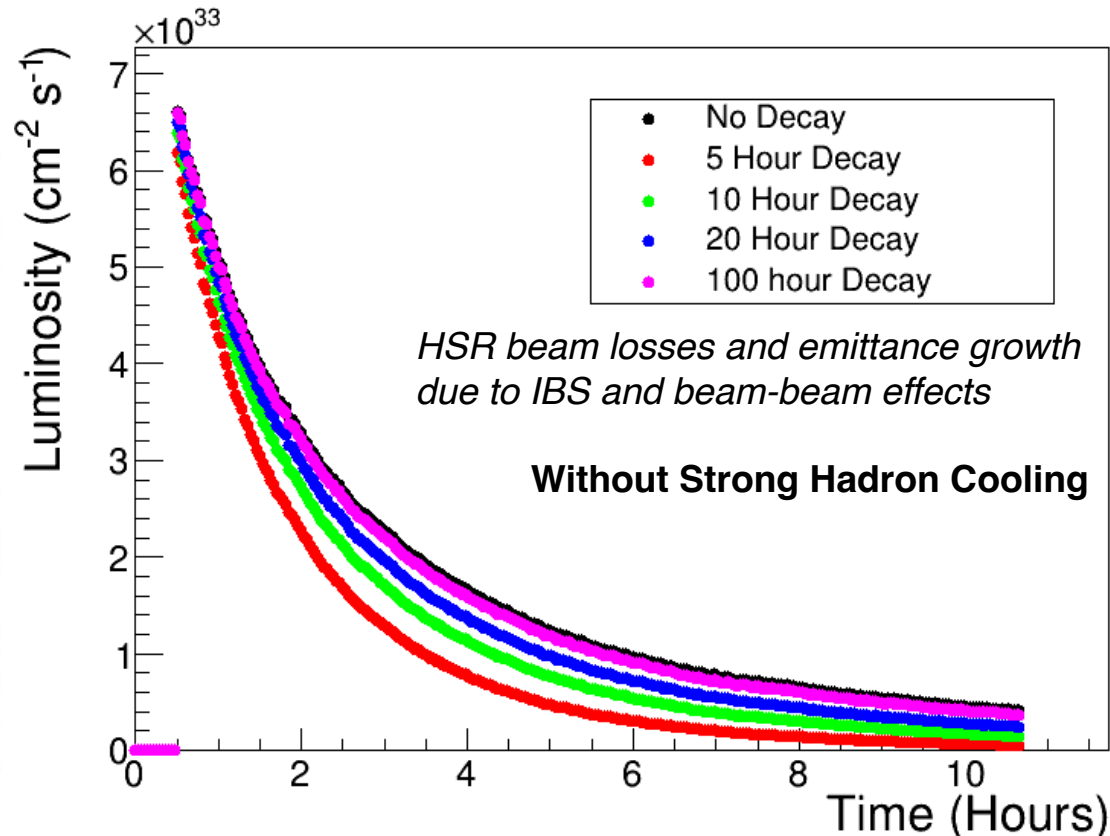
Under Discussion (2024)

Option-2:

- RCS is out of the main ring tunnel
- **No swap-out** bunch replacement due to cost and complexity
 - Current accumulation in the ESR
 - **Current decay** after injection
- **The ESR lifetime is essential**
 - Shorter lifetime $\rightarrow$ more frequent refill $\rightarrow$ shorter Physics Run

Luminosity : 10x275 GeV

William Bergan (BNL)



- No electron decay (**swap-out**): $1.96 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ with store of 3.45 hours
- 5 hour electron decay: $1.50 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ with store of 2.68 hours
- 10 hour electron decay: $1.70 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ with store of 3.02 hours
- 20 hour electron decay: $1.82 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ with store of 3.20 hours
- 100 hour electron decay: $1.93 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$ with store of 3.37 hours

At above **10 hours** of the ESR beam lifetime, there is ~10% of the luminosity degradation.

Abstract

The Electron-Ion Collider (EIC), under construction at BNL, is a groundbreaking facility designed to explore the fundamental structure of matter. By colliding high-luminosity polarized electron and ion beams, the EIC will probe the spin, mass, and spatial distributions of quarks and gluons, addressing key questions in QCD. However, mitigating beam-induced backgrounds remains a critical challenge for preserving detector performance and physics measurements.

This talk will present recent progress in understanding and addressing these challenges. Key background mechanisms, including beam-gas scattering, synchrotron radiation, and Touschek scattering, are studied using advanced tools such as SynradG4 for synchrotron radiation modeling and Xsuite-based frameworks for multi-turn particle tracking. Findings on synchrotron radiation loads, electron beam losses, and mitigation strategies will be discussed. Lessons from other operated colliders guide efforts to ensure the EIC achieves its ambitious scientific goals.