ePIC Technical and Integration Council (TIC)

Synchrotron Radiation Studies in the EIC Experiment

Andrii Natochii

natochii@bnl.gov

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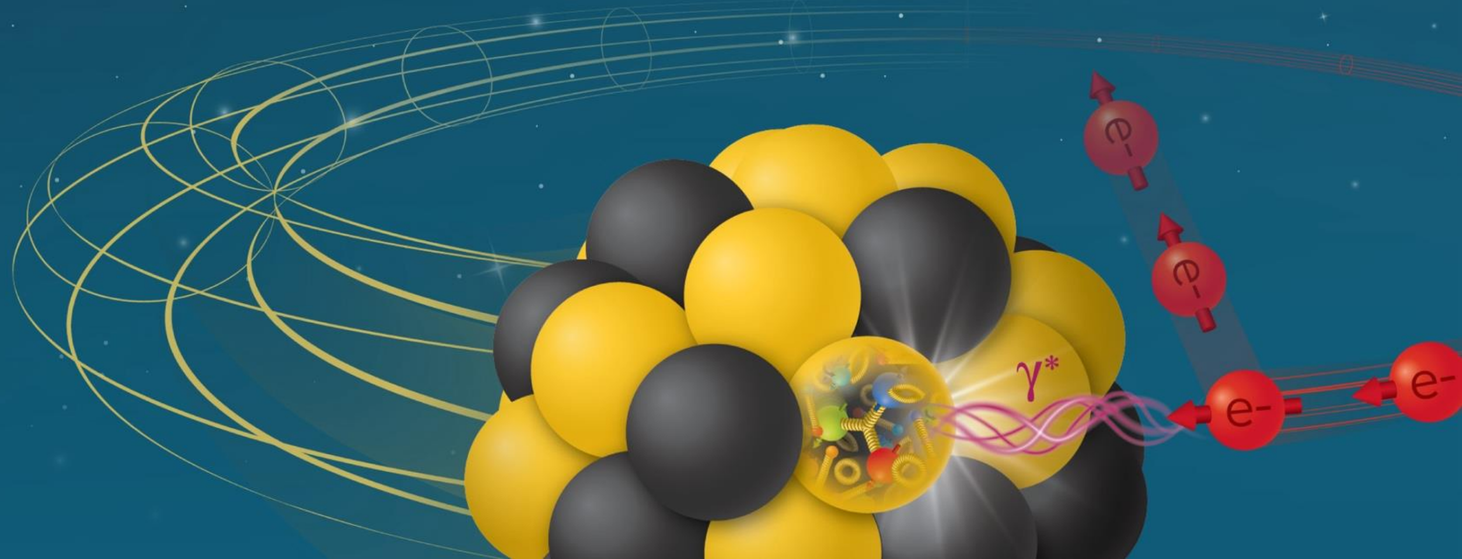
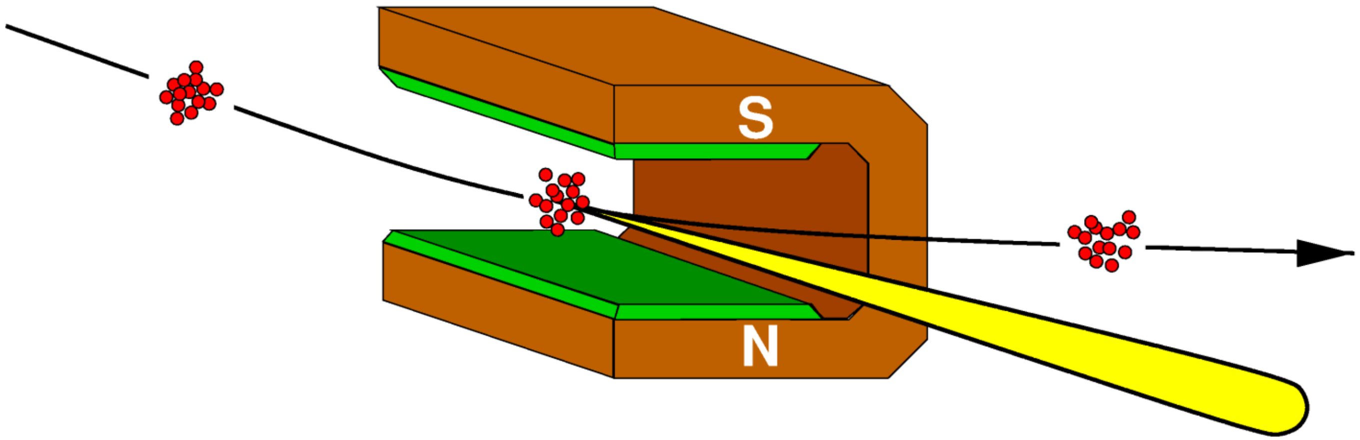


Electron-Ion Collider

Outline

- SR Simulation Framework
- Background Estimation in ePIC
- Miscellaneous Studies
  - SR Masking with Ante-Chambers
  - B2eR Relocation
  - Low-Q^2 Tagger Beam Pipe
- Summary



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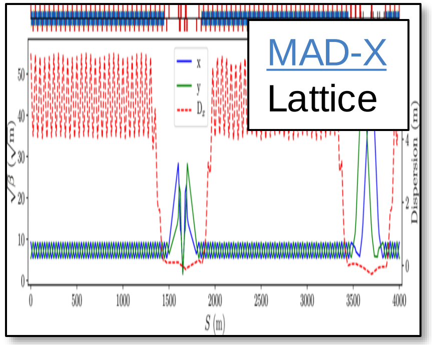
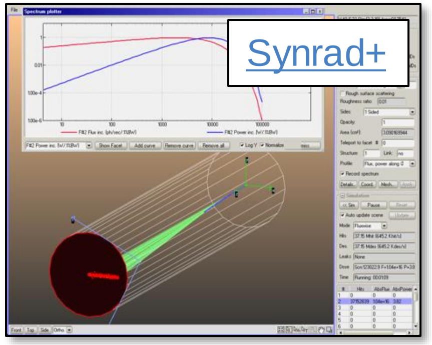
Typical SR Simulation Approach in ePIC

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

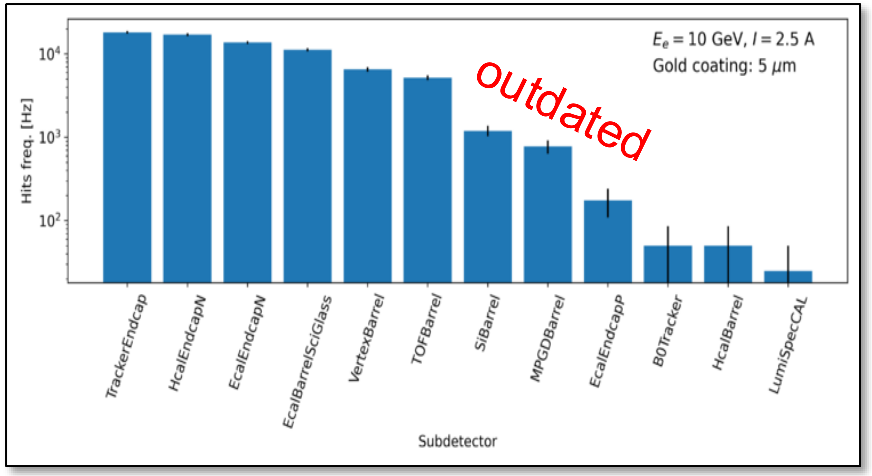




Event generator
CSV → HepMC

EIC-Shell:
DD4Hep

EIC-Shell:
EIC-Recon



SR background rates in ePIC sub-detectors

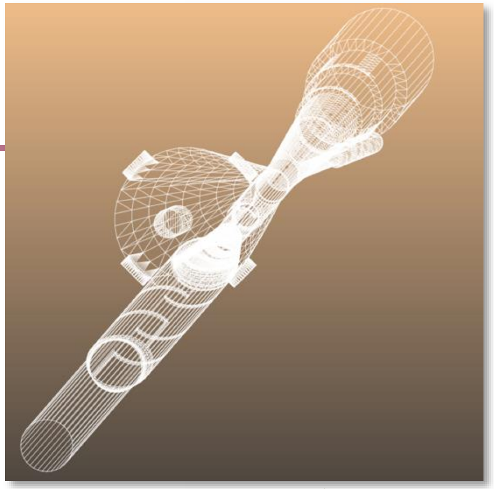
1. Time-consuming procedure:
   - Synrad+ stores photon coordinates on one facet at a time.
   - The IR beam pipe consists of ~30k facets.
2. Detailed SR masking design is limited:
   - Synrad+ describes SR photons as virtual photons with intrinsic weights, representing sampled flux and power generated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

Simulation Improvements

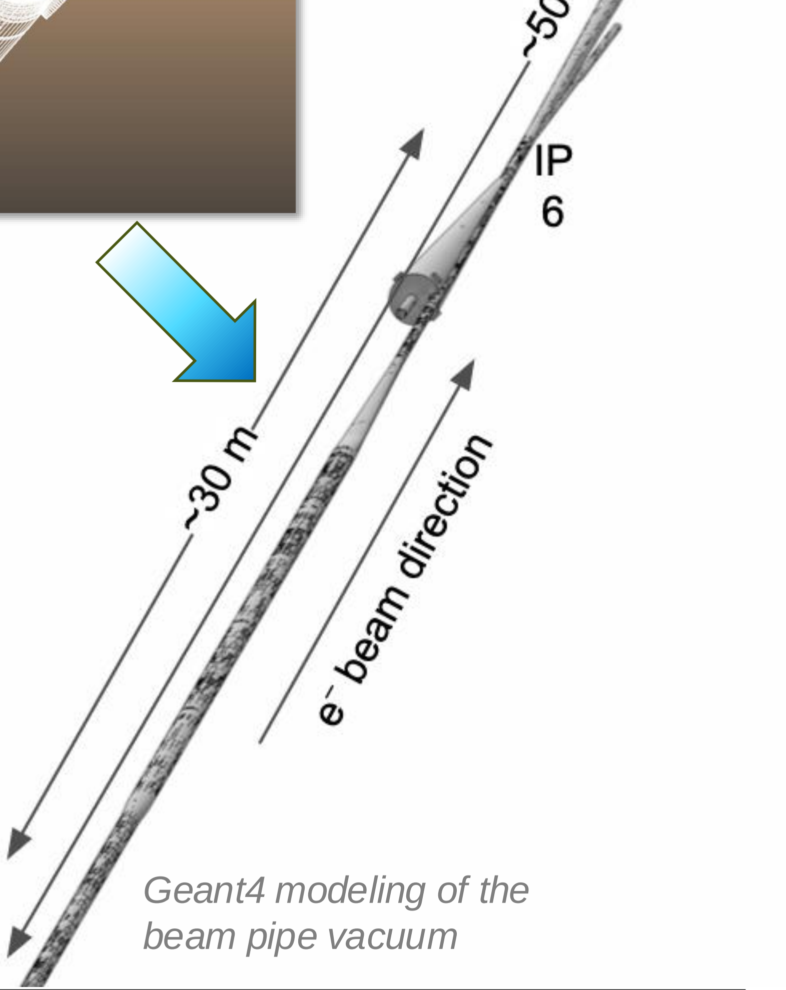
Synrad+ constrains/issues:
- Limited SR background studies
- Inadequate simulation results

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:

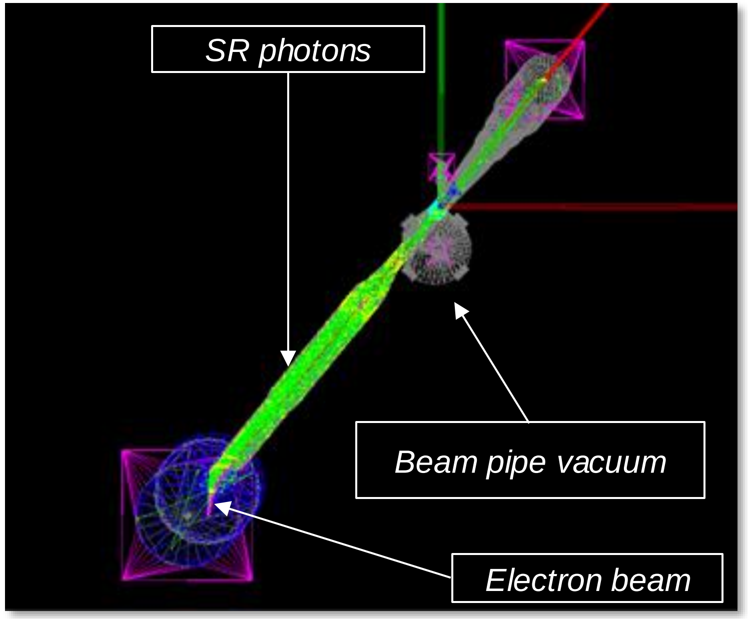
- X-ray reflection was missing in Geant4
  - Recent (Dec. 2023) implementation ← so-called *geant4-release*
    - Specular (mirror-like) reflection + attenuation factor for roughness

Solution:

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

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. **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

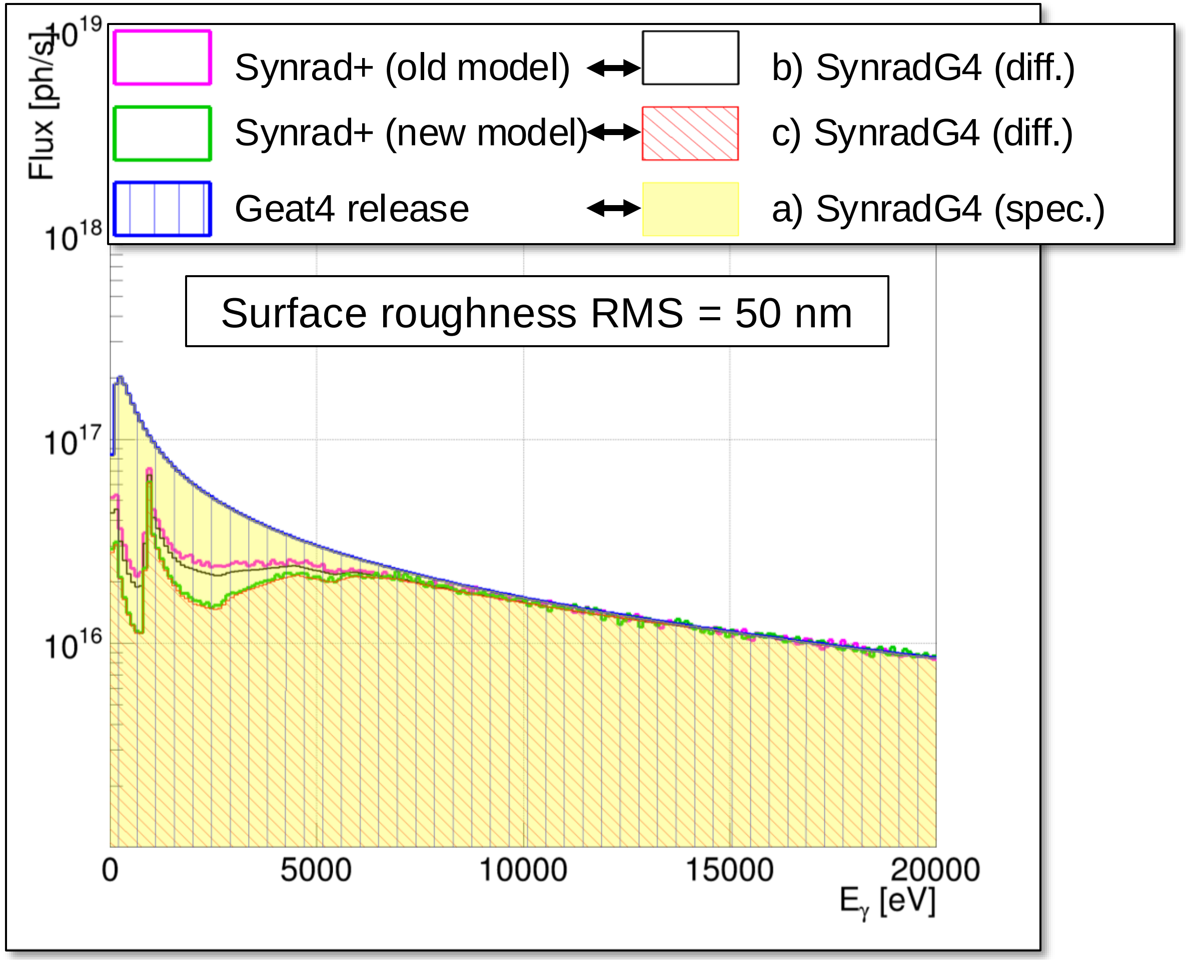


Geant4 geometry

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.
- After adding IR magnets (dipoles, quads, and solenoids), the absorbed **SR photons can be transferred to DD4Hep.**
- Recently **more benchmarks** (including the Synrad3D framework) were conducted and reported in Ref.[https://arxiv.org/abs/2408.11709].

The tool is ready for the SR background simulation !



Absorbed SR photon spectrum on the arbitrary beam pipe vacuum facet

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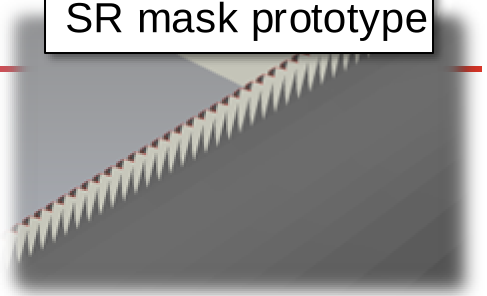
SR masking (0.227 A at 18 GeV)

SR mask prototype



- **Without SR masks:**
  - The estimated SR background rate in the innermost vertex detector is **~1 THz**.
- **With SR masks:**
  - The SR background rate dropped below **~1 GHz**.

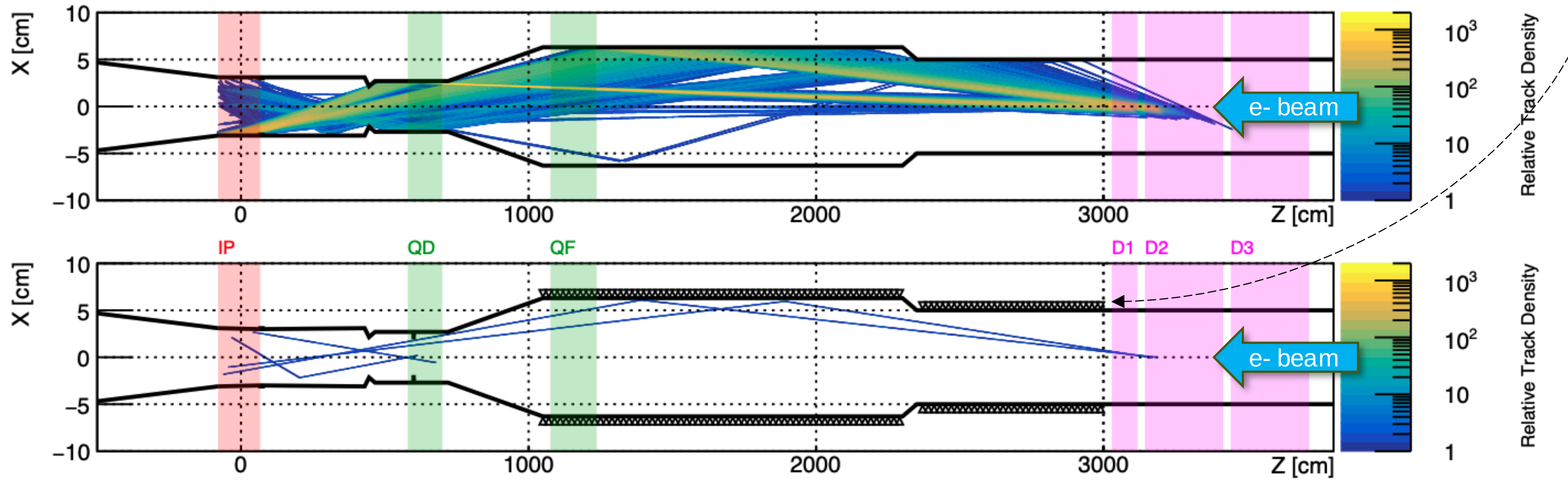


Figure 9: IP beam pipe absorbed SR tracks with $E_\gamma > 10\,\text{keV}$. Top: without SR masks. Bottom: with SR masks shown with black, open triangles. Red, green, and magenta vertical bends show the IP beam pipe, quadrupole magnet (QD – defocusing, QF – focusing in the horizontal plane), and dipole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

https://arxiv.org/pdf/2408.11709

Beam energy scan (Lattice v6.3.1)

SynradG4 simulation

The highest SR is expected for the 10 GeV electron beam at 2.5 A.

Critical photon energy:

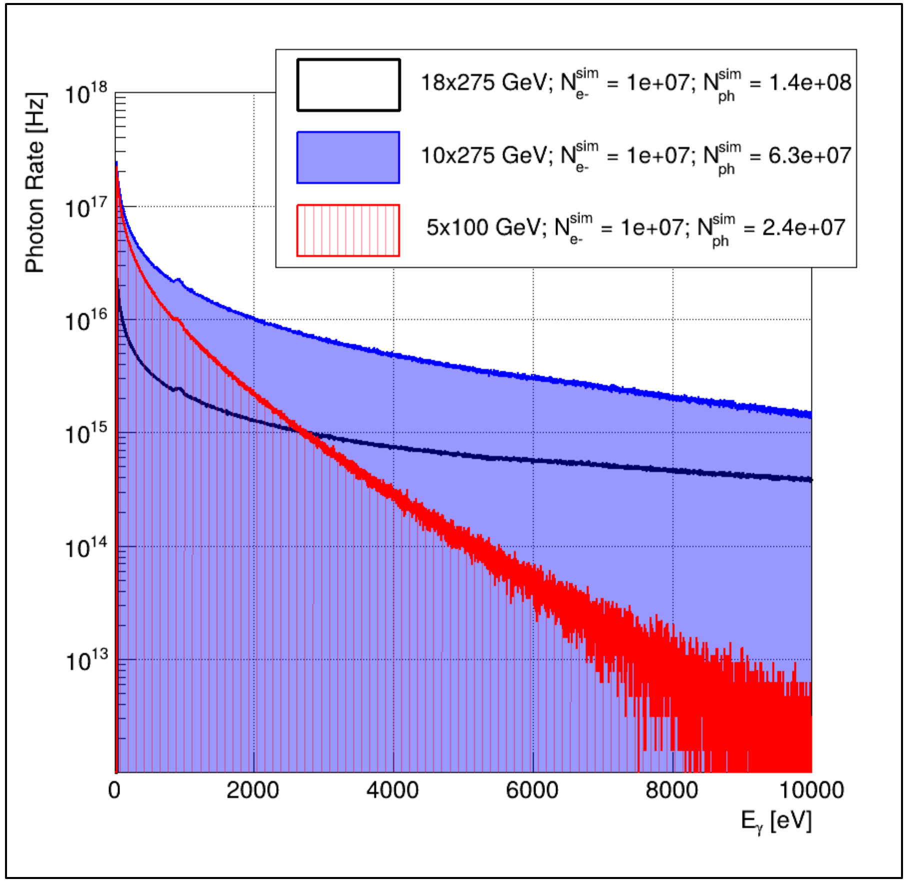
$$\varepsilon_c \sim \frac{\gamma^3}{\rho}$$

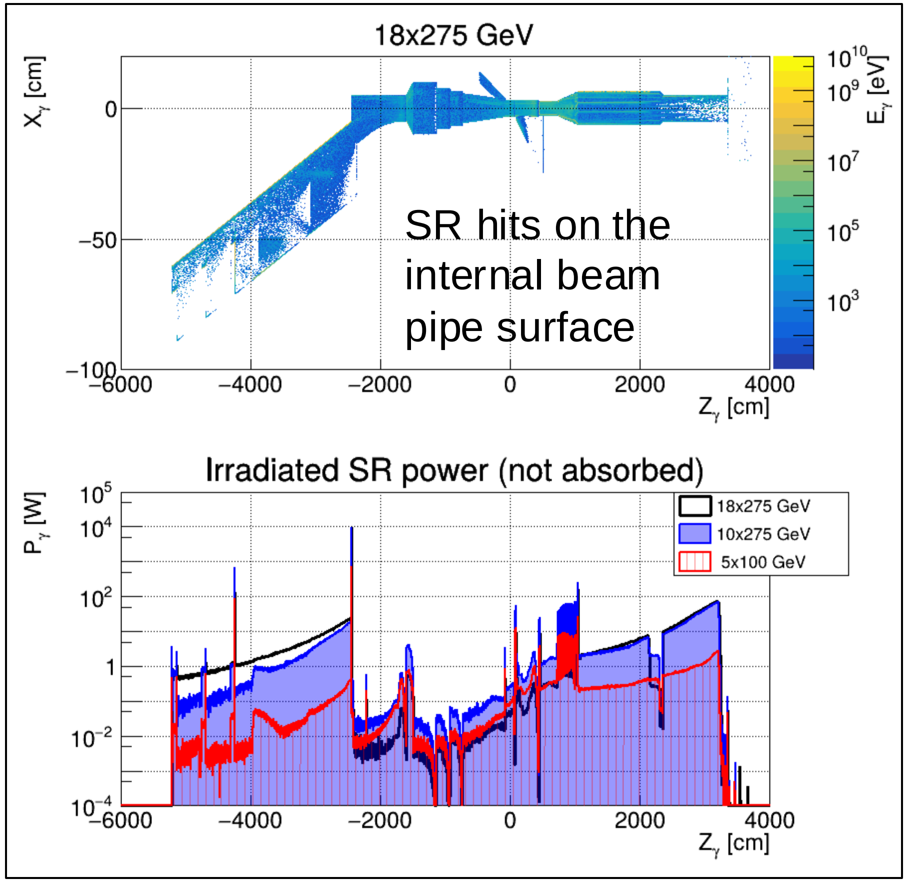
SR power:

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

SR photon rate:

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





SR around IP6

The highest SR is expected for the 10 GeV electron beam at 2.5 A.

- IP6 beam pipe: 1.47 m long and 0.76 mm thick Be + 5 µm Au coating
- Cryostat beam pipe: ~30 m long and 2 mm thick SS + 30 µm Cu coating
- Ring beam pipe: ~4 km long and 3 mm thick Cu

Critical photon energy:

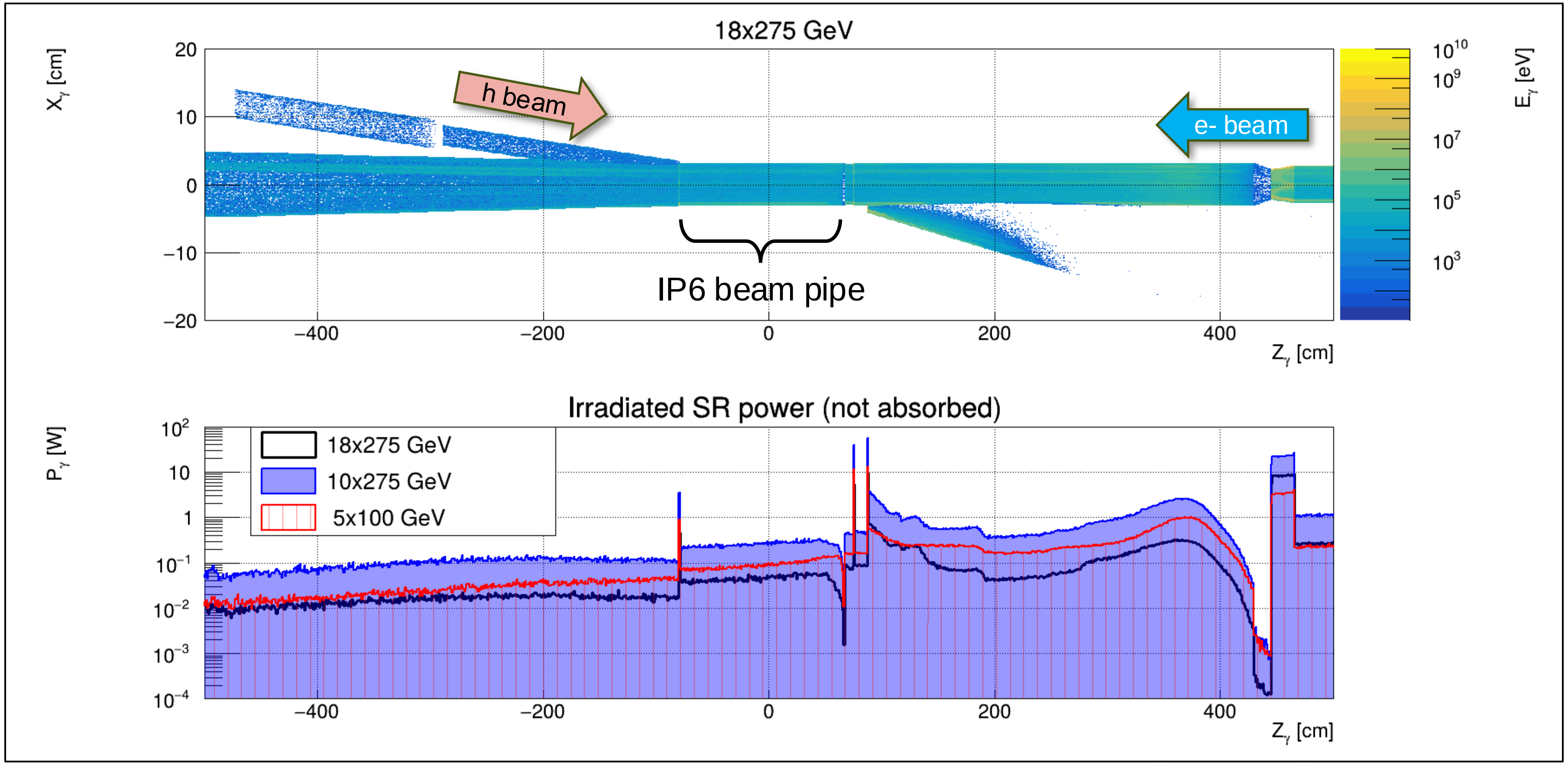
$$\varepsilon_c \sim \frac{\gamma^3}{\rho}$$

SR power:

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

SR photon rate:

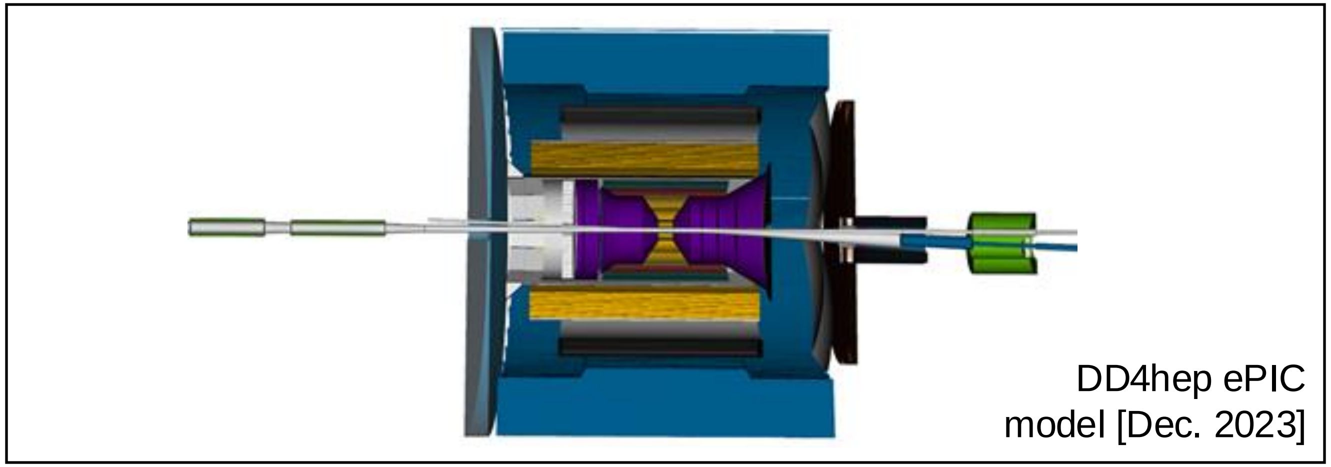
$$\dot{N}_{ph} \sim \frac{P_\gamma}{\varepsilon_c}$$



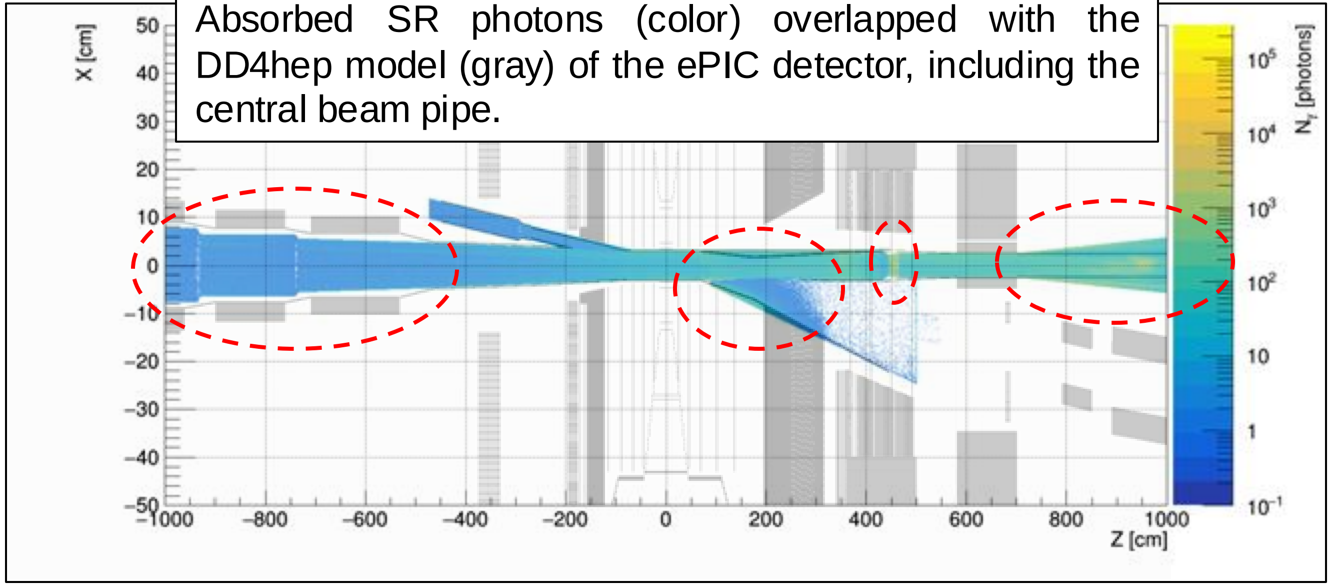
SynradG4 simulation

DD4hep simulation issue

- Significant **disagreement** exists **between beam pipe models** in the DD4hep and SR frameworks.
  - We have to check it after the latest DD4hep updates.
  - Then fix the remaining discrepancies using the latest beam pipe STEP files from the EIC vacuum group.



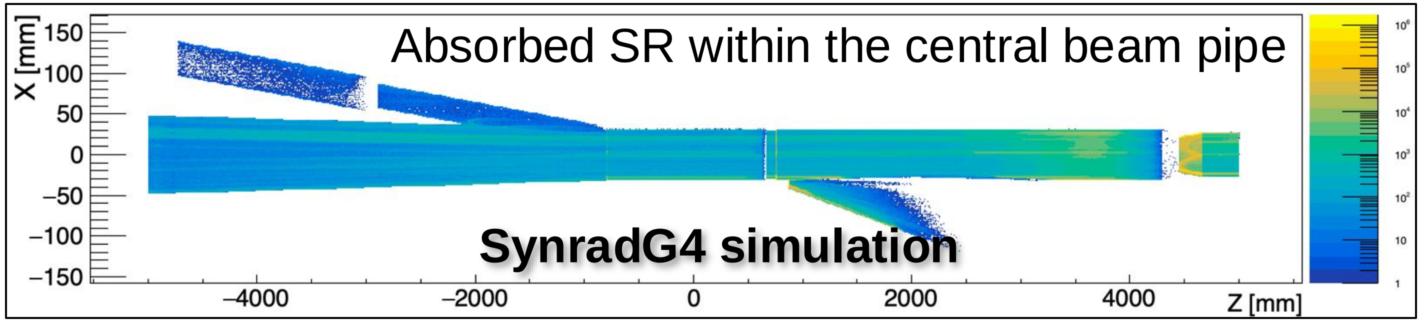
DD4hep ePIC model [Dec. 2023]



Absorbed SR photons (color) overlapped with the DD4hep model (gray) of the ePIC detector, including the central beam pipe.

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

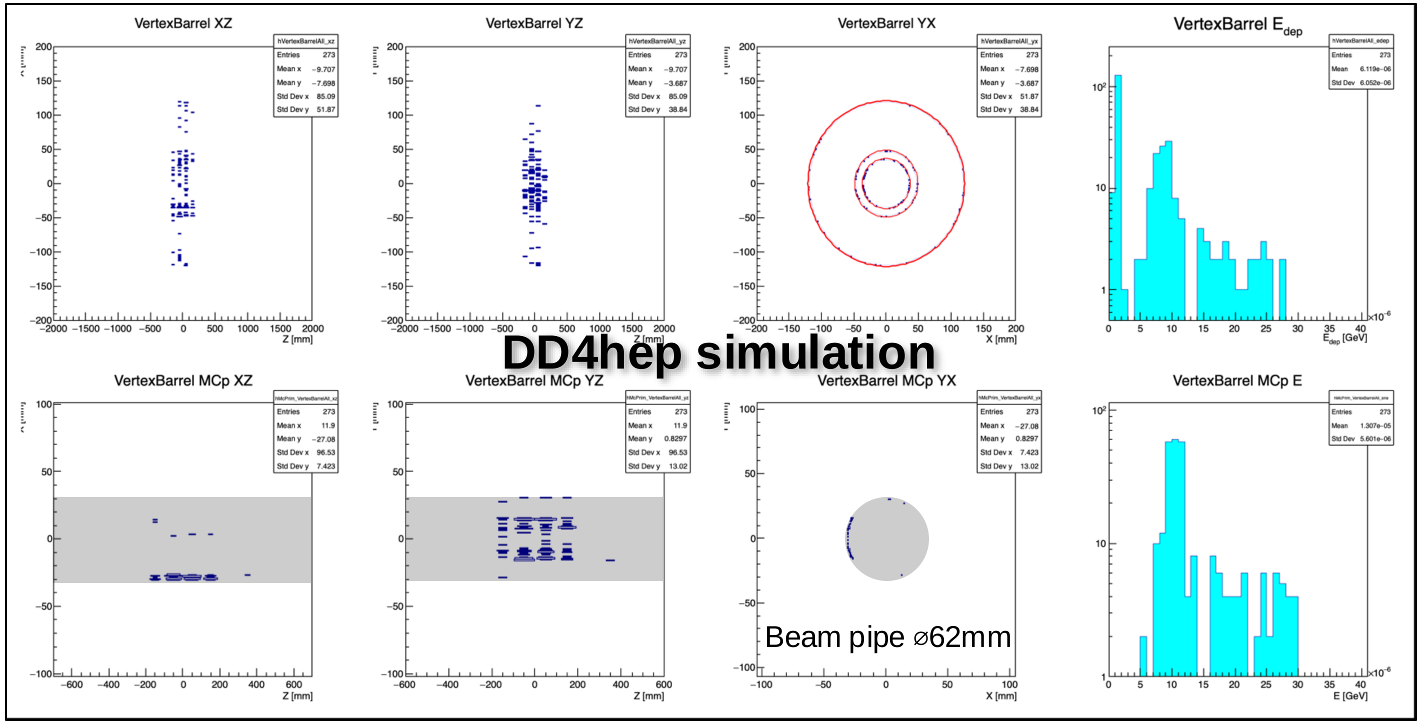
- Most of the SR will be absorbed by thick cryostat beam pipe walls.
- The tracking system sees SR photons primarily from the IP beam pipe.



- Only the SR photons with E_γ > 5 keV produce hits in the detector.
- Let's study background rates in ePIC using the SR from the IP beam pipe region only.

Vertex SimHits

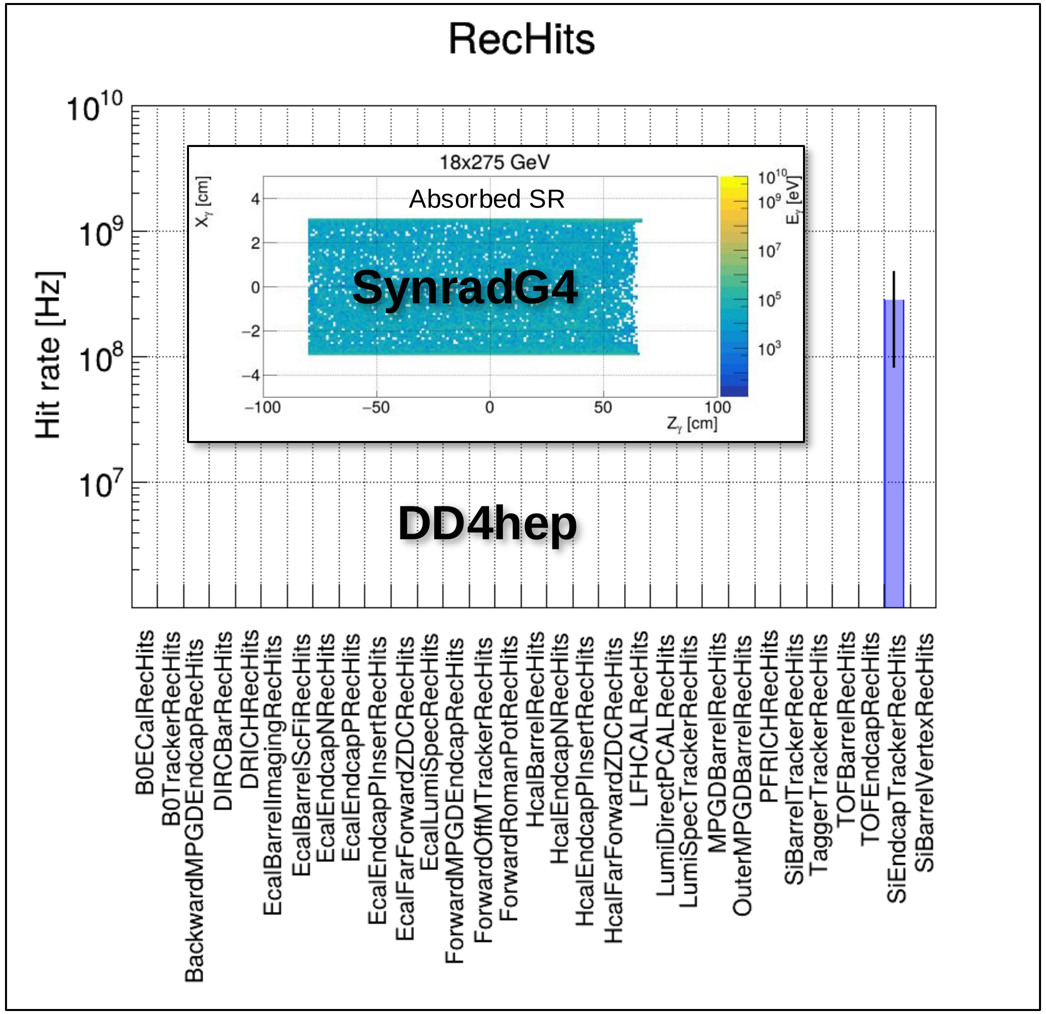
Production Vertices



Detector Hits (18 GeV, w/ SR masks)

- For **simulated 10^9 electrons** at 18 GeV with the SR cross-section scaled by a factor of 10, only **2 hits are detected** in the tracker, induced by 2 photons with energies between 8 and 10 keV.
- Simulation time:
  - Jlab iFARM: **156 ms/event** → used 43k CPU·hours
  - BNL SDCC: **285 ms/event** → used 79k CPU·hours

  1 event = 1 electron with the SR cross-section scaled (dialed up) by 10
- To study the SR impact on the ePIC tracking performance, we **have to increase the statistics** by a few orders of magnitude (1-10M CPU·hours) with further SR masking improvements.



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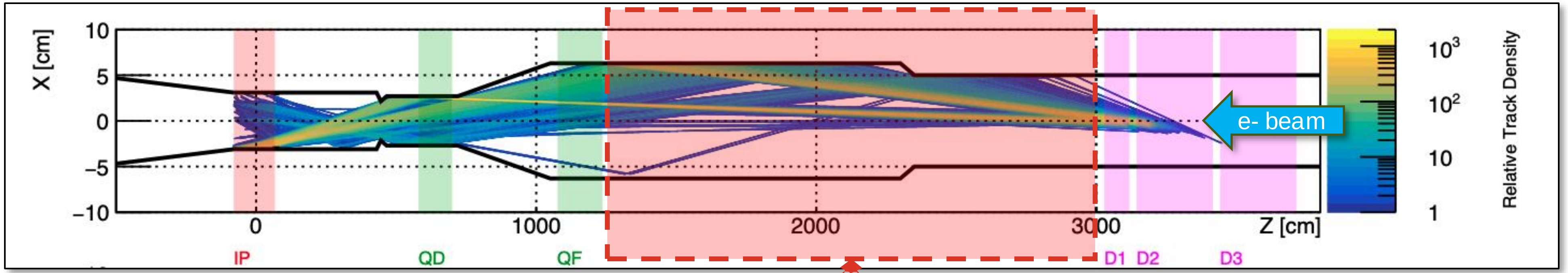
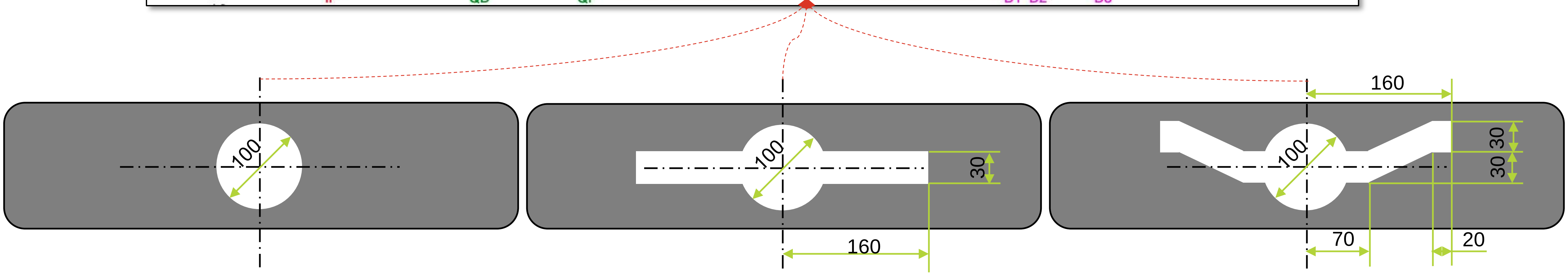
FWD Ante-Chamber

- Study the impact of a beam pipe with an ante-chamber in the FWD region.
- Can the ante-chamber replace SR masks?





W/o ante-chamber *W/ SKB-like ante-chamber* *W/ PEP2-like ante-chamber*

Ante-Chamber Performance

SynradG4 simulation

W/o ante-chamber

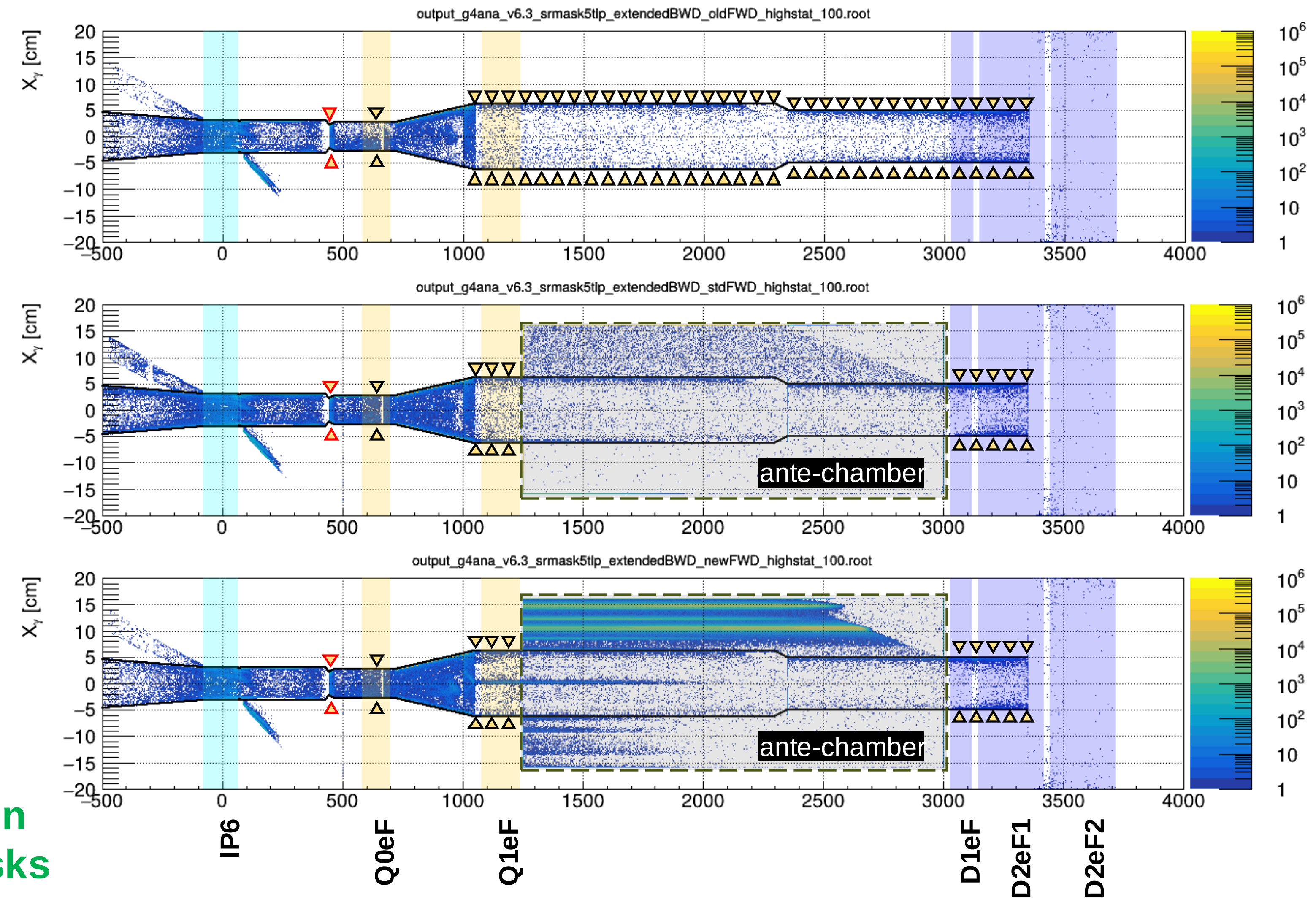
$N_\gamma(IP)$ = 1.4e15 [ph]
$P_\gamma(IP)$ = 0.07 [W]

W/ SKB-like ante-chamber

$N_\gamma(IP)$ = 2.9e15 [ph]
$P_\gamma(IP)$ = 0.27 [W]

W/ PEP2-like ante-chamber

$N_\gamma(IP)$ = 1.5e15 [ph]
$P_\gamma(IP)$ = 0.07 [W]



The ante-chamber can reduce SR on the IP beam pipe similarly to SR masks

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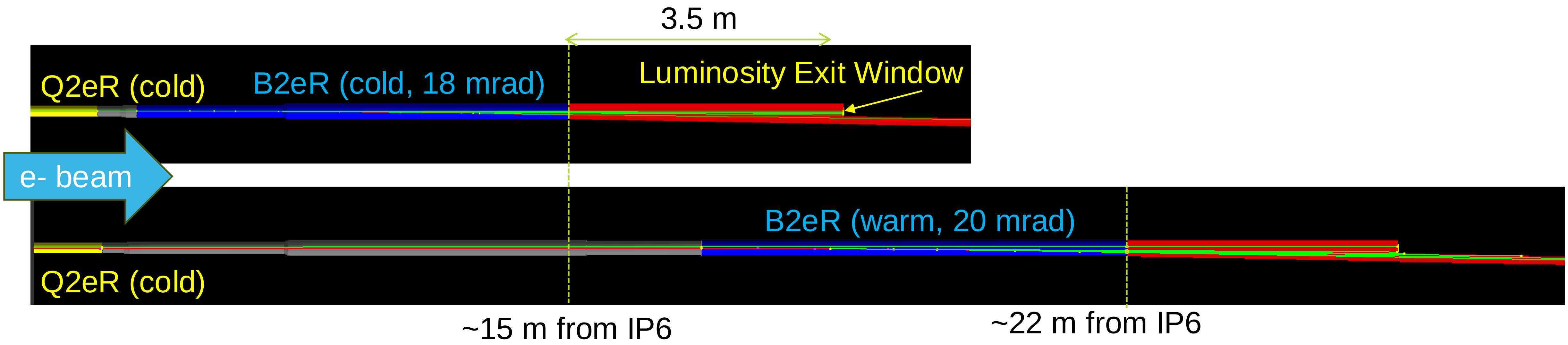
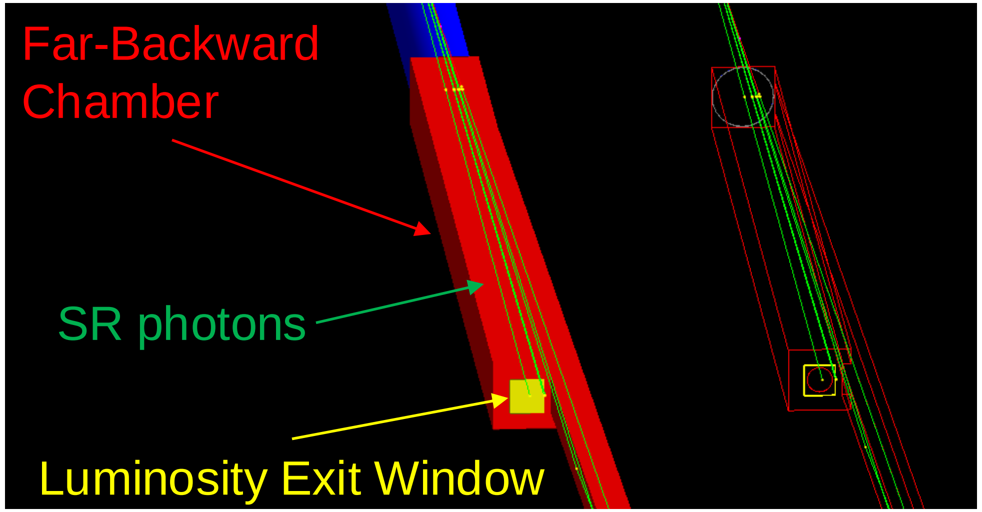
B2eR relocation: Cold → Warm

SynradG4 model



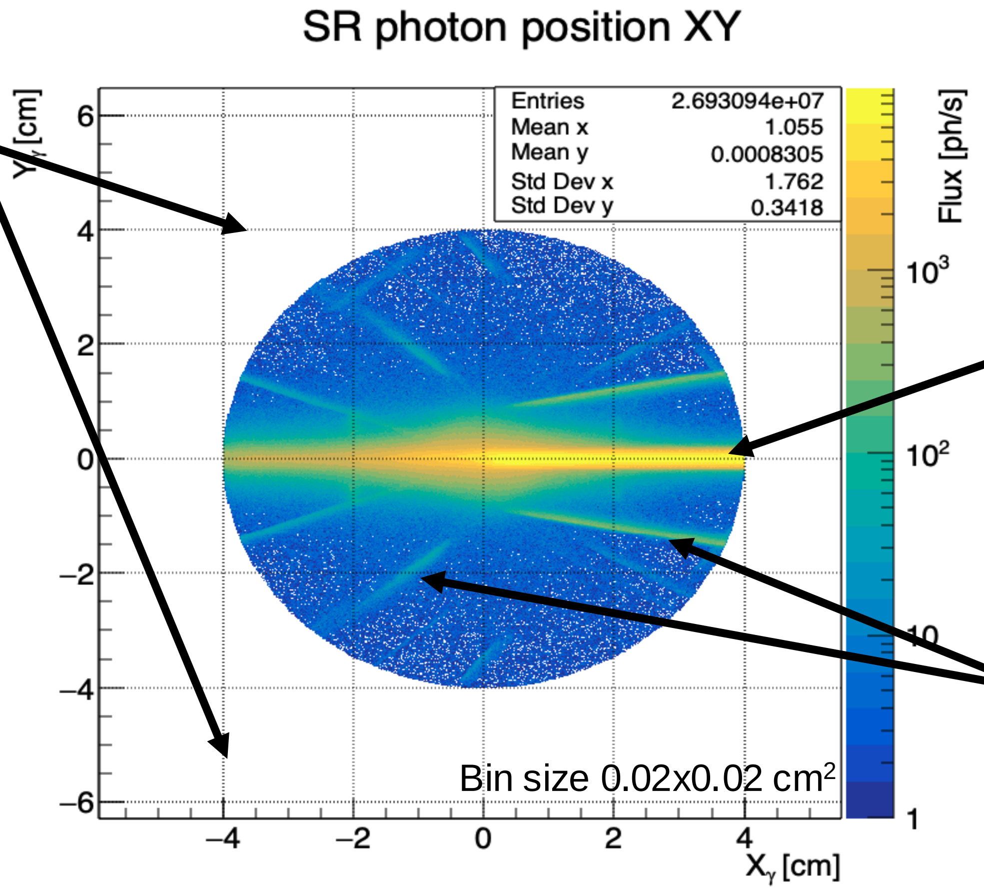
- Starting from the ESR lattice v6.3, the B2eR dipole magnet is moved outside the BWD cryostat.
  - What is the change in SR on the Luminosity Window?
  - What are the benefits of this modification?



SR on the Lumi Window

SynradG4 simulation

- This (white) area is shadowed by the beam pipe in front of the window.
- The beam pipe hole is round.



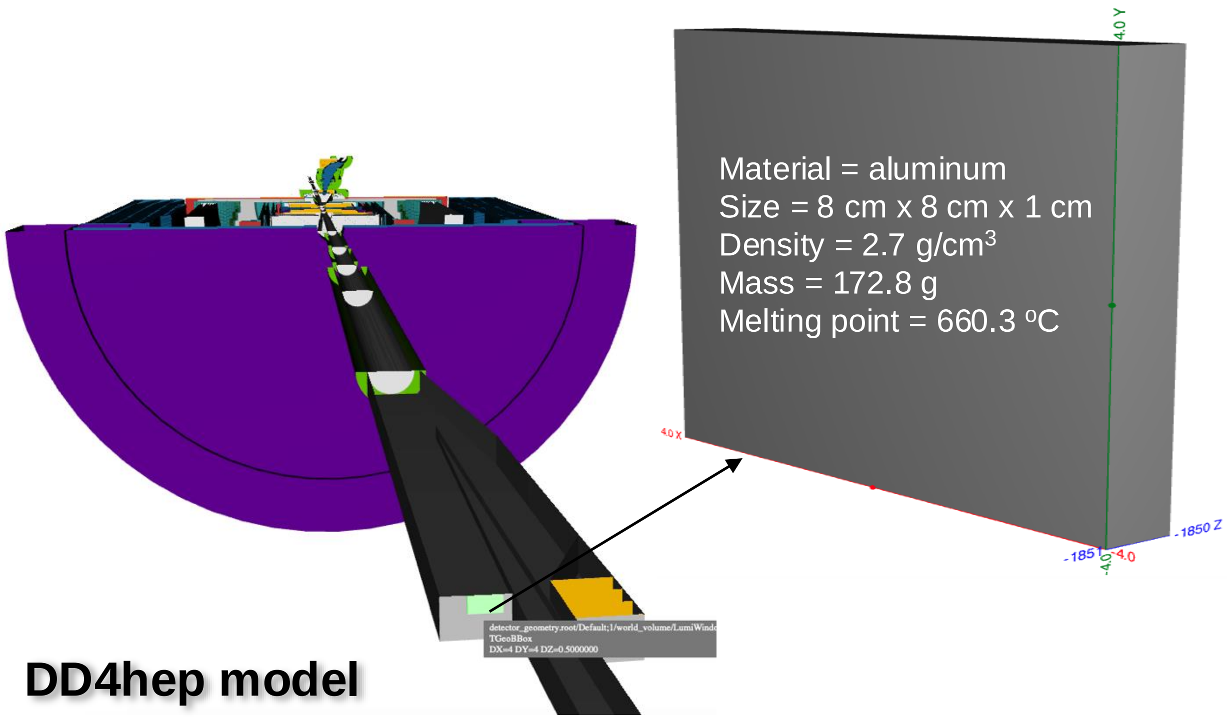
0.227 A, 18 GeV, v6.2 (cold B2eR)

This distribution hits the aluminum Lumi Window.

These "islands" are artifacts due to the reflection of SR photons from beam pipe faces.

Relocation Impact and Benefits

- A 10% increase in the bending angle leads to about **20% increase** in the radiated SR energy.
- The absorbed SR power in the aluminum window is about **4 kW** with a temperature rise of **~1500 ºC/min**.
  - Without proper cooling, the **window will melt** in less than a minute!



DD4hep model

1. A warm B2ER may **permit a reduction in the beam pipe aperture**, depending on requirements arising from beam size and Lumi photon fan size.
   a) The cold B2eR beam pipe diameter is 196 mm → To reduce SR load in the BWD cryostat.
   b) The warm B2eR beam pipe can absorb a higher SR power and extract it via water cooling.
2. A narrower (100 mm) beampipe has obvious **advantages for the magnet design**, as well as e.g. beamline isolation, and shielded gate valves.
3. A narrower beampipe makes it possible to **place low-Q^2 taggers closer to the beam core**.

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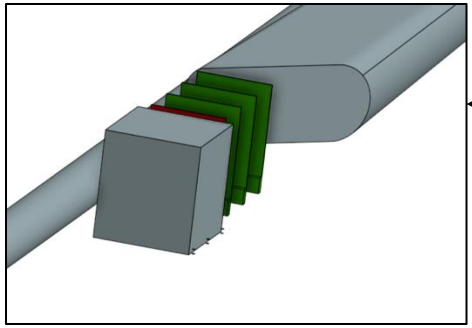
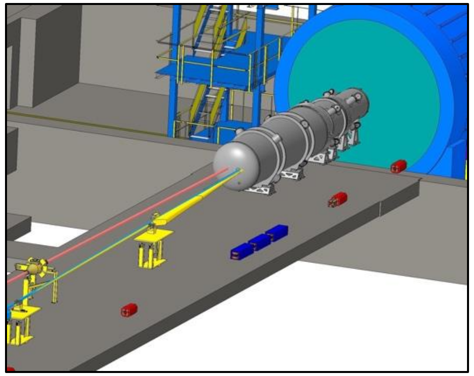
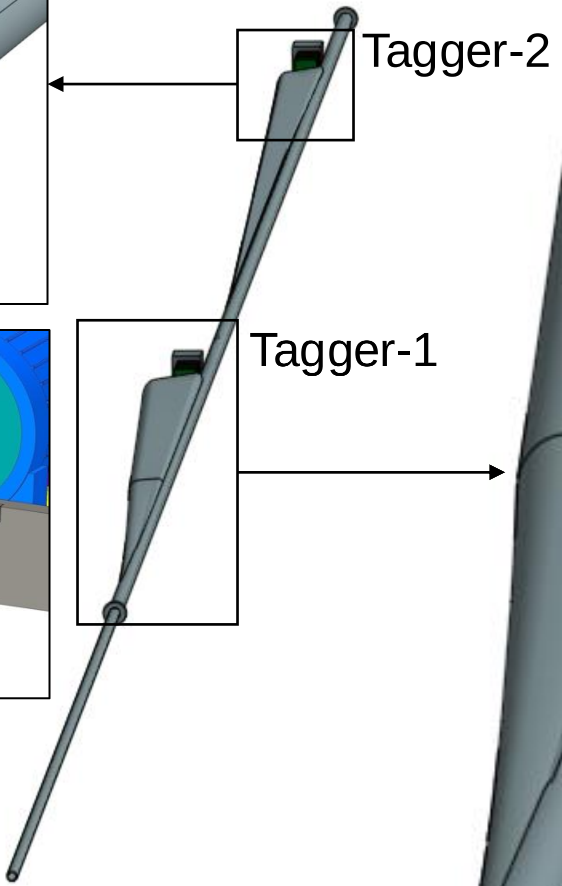
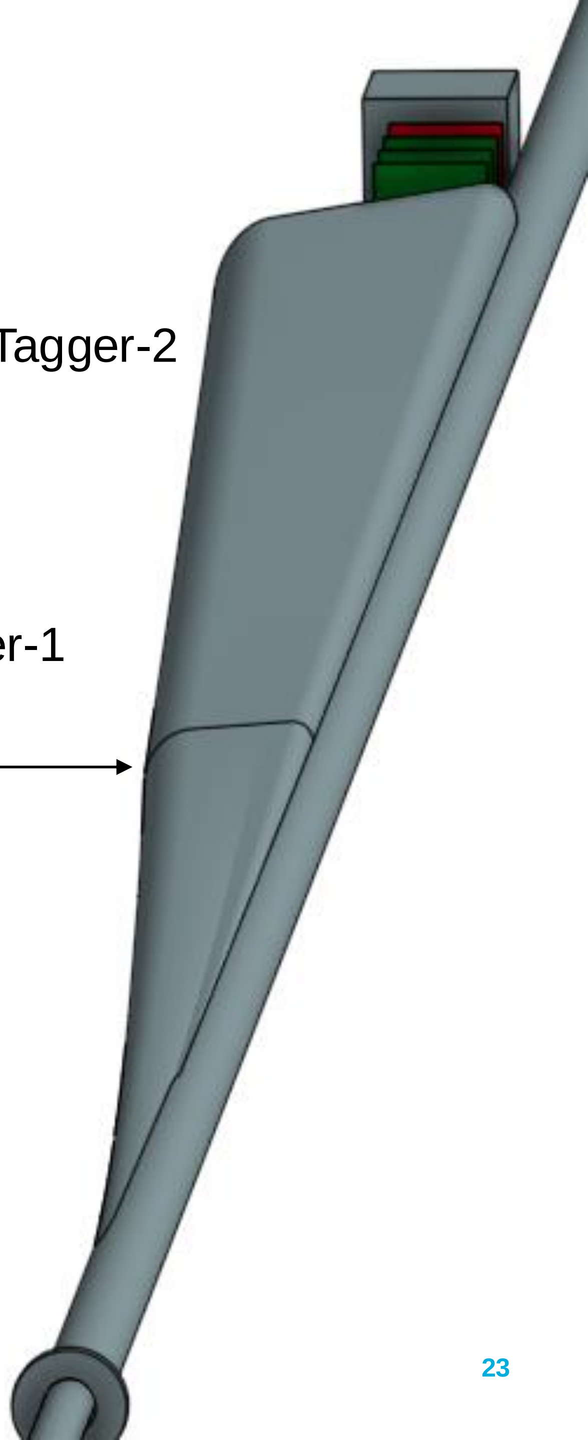
Baseline Design

- Current baseline setup:
    - Tagger sensor planes are placed in the secondary vacuum
    - Tagger wings and the main beam pipe – primary vacuum
- It may strongly affect machine impedance.
- Is there any option to improve the tagger chamber?



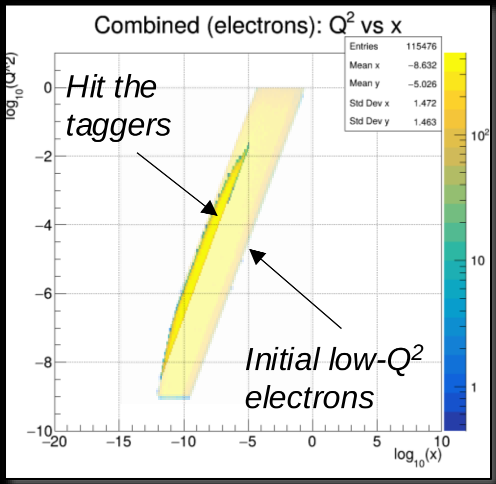




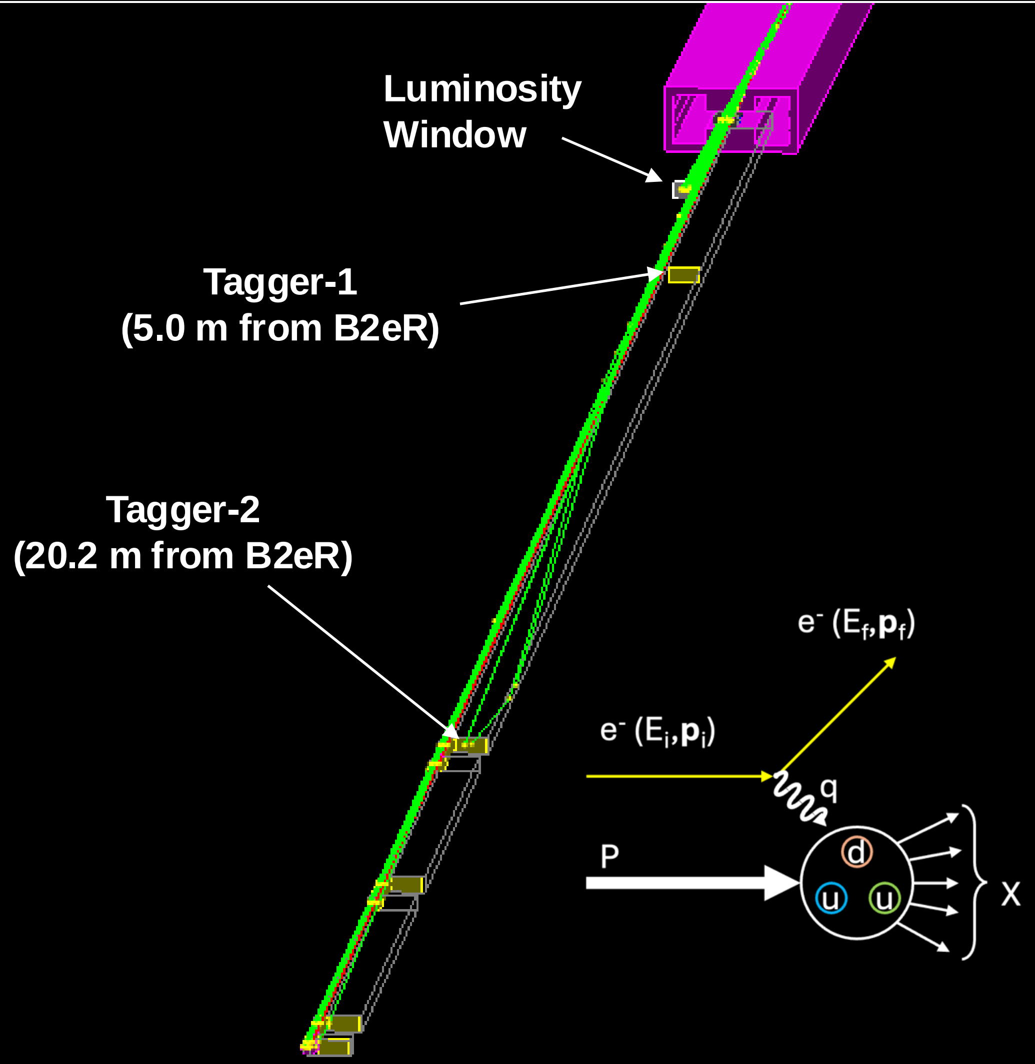


Alternative Configuration – Ante-Chamber

- With a warm B2eR, we can potentially make the BWD beam pipe narrower (from ⌀20 cm to ⌀10 cm) and place taggers closer to the beam core.
- We can place the taggers in the ante-chamber without losing much in the acceptance.



- By placing the taggers upstream of the horizontal focusing Q3eR quad, we **detect about 12%** of the initially scattered electrons (low-Q^2).
  - A big part of the electrons (~65%) goes through the quad.
- Further tunings of BWD optics and tagger's configuration are ongoing.



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Summary

- The high-energy and high-current electron beam SR is an important background for ePIC.
  - It will have a detrimental effect on detector longevity and physics analysis performance.
- A new Geant4-based Monte-Carlo simulation code, **SynradG4** [https://arxiv.org/abs/2408.11709], is developed to study SR in the EIC.
  - It includes precise X-ray photons' specular and diffuse reflection models.
  - Moreover, it avoids some critical functionality limits of well-known SR simulation codes (e.g., Synrad+, Synrad3D).
- At the current stage of the simulation with implemented masks, the SR background rates in the ePIC tracking system are of the order of 100 MHz at 18 GeV and 0.227 A.
- Further SR countermeasure development and simulation statistics increase are foreseen.
  - However, this requires many computation resources.
  - Currently available clusters should be enough for the study: **- SDCC @BNL** **- iFARM @JLab** **- NERSC @LBNL**
- The framework is intensively used to design the new IR beam pipe for the EIC/ePIC project and study the impact of various machine configuration changes.

Acknowledgements

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

Thanks for your attention!

Backup

Electron-Proton/Ion Collider (ePIC) detector

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

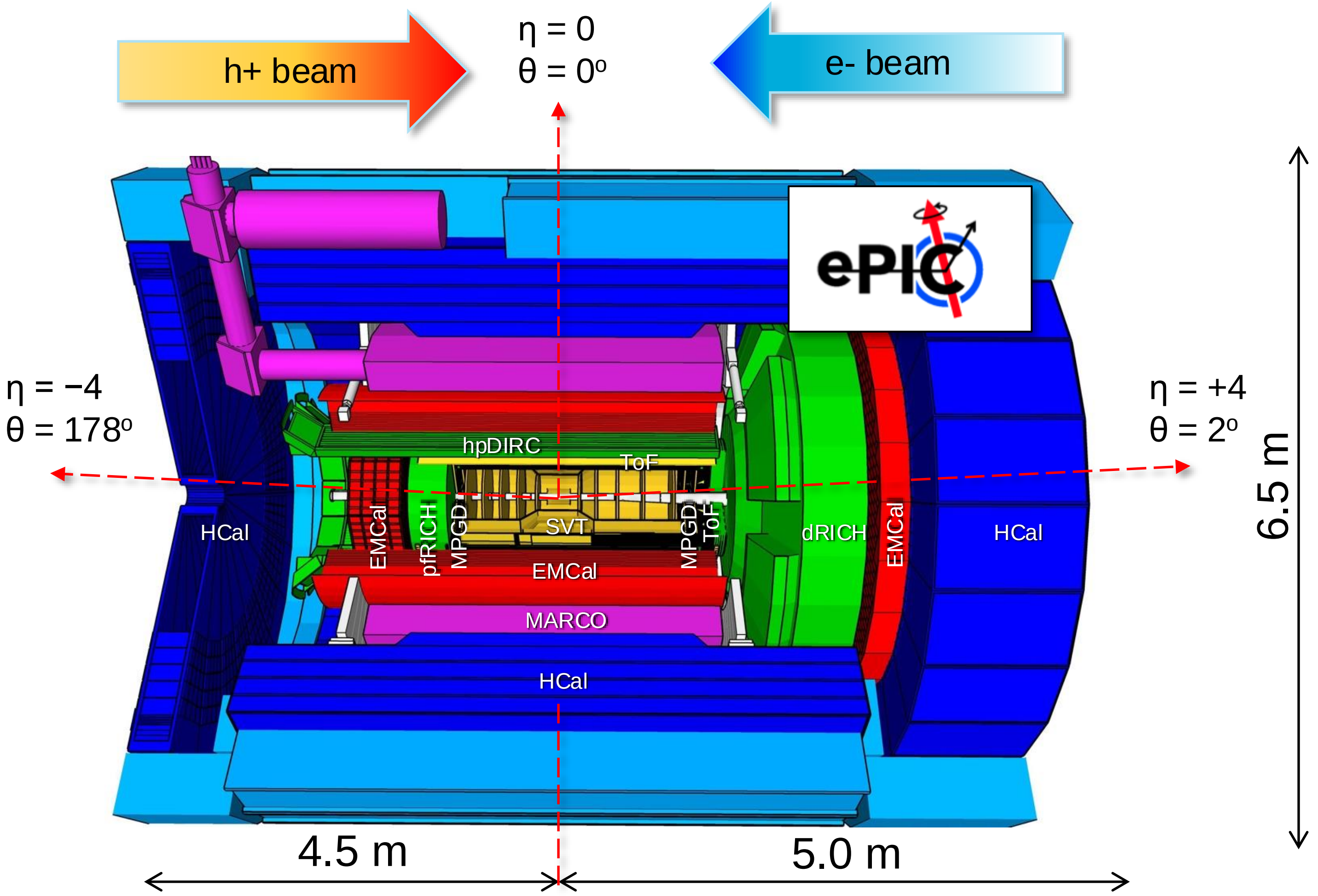
Tracking:
- *Primary and secondary vertexing*
- *High-precision low mass tracking*
  - 1.7 T Solenoid (MARCO)
  - Silicon Monolithic Active Pixel Sensors (MAPS) Tracker (SVT)
    - Vertex Barrels + Endcap Disks
  - Micro Pattern Gas Detectors (MPGDs)

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

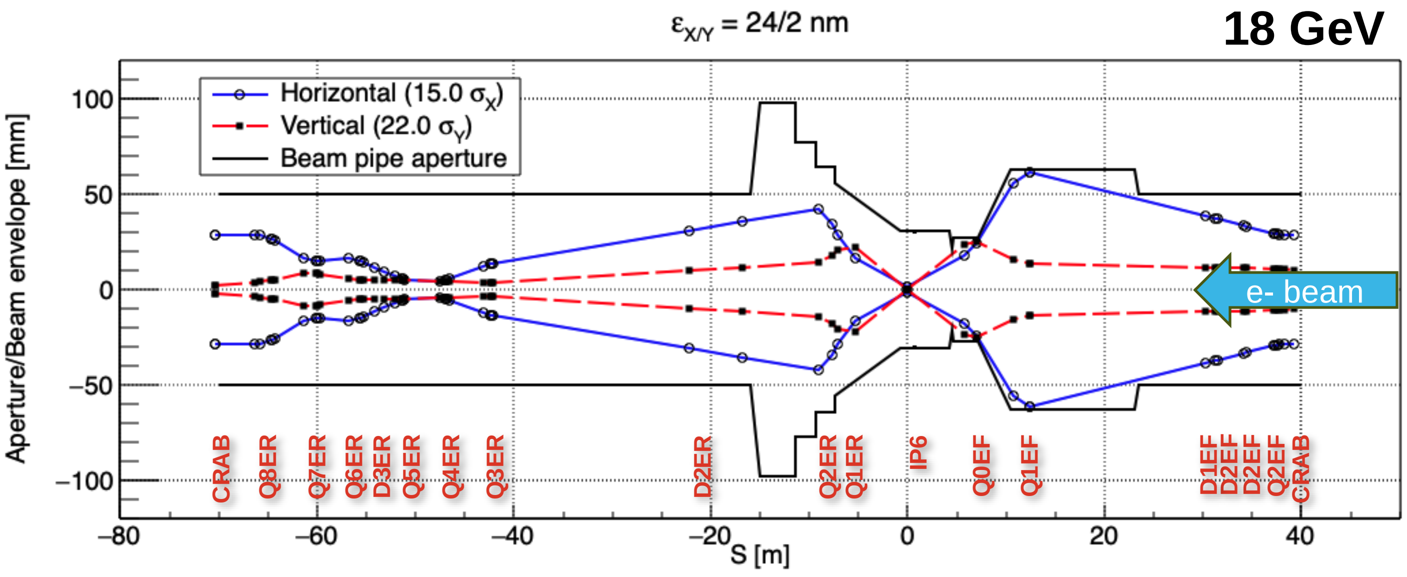
Hadron calorimetry (HCal):
- *Charged hadron, neutron, and K_L measurements*
  - Backward e-endcap, forward h-endcap, barrel

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.

Beam Parameters



3 COLLIDING BEAM PARAMETERS FOR THE HSR AND ESR

Table 1 Main parameters for the electron-proton operation in high divergence 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}	19.1	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		0.47	71	0.3	26	0.29	26	0.25	18	0.45	34
RMS emittance	H	nm	18	24.0	11.3	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	80	59	80	45	63	96	61	78	90	196
	V		7.1	5.7	7.2	5.6	5.7	12	5.5	7.1	7.1	21
IP RMS beam size	H	µm	119		9.5		138		125		198	
	V		11		8.5		12		11		27	
Kx		-	11		11		11		11		7.3	
RMS divergence	H	µrad	150	202	119	211	220	145	206	160	220	101
	V		150	187	119	252	220	105	206	160	380	129
BB parameter	H	10^{-3}	3	93	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	53/42
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	6.3	2.1	7.9	2.4	6.3	1.8	7	2	4.2	1.1
Longitudinal IBS time		hrs	2		2.9		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		-	0.9		0.9		0.9		0.9		0.9	
Luminosity		$10^{33} cm^{-2} s^{-1}$	1.5		10		4.5		3.7		0.4	

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

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