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Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

A New Framework for Synchrotron Radiation Studies in the EIC Experiment

Andrii Natochii

natochii@bnl.gov

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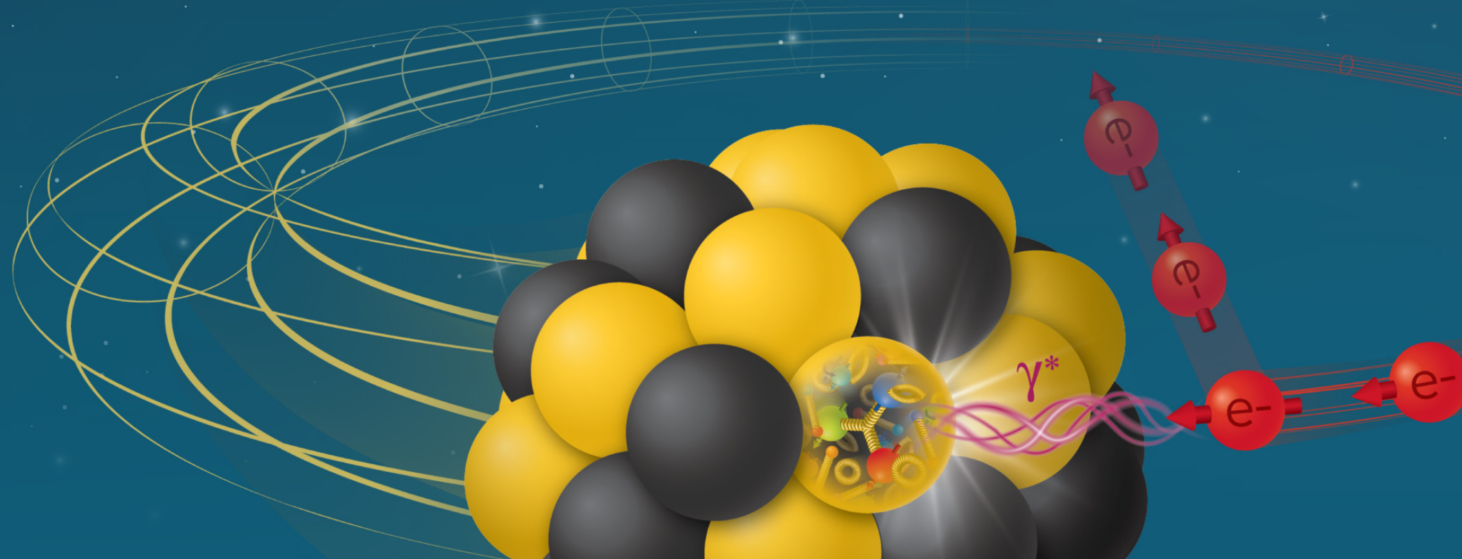
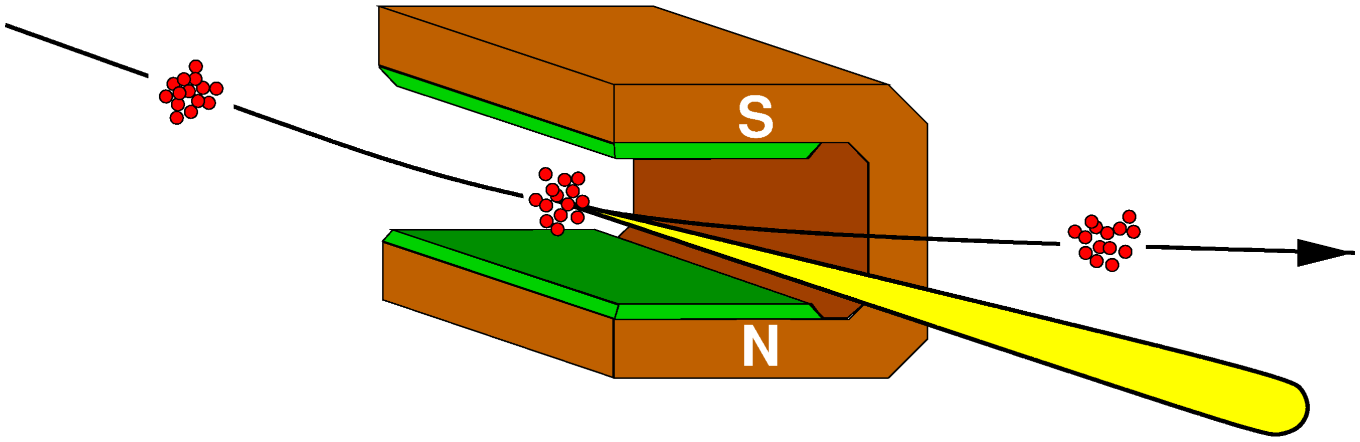
Electron-Ion Collider



Outline

- Electron-Ion Collider (EIC) Science Highlights
- Machine Design
- Electron-Proton/Ion Collider (ePIC) Detector
- Synchrotron Radiation (SR) Background Simulation
  - Typical approach
  - Improvements
  - Benchmark
  - Estimated detector rates
  - SR masking
- Challenges and Plans
- Summary



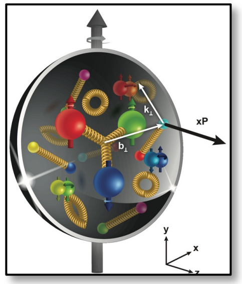
Science Highlights

Spin is one of the fundamental properties of matter.

The EIC will unravel the different contributions from the quarks, gluons, and orbital angular momentum.

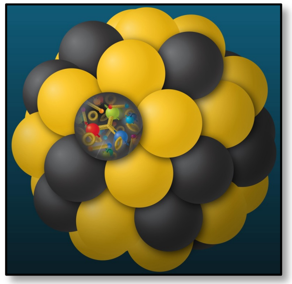
Does the **mass** of visible matter emerge from quark-gluon interactions?

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**?

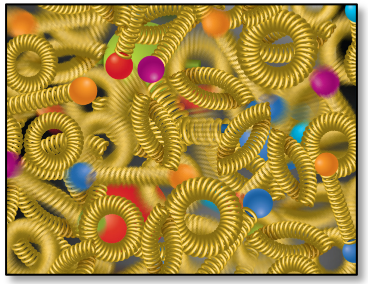


Is the **structure** of a free and bound nucleon the same?

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

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

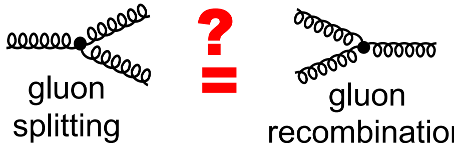
How do the quark-gluon interactions create **nuclear binding**?



How many gluons can fit in a proton?

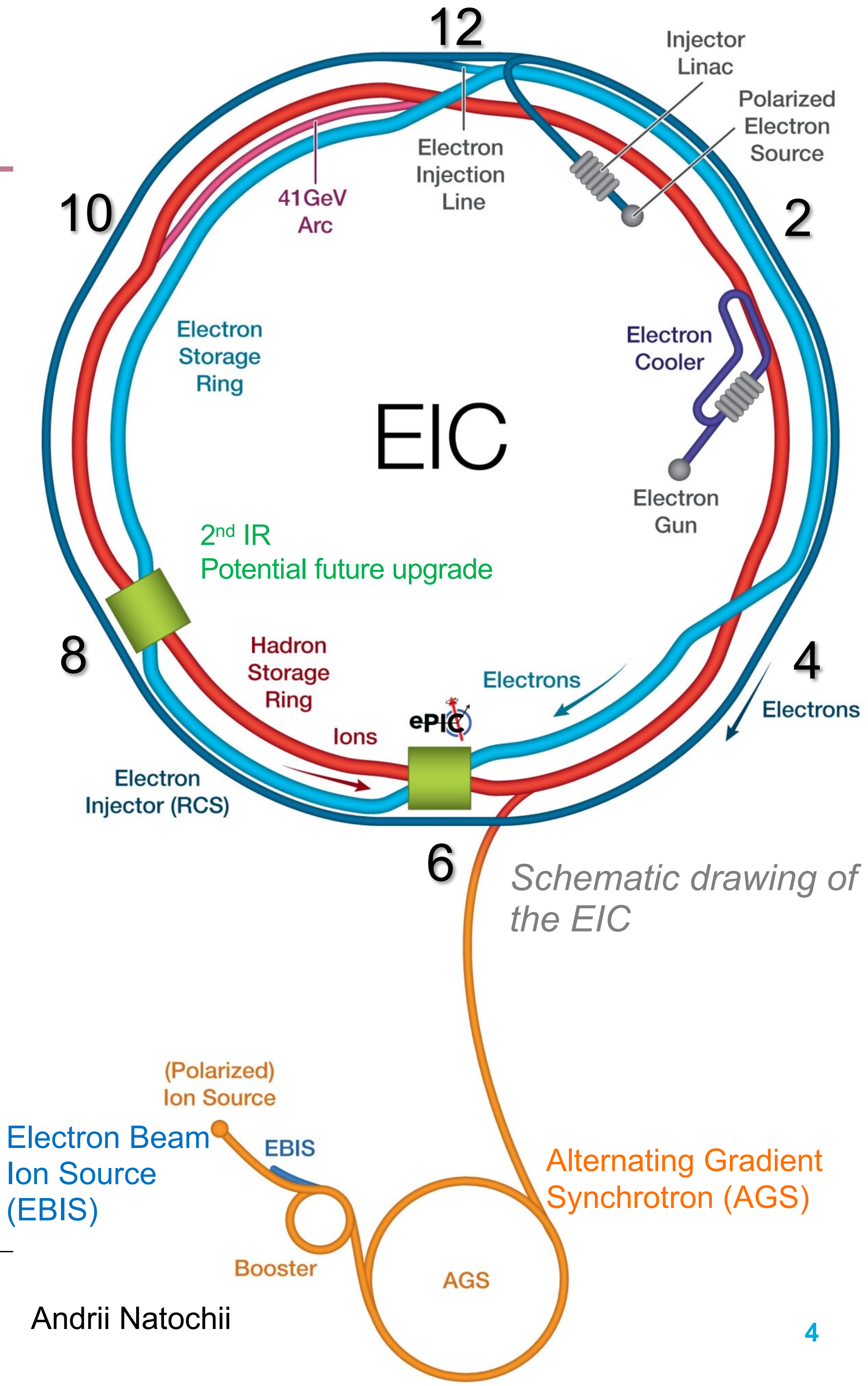
How does a **dense nuclear environment** affect the quarks and gluons, their correlations, and their interactions?

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)**
  - Large range of ion species (H–U)
  - E_{HSR} = 41, 100–275 GeV
  - I_{HSR} = 0.38–1.0 A
- **Electron Storage Ring (ESR)**
  - E_{ESR} = 5–18 GeV
  - I_{ESR} = 0.227–2.5 A
- High polarization of ~70% for electron and light ion beams
- E_{CM} = 20–141 GeV
- $L = 10^{33}$–10^{34} cm^{-2}s^{-1}
- Crossing angle of 25 mrad with Crab Cavities
- **Start commissioning in the 2030s**



Schematic drawing of the EIC

Detector

IP6 beam pipe:
- ***1.47 m long*** *and 0.76 mm thick Be pipe + 5 μm Au coating*

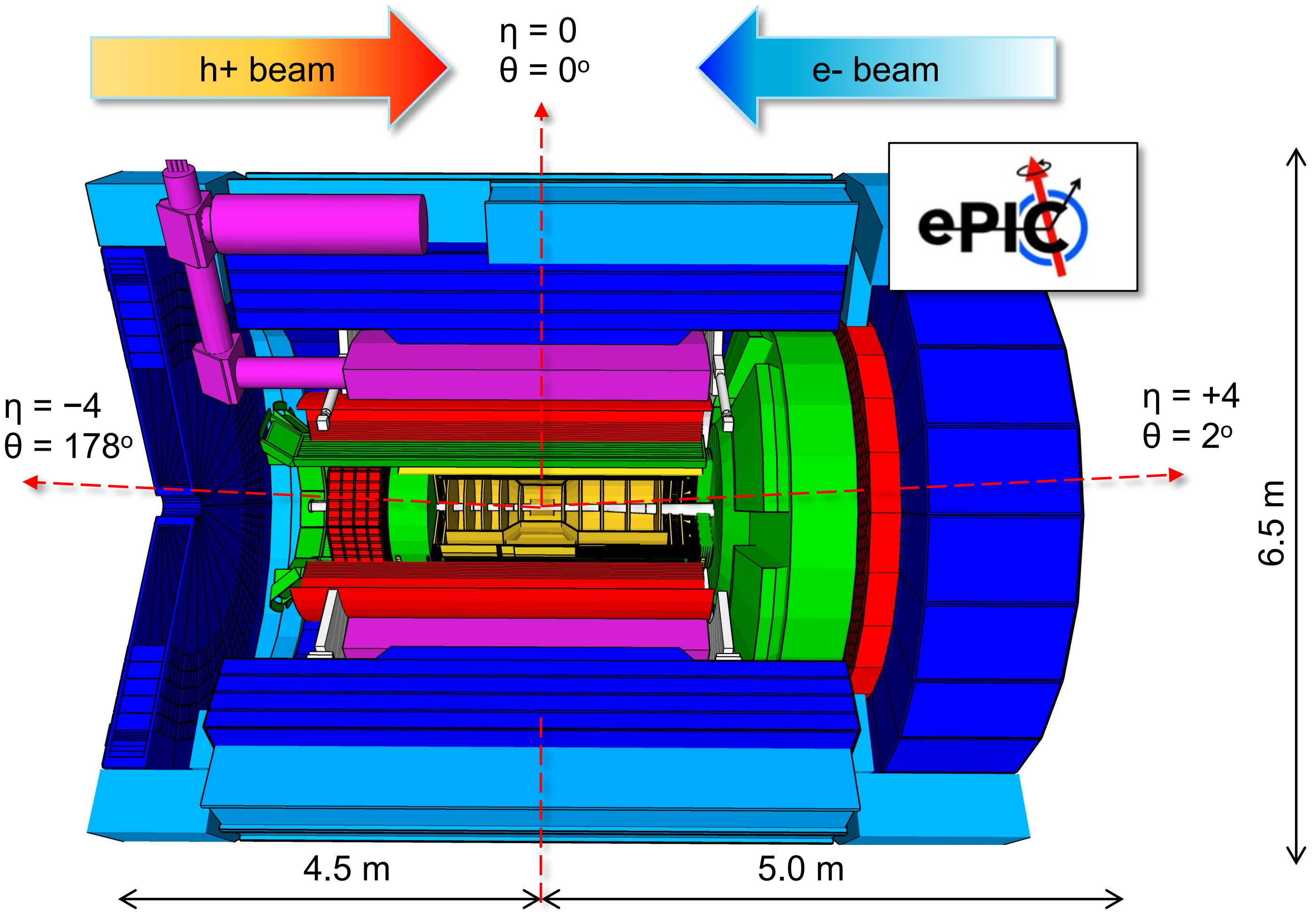
Tracking:
- *Primary and secondary vertexing*
- *High-precision low mass tracking*

Particle identification (PID):
- *High-performance single track PID for π, K, p separation*

Electromagnetic calorimetry (EMCal):
- *Photon measurements and electron identification*

Hadron calorimetry (HCal):
- *Charged hadron, neutron, and K_L measurements*

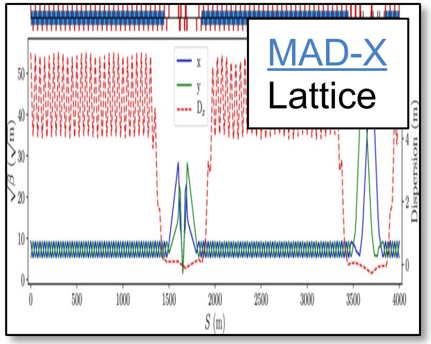
Auxiliary detectors (> 5 m from the IP):
- *Luminosity photon measurements*
- *Scattered e-, γ, n, and h detection*

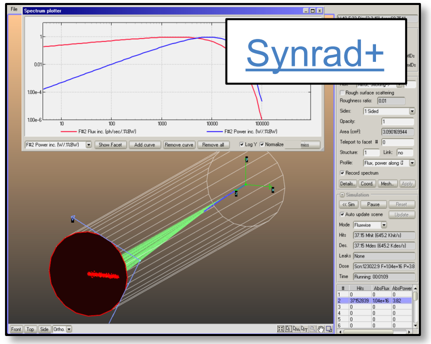


Schematic drawing of the ePIC detector

Typical SR Simulation Approach in ePIC

ESR lattice design → SR production & tracking → Data sampling → Detector simulation → Data analysis



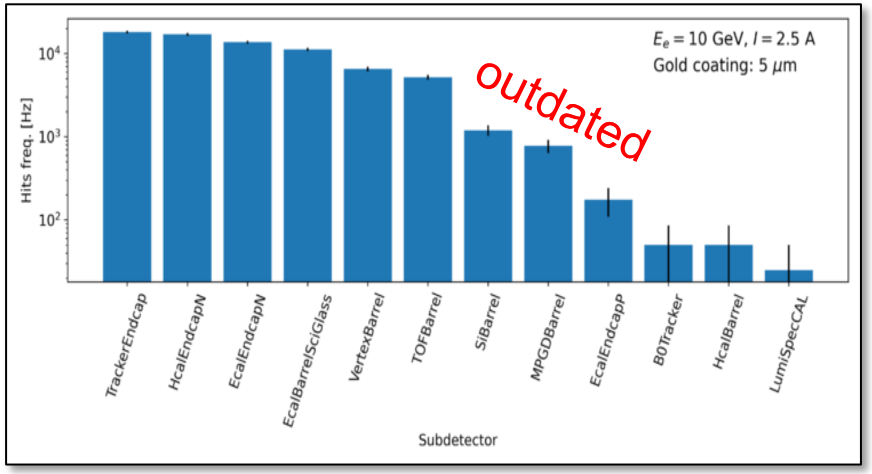


Event generator
CSV → HepMC

EIC-Shell: DD4Hep

EIC-Shell: EIC-Recon

1. Time-consuming procedure:
   - Synrad+ stores photon coordinates on one facet at a time.
   - The IR beam pipe consists of ~30k facets.
2. Detailed SR masking design is limited:
   - Synrad+ describes SR photons as virtual photons with intrinsic weights, representing sampled flux and power generated by the given SR source.



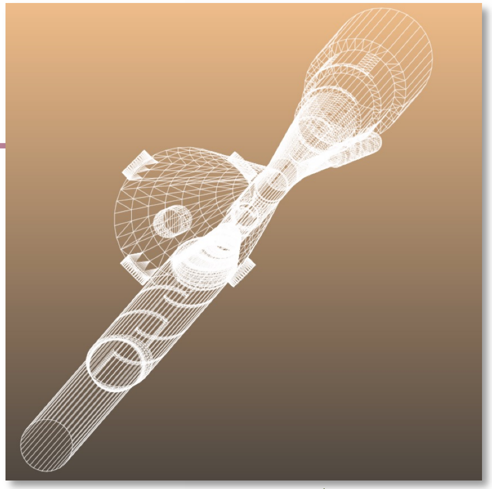
SR background rates in ePIC sub-detectors

Simulation Improvements

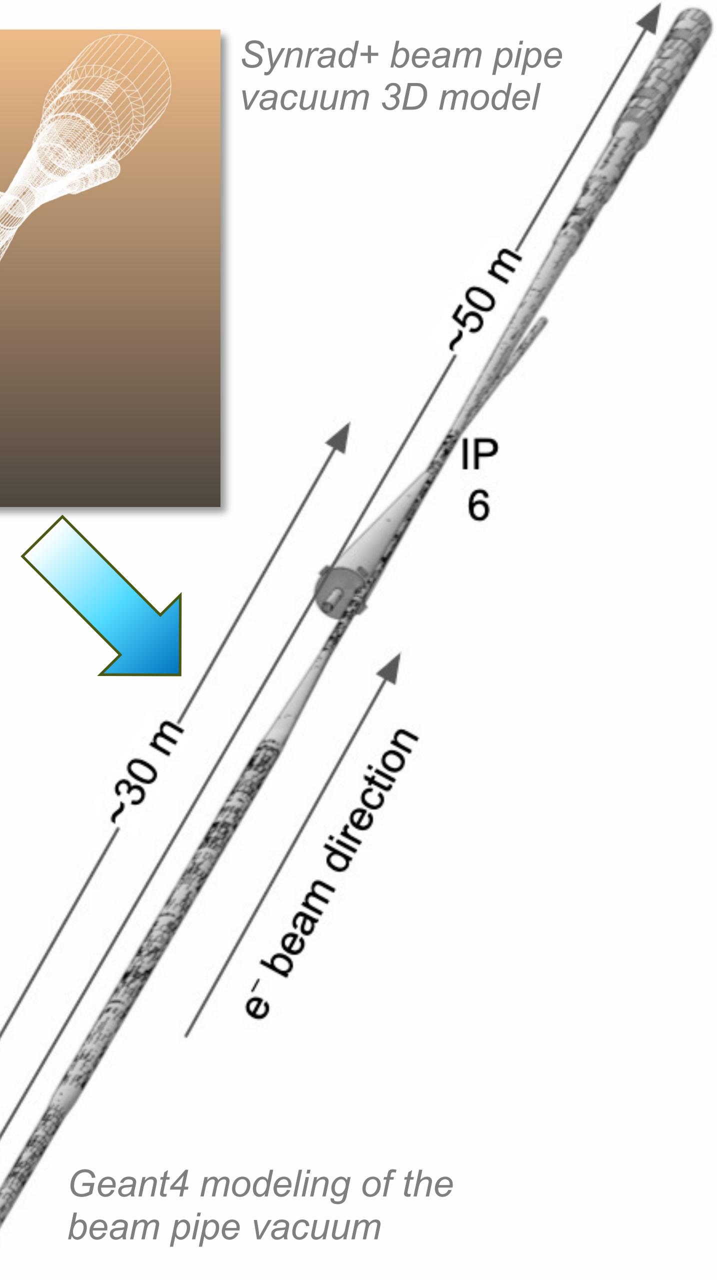
Synrad+ constrains/issues:
- Limited SR background studies
- Inadequate simulation results

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



Synrad+ beam pipe vacuum 3D model



Geant4 modeling of the beam pipe vacuum

X-ray Reflection Physics in Geant4

Availability:

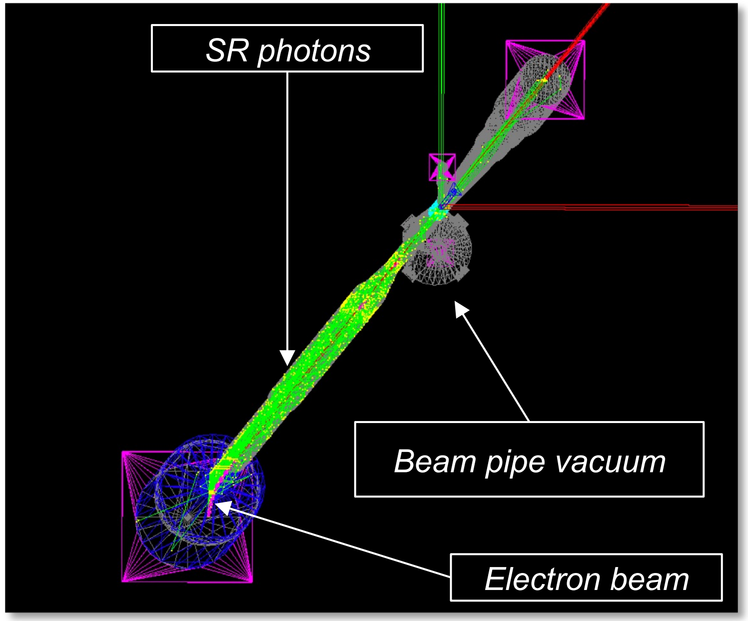
- X-ray reflection was missing in Geant4
  - Recent (Dec. 2023) implementation ← so-called *geant4-release*
    - Specular (mirror-like) reflection + attenuation factor for roughness

Solution:

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

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

1. **Synrad+** (with bugfixes) – diffuse reflection
   a) Old reflection model based on Synrad (1993)
   b) New reflection model based on Synrad3D (2013)
2. **Geant4-release** – specular reflection
3. **Custom-built Geant4**
   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

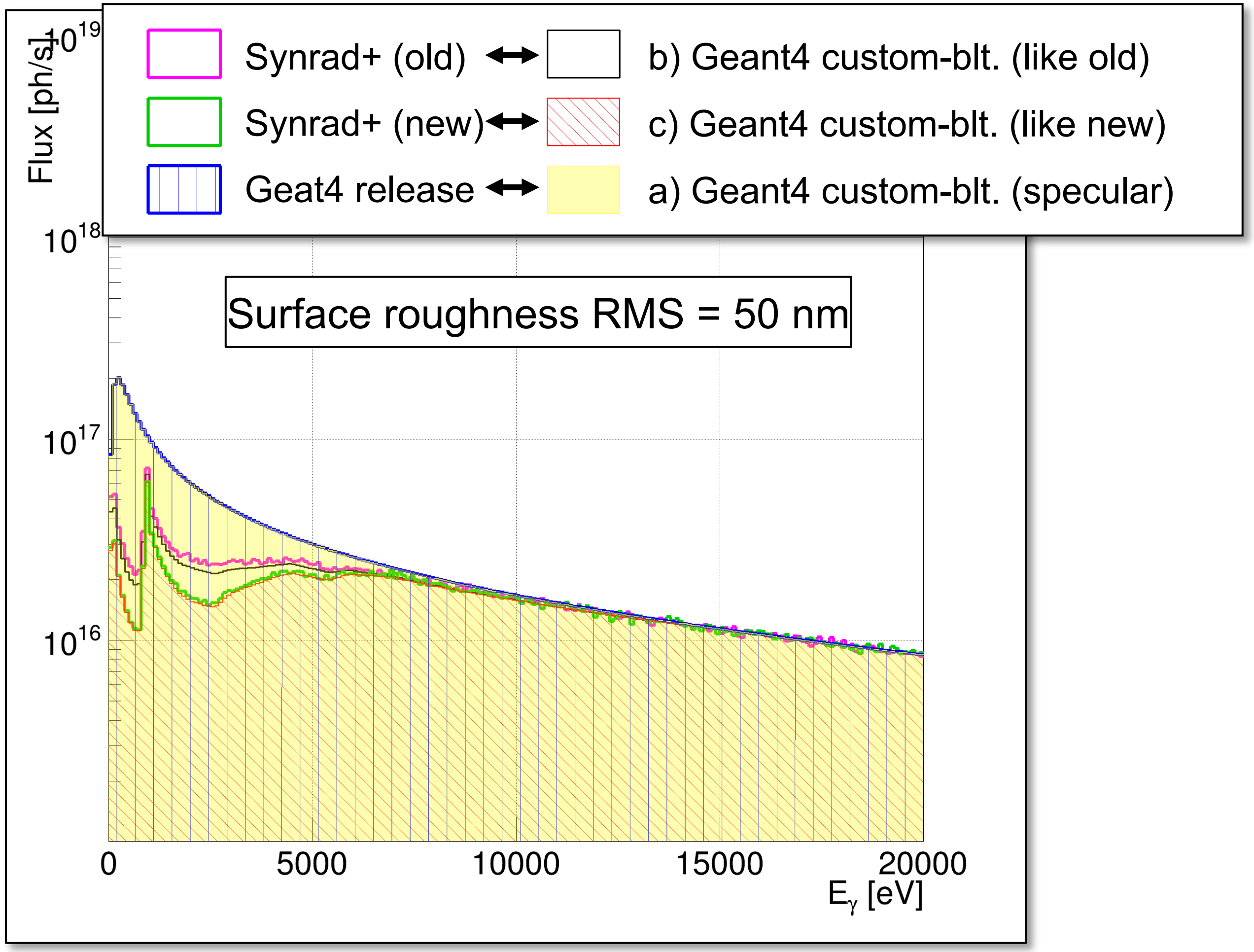


Geant4 geometry

Benchmark

- There is a **good agreement** between custom-built G4 and Synrad+/G4-release
- **Confirms correct implementation** of X-ray reflection into the new custom-built code
- After adding IR magnets (dipoles, quads, and solenoid), the absorbed **SR photons can be transferred to EIC-Shell/DD4Hep**

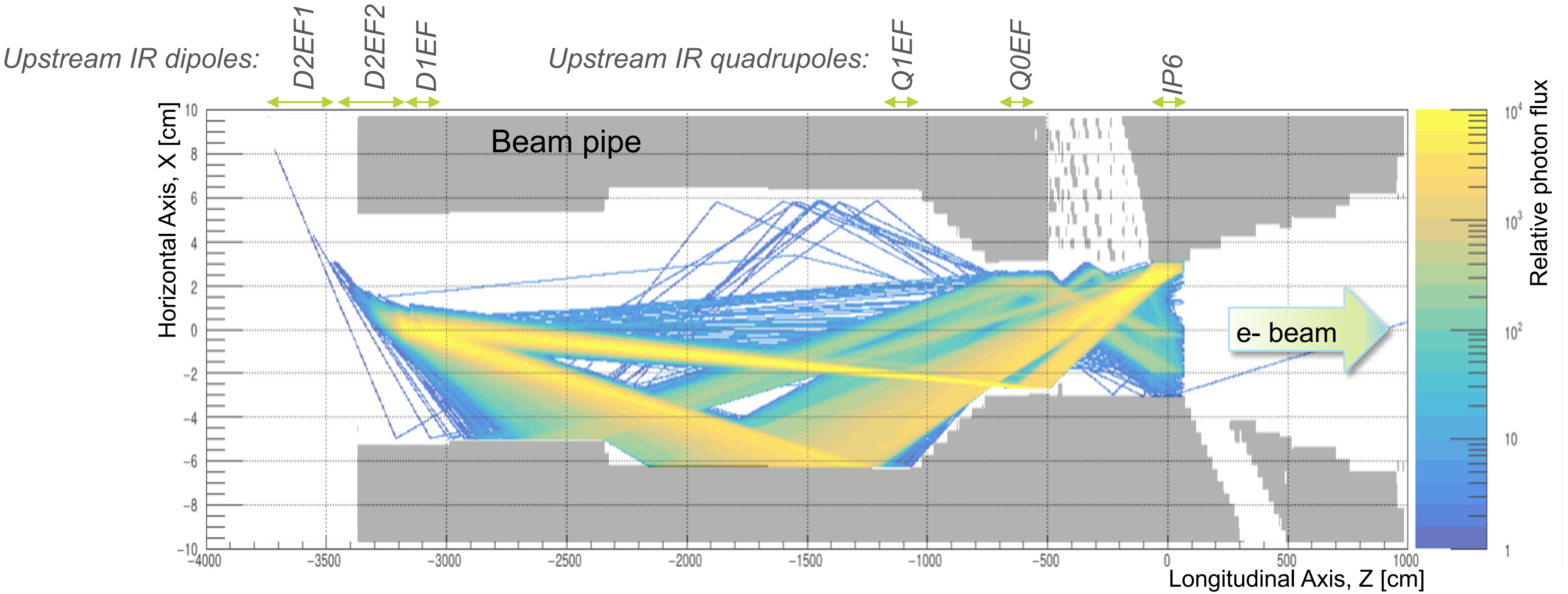
The tool is ready for the SR background simulation !



Absorbed SR photon spectrum on the arbitrary beam pipe vacuum facet

SR Background (w/o SR masks)

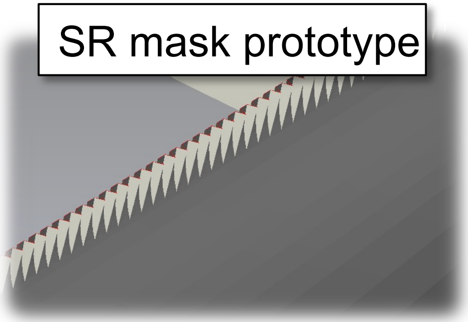
The estimated SR background rate in the innermost vertex detector is **~1 THz** for 0.227 A of the 18 GeV electron beam.

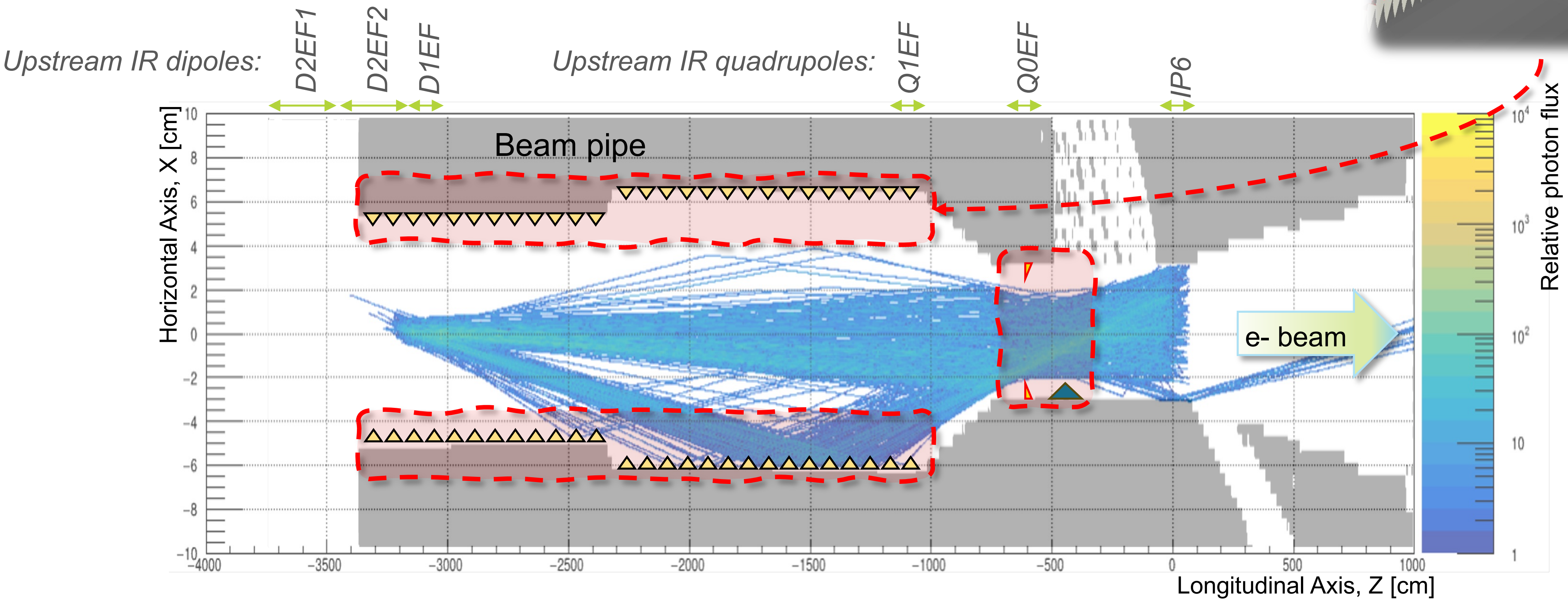


Trajectories of 10 keV SR photons that hit the IP beam pipe

SR Background (w/ SR masks)

The estimated SR background rate in the innermost Vertex detector dropped below **~1 GHz**.





Trajectories of 10 keV SR photons that hit the IP beam pipe

Challenges and Plans

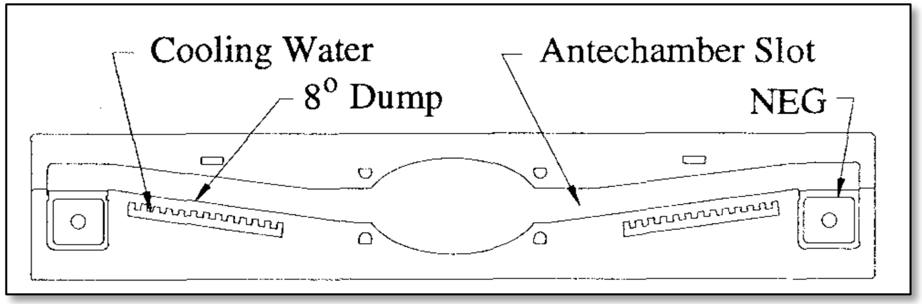
Computational resource requirements:

- One event (electron) simulation → **~100 ms for 2.1-GHz CPU**
- **3 x10^7 CPU · hours** are required for an accurate SR background study at the **MHz level** (~μs integration time)
- Performed simulation **optimization** (SR cross-section, tracking range, parallel photons)
  - Still a large amount of computation resources, **~3 x10^6 CPU · hours**, is required

Ongoing works and studies:

- Beam pipe geometry review following the latest updates
- Sophisticated SR mask implementation
  - Thicker IP beam pipe Au coating?
  - Ante-chambers? →
- SR load for beam pipe cooling
- Further SR simulation optimizations
- SR from the beam halo

SuperKEKB ante-chamber



PEP-II wiggler vacuum ante-chamber

Summary

- The high-energy and high-current **electron beam SR** is an important **background for ePIC**
  - Detrimental effect on detector longevity and physics analysis performance
- Built a **new Geant4-based Monte-Carlo simulation code** to study the SR in the EIC
  - **Precise X-ray photons' specular and diffuse reflection models**
  - **Avoids some functionality limits** of well-known SR simulation codes
- Further SR **countermeasure development is foreseen** for the detector safety
  - Requires many **computation resources** → optimization is ongoing
- The framework is **intensively used to design the new IR beam pipe** for the EIC project
- Potential benefits of the new code extend **beyond the EIC project**
  - Could **improve SR studies** at other e+e− colliders, such as **FCC-ee** and **SuperKEKB**

Acknowledgements

Many thanks to the EIC/ePIC people involved in this research for their hard work and contributions.

Thanks for your attention!

Backup

Abstract

Title: A new framework for synchrotron radiation studies in the EIC experiment

Author: Dr. Andrii Natochii (BNL) natochii@bnl.gov

The Electron-Ion Collider (EIC) is an advanced particle accelerator designed to explore matter's fundamental structure at the subatomic scale. It collides high-energy polarized electron beams with ions, like protons or lead nuclei, enabling scientists to scrutinize quark and gluon interactions. The EIC's unique setup provides a platform to study these interactions within atomic nuclei, shedding light on nuclear matter and extreme conditions in the universe. Collaboration among multiple institutions drives the construction and operation of the EIC, with the overarching goal of advancing our understanding of the fundamental forces and particles.

The EIC plans to operate at high beam currents and luminosities to probe dense gluon systems and unravel the origins of nucleon mass and spin. However, this strategy increases beam-induced background rates in the ePIC spectrometer located at the interaction point. Notably, synchronous radiation (SR) emitted from the electron beam is a significant source that negatively impacts detector longevity and physics analysis performance.

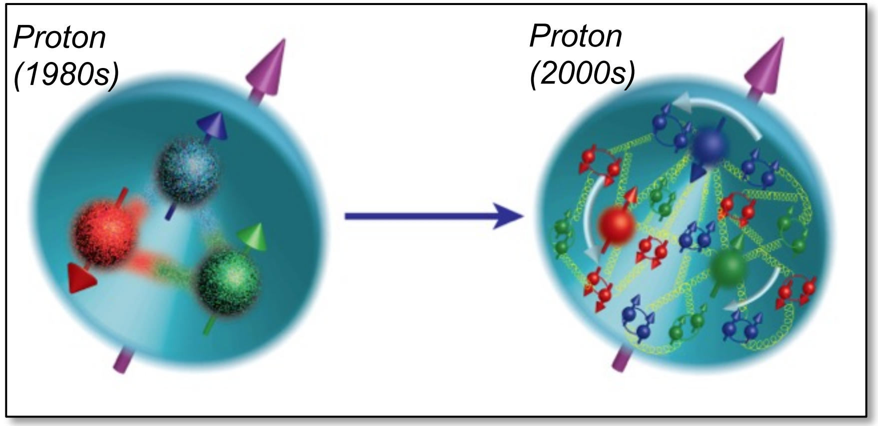
This talk describes the Monte-Carlo simulation method for the SR background in the ePIC setup at the EIC. It introduces a new framework to accurately model X-ray photons' specular and diffuse reflection on vacuum-metal interfaces. In addition, it utilizes the extensive functionalities of Geant4 classes for particle-matter interaction studies. Moreover, the talk presents updated estimates of SR rates in various ePIC subsystems and proposes countermeasures to protect sensitive electronics, ensuring a stable detector operation.

EIC: The Next QCD Frontier

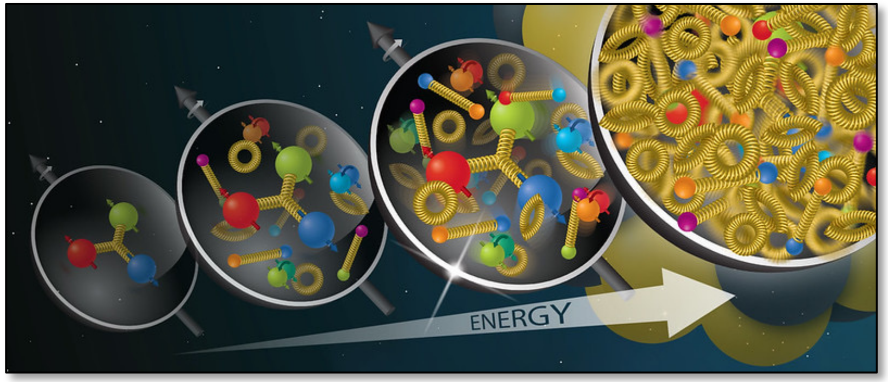
Nucleon Spin and Mass

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.

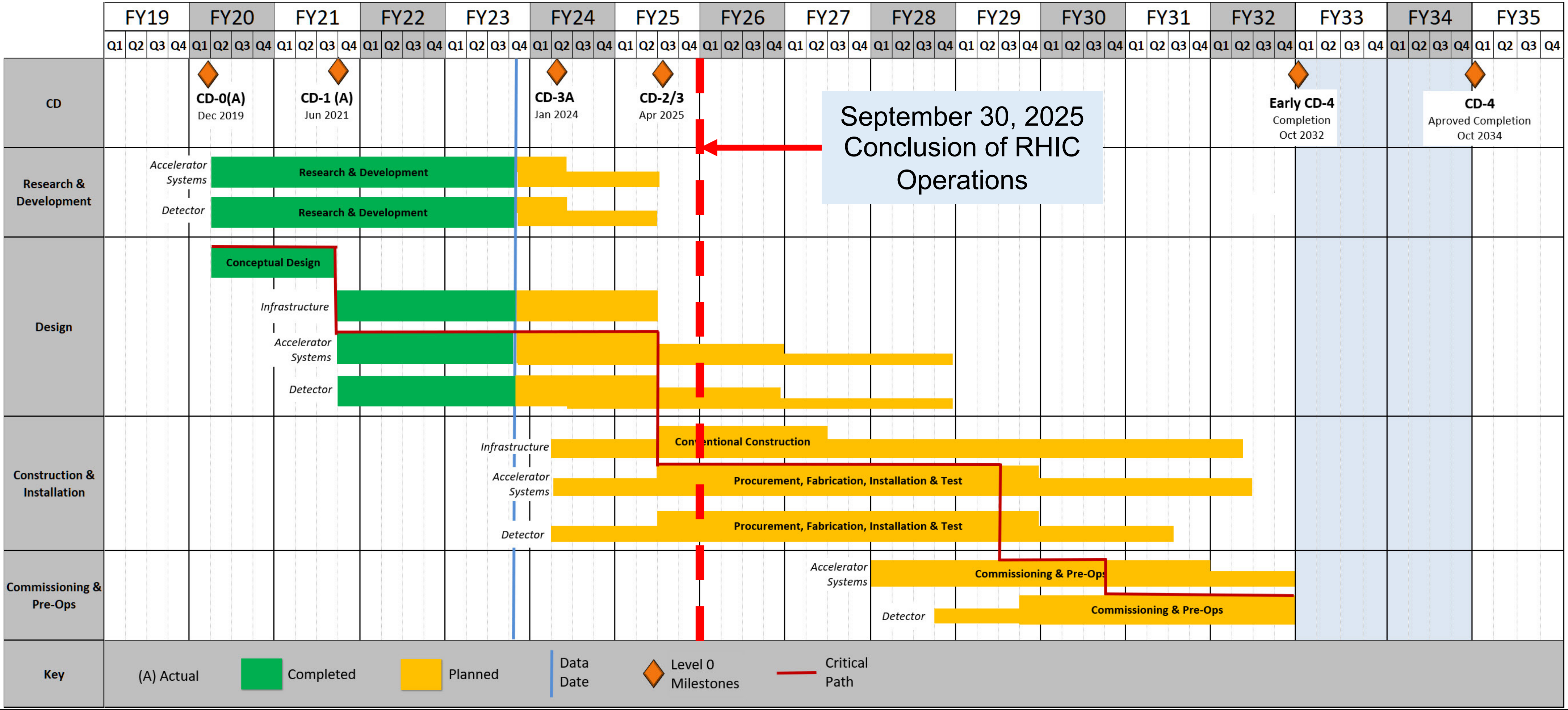
Gluon saturation

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.



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X-ray reflection physics in Geant4

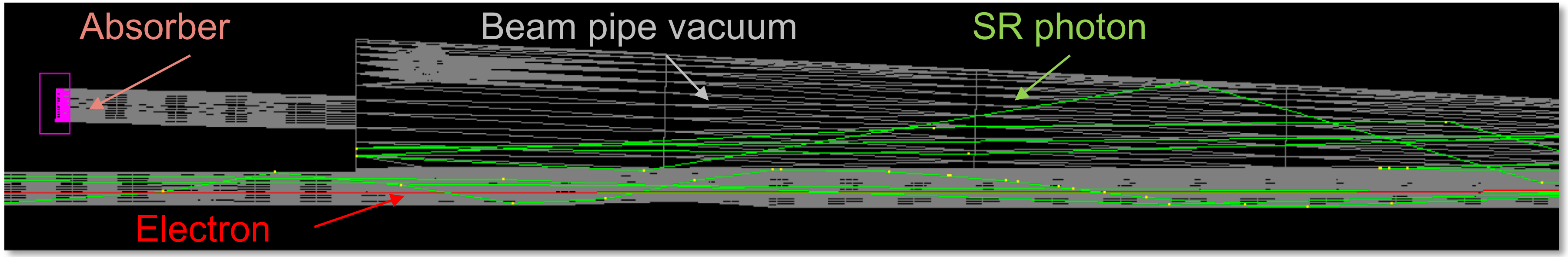
- Since X-ray reflection as a standard gamma process was missing in Geant4, the Geant4 developers have recently (Dec. 2023) implemented this process [#50 FCC-ee MDI meeting] ← so-called *geant4-release code*
  - The same material reflection data [B.L. Henke et al. (1993)] as in Synrad+ are used.
  - **Only specular (mirror-like) reflection** with an attenuation factor is considered to include surface roughness.

Solution:

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

Compare the following codes for benchmark (all use the same material reflect. data):

1. **Synrad+** (after recent discussions and bugfixes [Synrad+/Molfow+ Forum]) – diffuse reflection
   a) Old reflection model (based on Synrad [R.Kersevan, SSC 1993, 10.1109/PAC.1993.309821])
   b) New reflection model (based on Synrad3D [G.Dugan, D.Sagan, Cornell 2013, 10.5170/CERN-2013-002.117])
2. **Geant4-release** with the Névot-Croce attenuation factor – specular reflection [geant4-11.2.0]
3. **Custom-built Geant4** code
   a) With the Debye-Waller attenuation factor (same as geant4-release) – specular reflection
   b) With the reflection surface normal random tilt (same as the old model in Synrad+) – diffuse reflection
   c) With the Debye-Waller att. fact. + scattering parametrization (same as the new model in Synrad+) – diffuse reflection



Custom-built Geant4: SR photon propagation in the beam pipe vacuum with defuse reflection

Electron-Proton/Ion Collider (ePIC) detector

IP6 beam pipe:

- ***1.47 m long*** *and 0.76 mm thick Be pipe + 5 μm Au coating*

Tracking:

- *Primary and secondary vertexing*
- *High-precision low mass tracking*
  - 1.7 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):

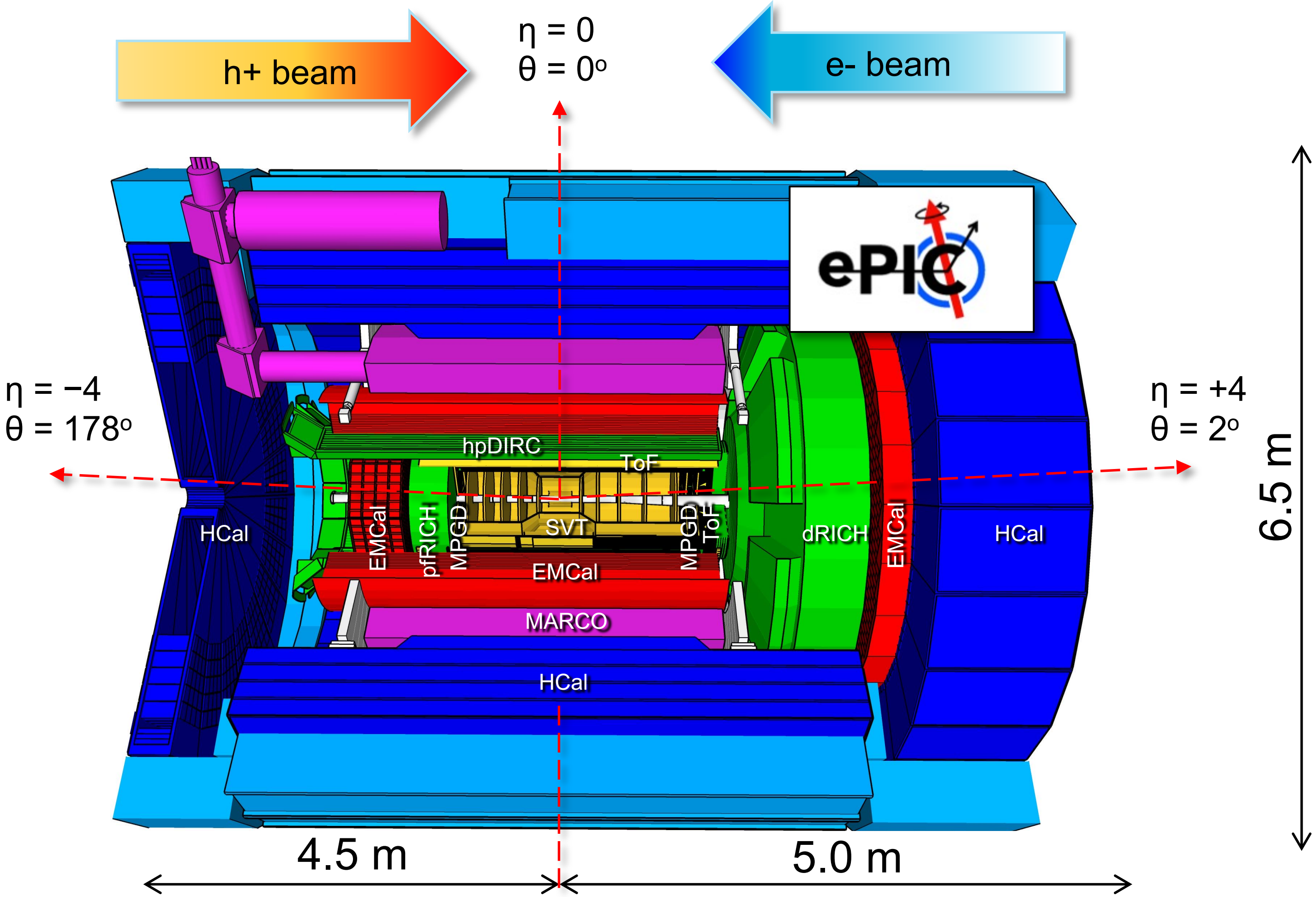
- *Photon measurements and electron identification*
  - Backward e-endcap, forward h-endcap, barrel

Hadron calorimetry (HCal):

- *Charged hadron, neutron, and K_L measurements*
  - Backward e-endcap, forward h-endcap, barrel

Auxiliary detectors (> 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



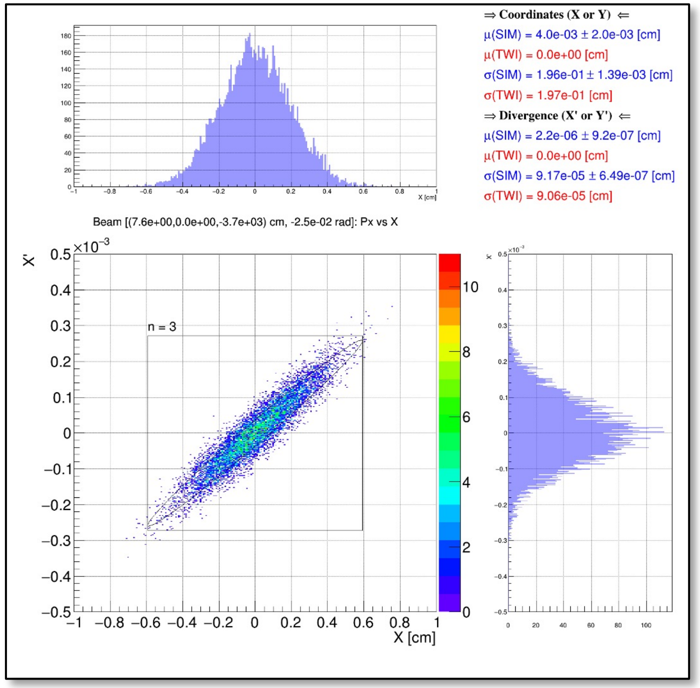
Schematic drawing of the ePIC detector.

Geant4 modeling of the EIC interaction region (IR)

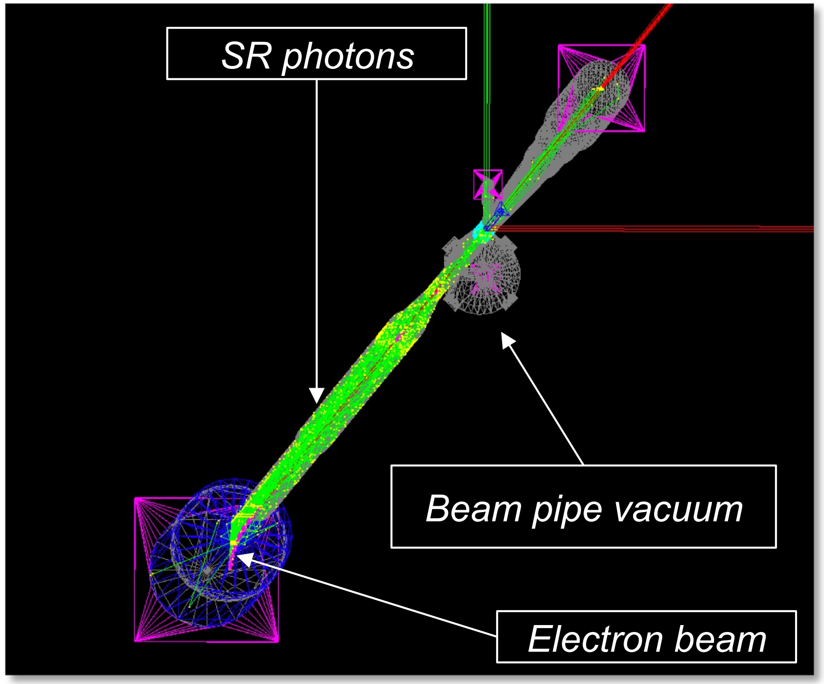
The code **propagates an electron beam through IR magnets** (3 upstream bends, 2 upstream quads, IP solenoid, 2 downstream quads, and 1 downstream bend) with the **SR production and custom-built reflection** (diffuse, new) processes.

- 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**.

The code is ready to be used for the SR background study in the ePIC detector.



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



Geant4 geometry

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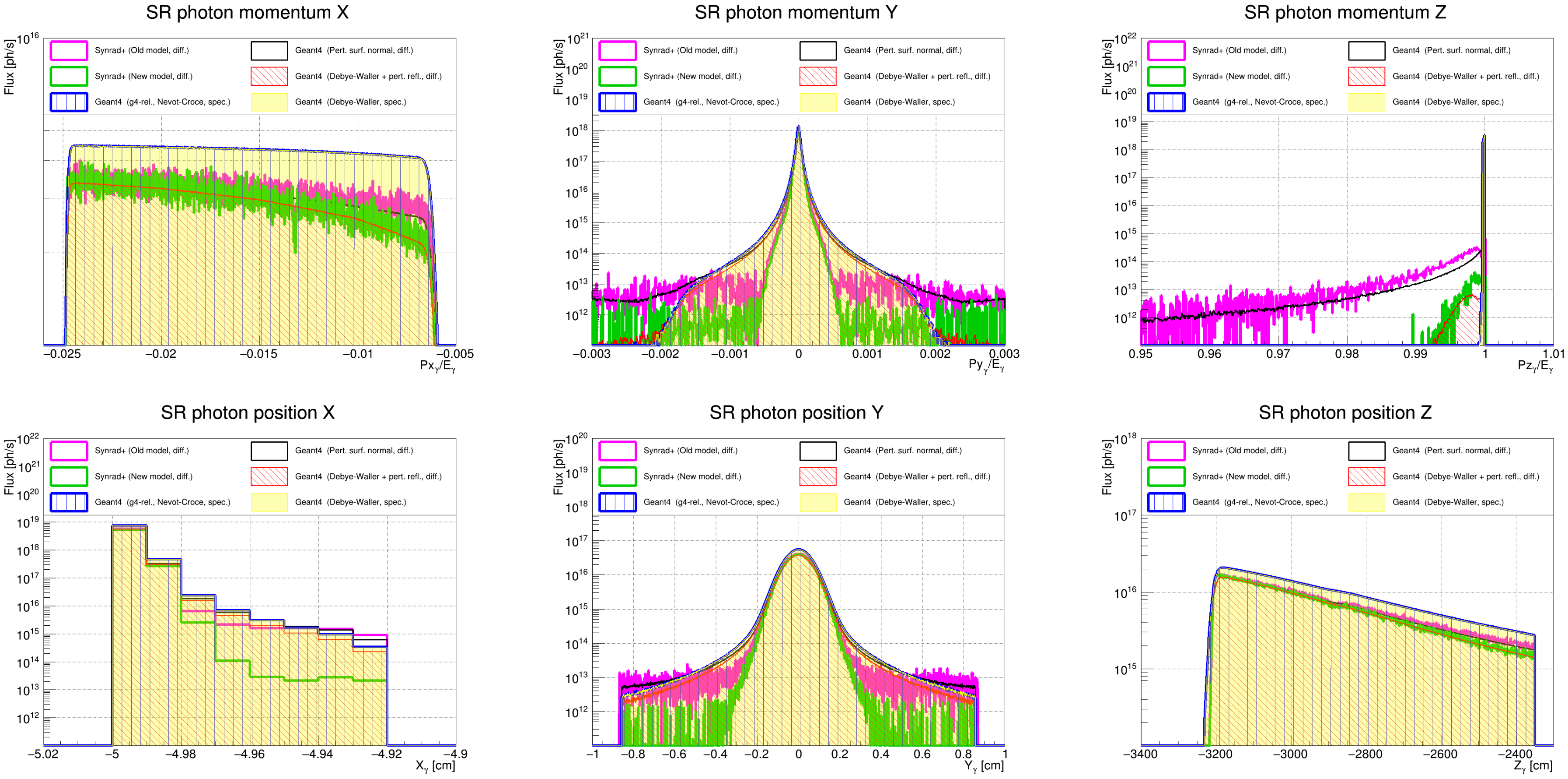
Synrad+ vs Geant4

Surface roughness = 50 nm



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Synrad+ vs Geant4

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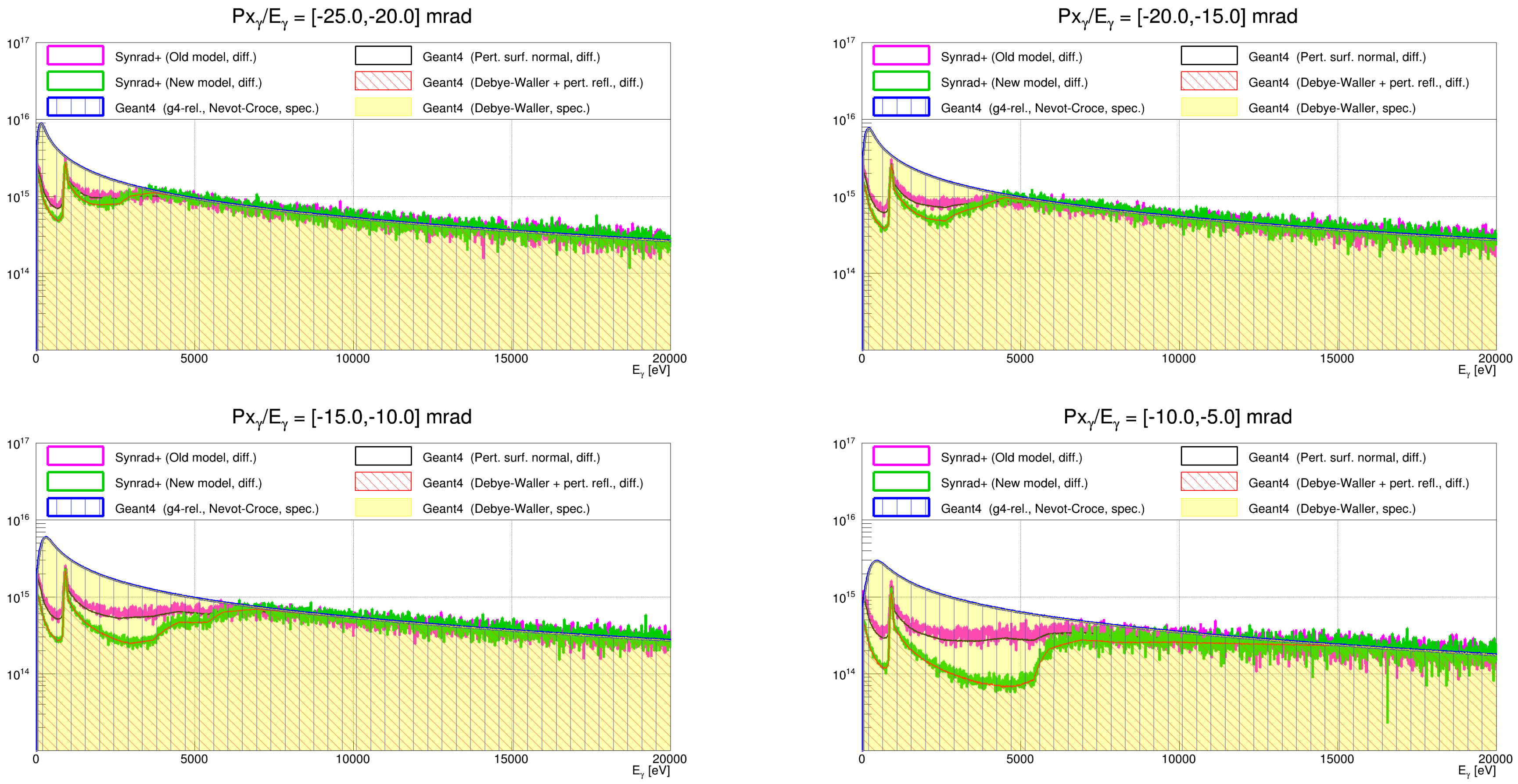

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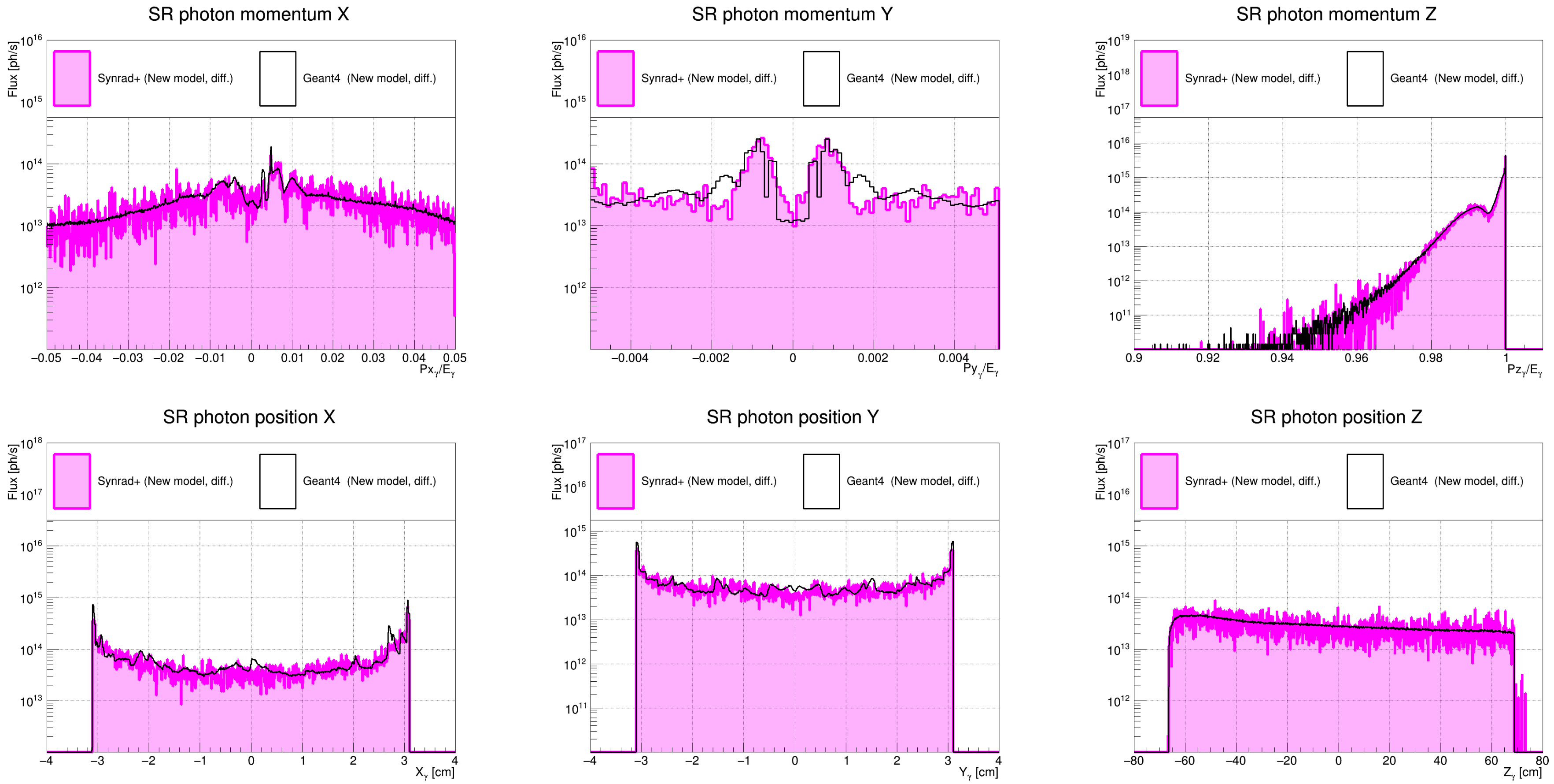
Synrad+ vs Geant4 (IP SR photon hits)



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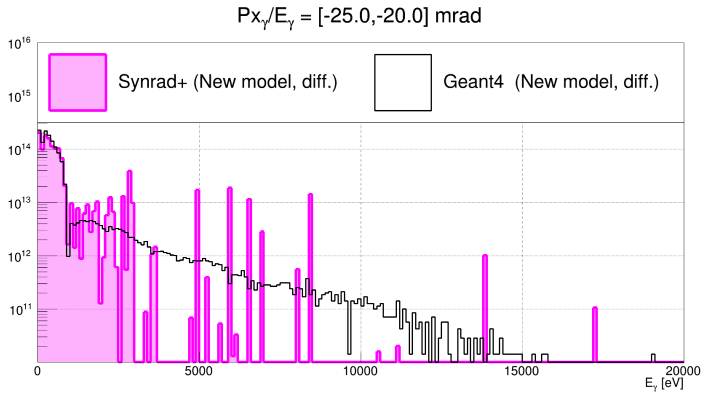
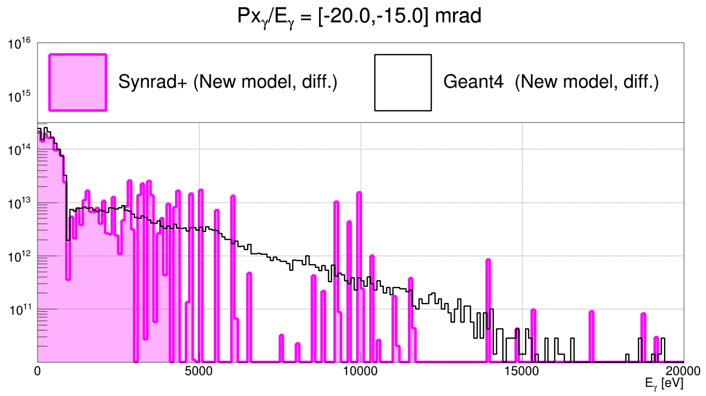
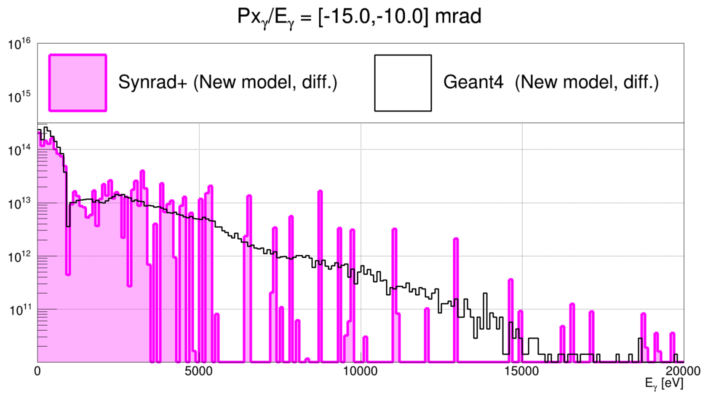
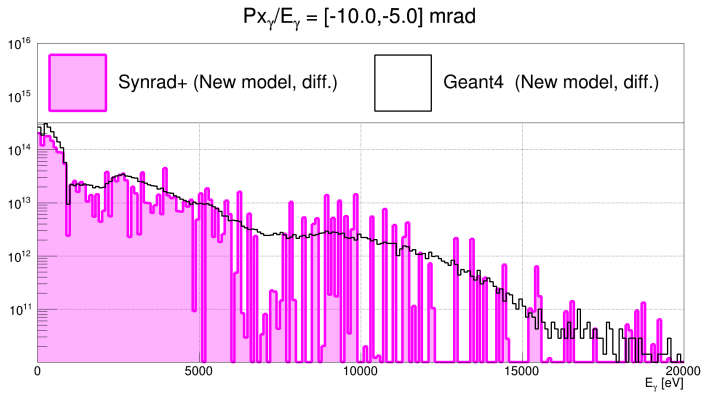
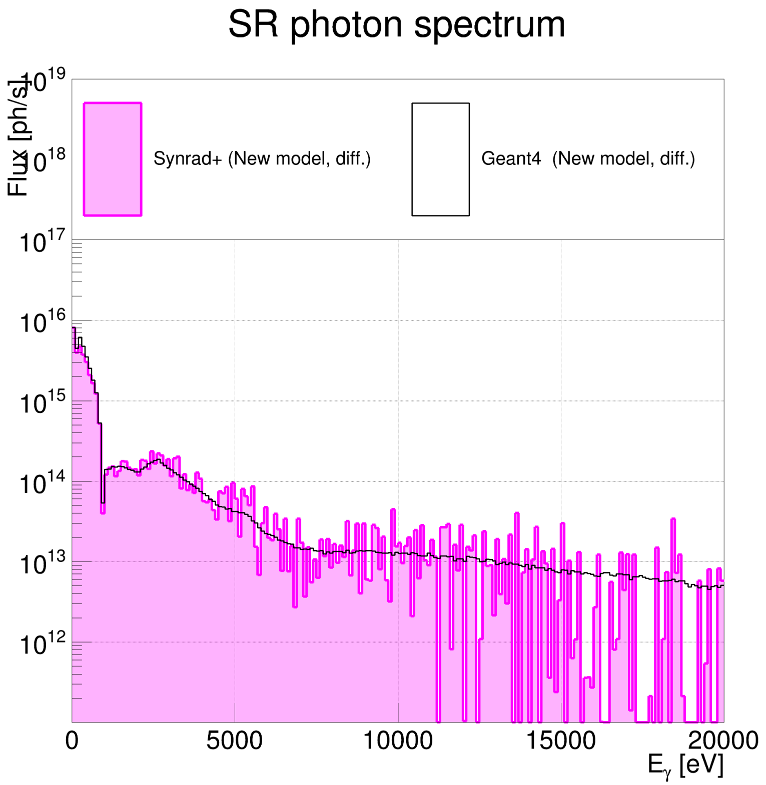
Synrad+ vs Geant4 (IP SR photon hits)



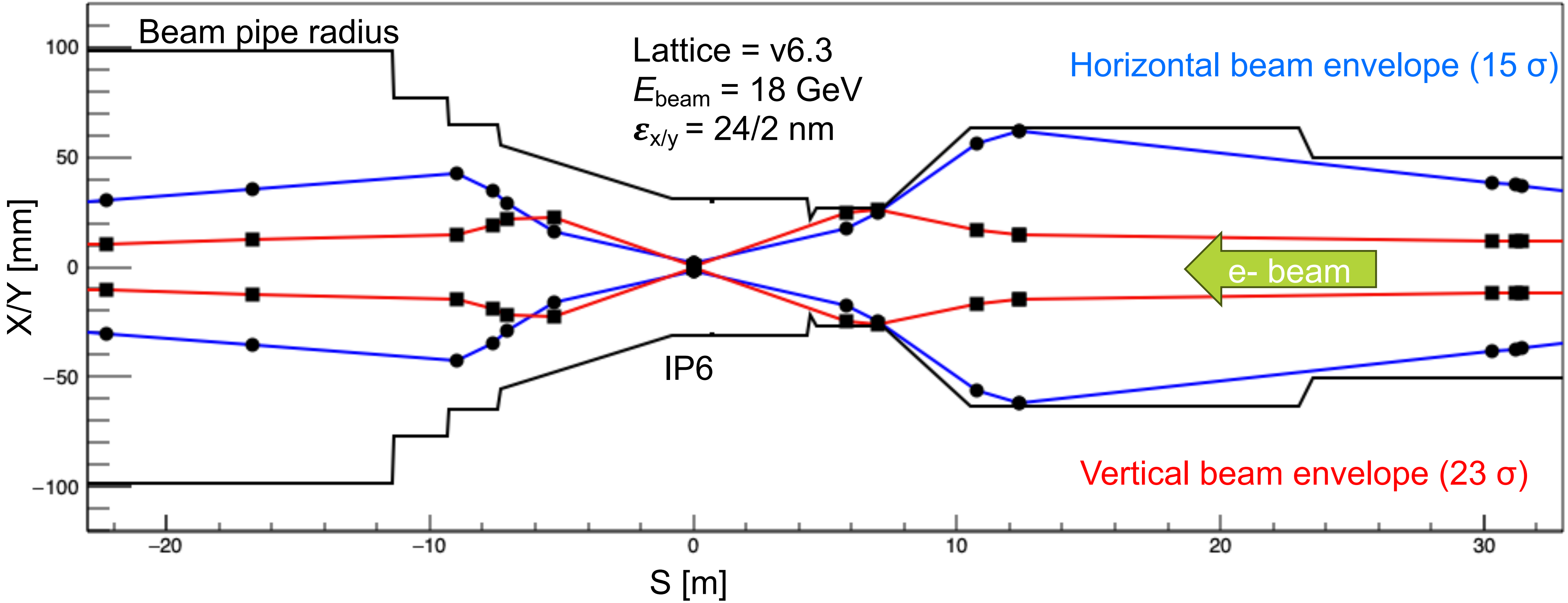








Beam Envelope



Machine Parameters

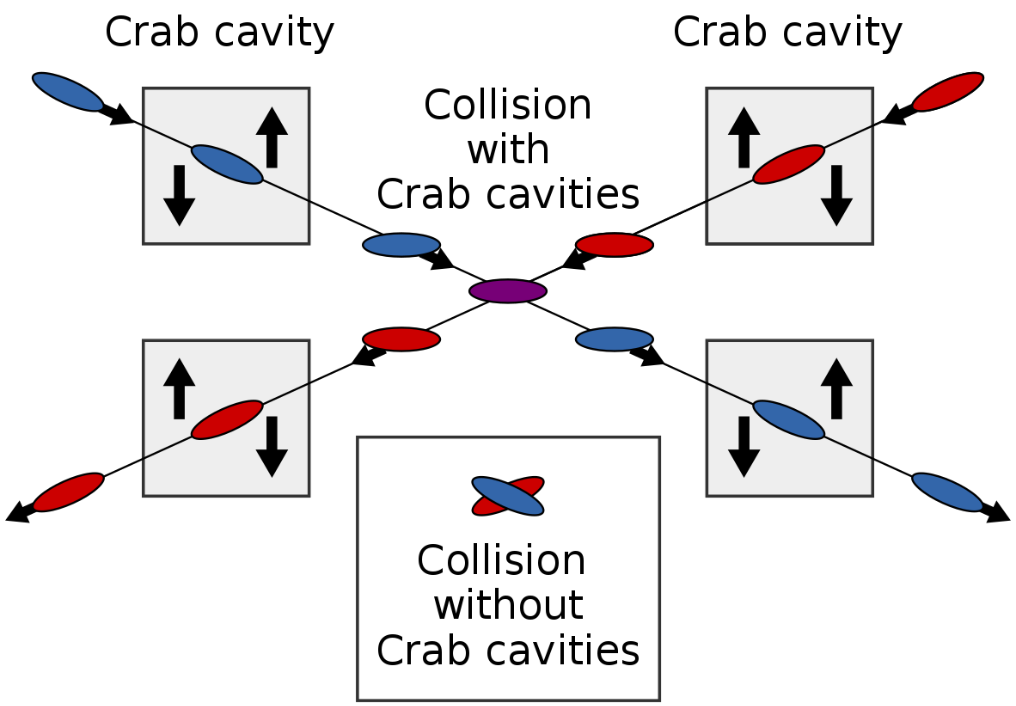


Table 2 Main parameters for the electron-proton operation in high acceptance operation mode.

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} 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 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		$10^{33}cm^{-2}s^{-1}$	0.3		3.1		3.1		2.9		0.4	

H=Horizontal, V=Vertical, Lrg = Large enough to not require cooling, Neg = Negligible.

Crab-Crossing