Synchrotron Radiation (SR) background in ePIC at the EIC

Andrii Natochii

natochii@hawaii.edu

Recap

From Dec. 2023 meeting

Next steps and missing ingredients

Simulation improvements

- ❑ The IR beam pipe modeling in eic-shell must be improved to fit the SR hits distribution that follows the actual vacuum beam pipe structure. [Who can be contacted for details?]
- ❑ Beam tails should be clarified. [Who can be contacted for details?]
- ❑ Implement the detector solenoid magnetic field. [Who can be contacted for details?]

SR background mitigation

- Study a possible BG mitigation through the SR masking inside the vacuum.
- Find the optimal energy cut for SR photon tracking to accurately study SR hit rates in ePIC and speed up the simulation for higher statistics.

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- Received IR beam pipe drawings from Charlie Hetzel
- Adjusted the eic-shell modeling

- Charlie plans to update the Synrad+ model in 2024

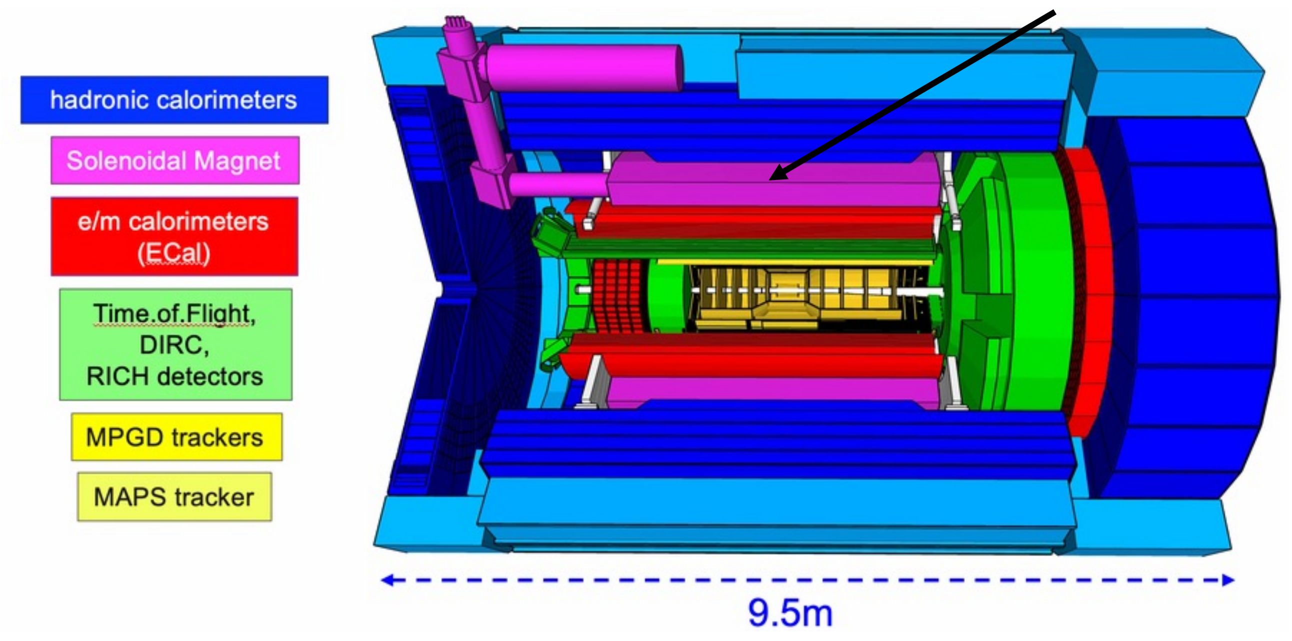
- Mike Sullivan shared his calculation of EIC beam tails based on Gaussian approximation ← more conservative model
- Plan to study the new model's impact on the EIC SR background

- Implemented the detector solenoid field. Thanks Elke Aschenauer for providing the details

Solenoid field

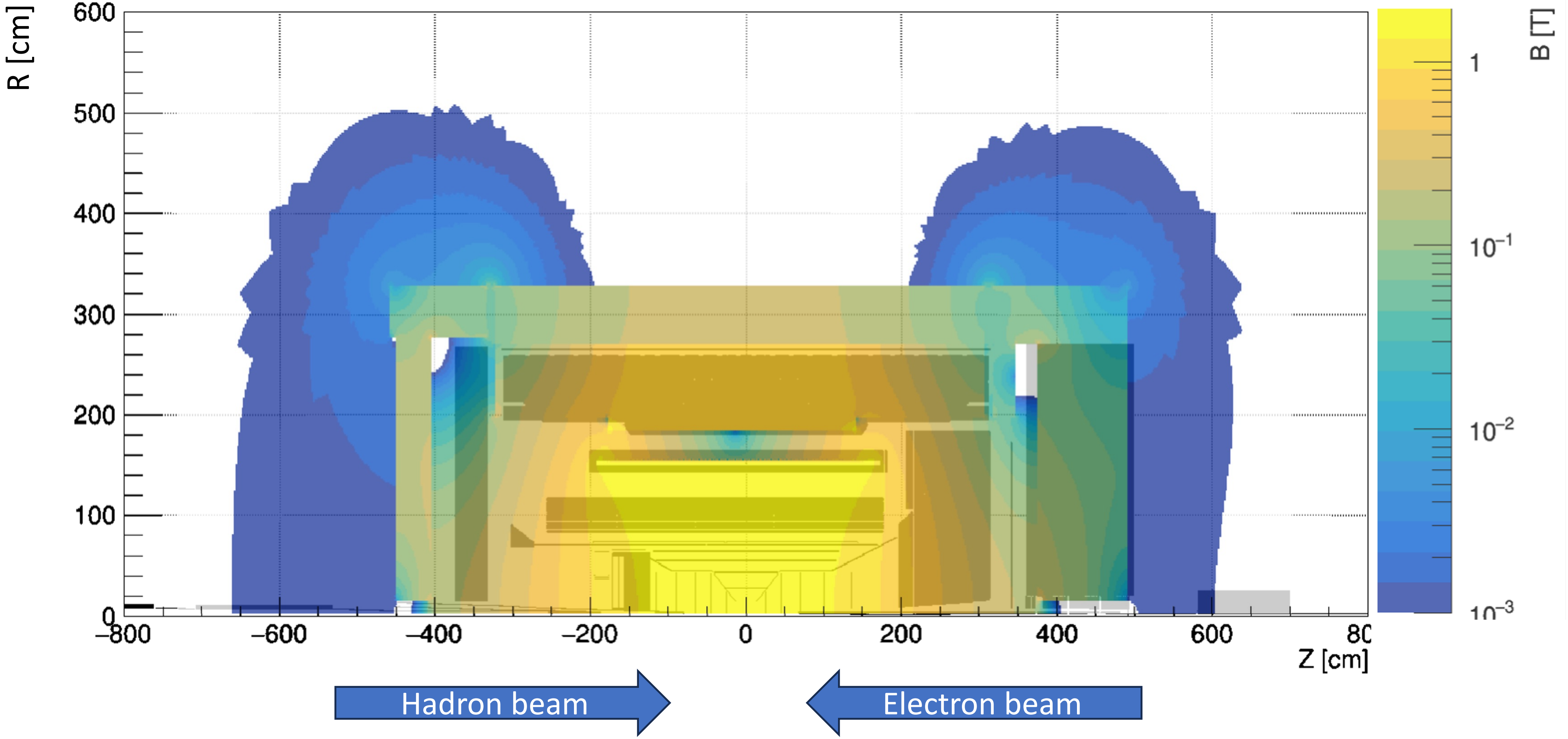
Solenoid magnet

- For ePIC, a new solenoid is developed as the experimental magnet with a central field of 1.7 T with an operational range of up to 2 T. The Magnet has been named **MARCO**. From Ref. [link].
  - Available field maps in a CSV format (as of Dec 2023): 1.7 T and 2.0 T (points are calculated every 2 cm)
  - The solenoid field is **off-centered by 8 cm** towards the electron beam direction, i.e., its center is at (0;0;-8) cm



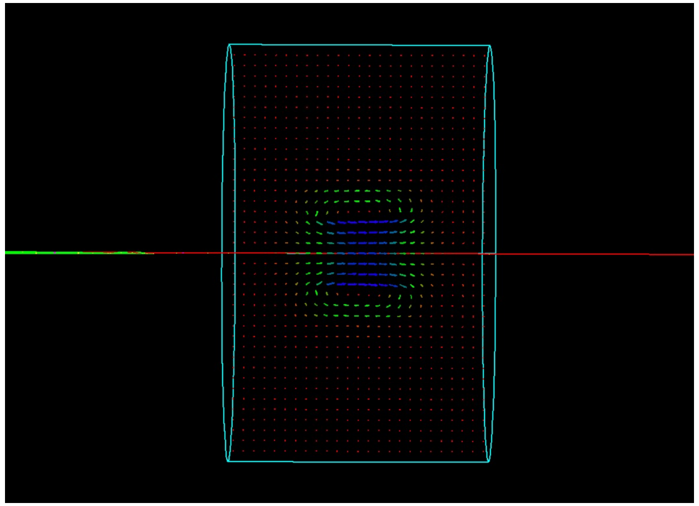
R(cm)	Z(cm)	Br(T)	Bz(T)
0.0	-800.0	0.0000	-0.0006
0.0	-798.0	0.0000	-0.0006
0.0	-796.0	0.0000	-0.0006
0.0	-794.0	0.0000	-0.0006
0.0	-792.0	0.0000	-0.0006
0.0	-790.0	0.0000	-0.0006
0.0	-788.0	0.0000	-0.0006
0.0	-786.0	0.0000	-0.0006
0.0	-784.0	0.0000	-0.0006
0.0	-782.0	0.0000	-0.0006
0.0	-780.0	0.0000	-0.0006
0.0	-778.0	0.0000	-0.0006
0.0	-776.0	0.0000	-0.0007
...			

Material scan (black) vs solenoid field (color)

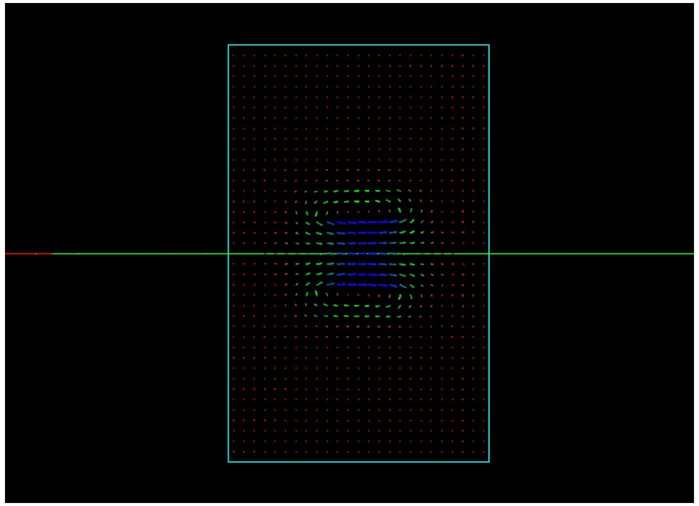


Detector solenoid field in the custom-built Geant4

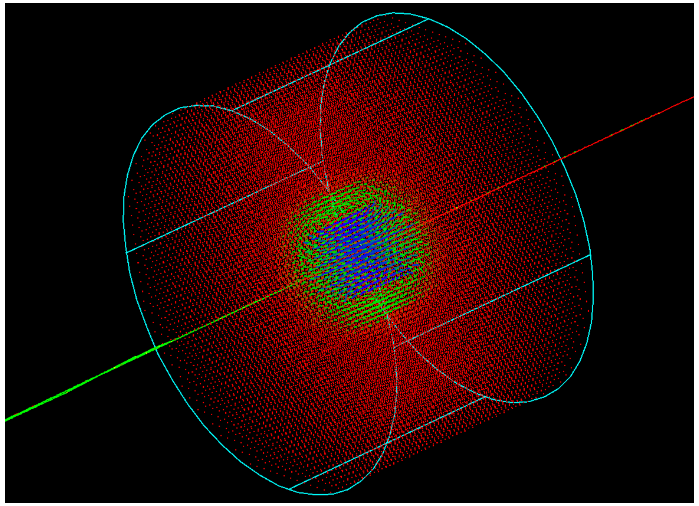
X-Z (|Y| <= 2cm)



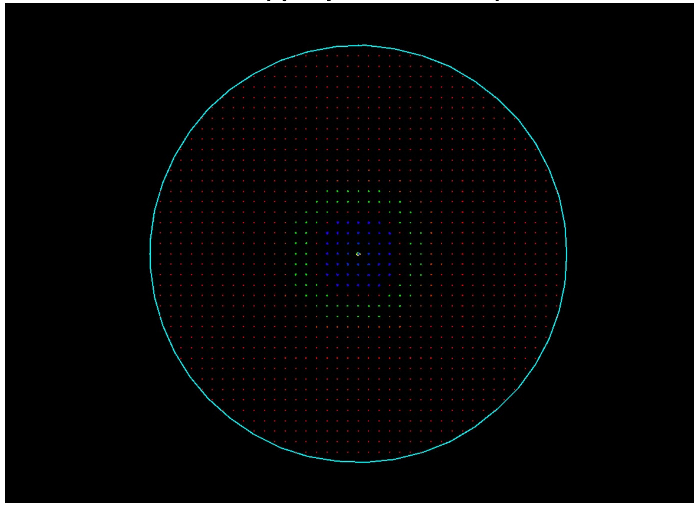
Y-Z (|X| <= 2cm)



X-Y-Z



Y-X (|Z| <= 2cm)



X-ray reflection process

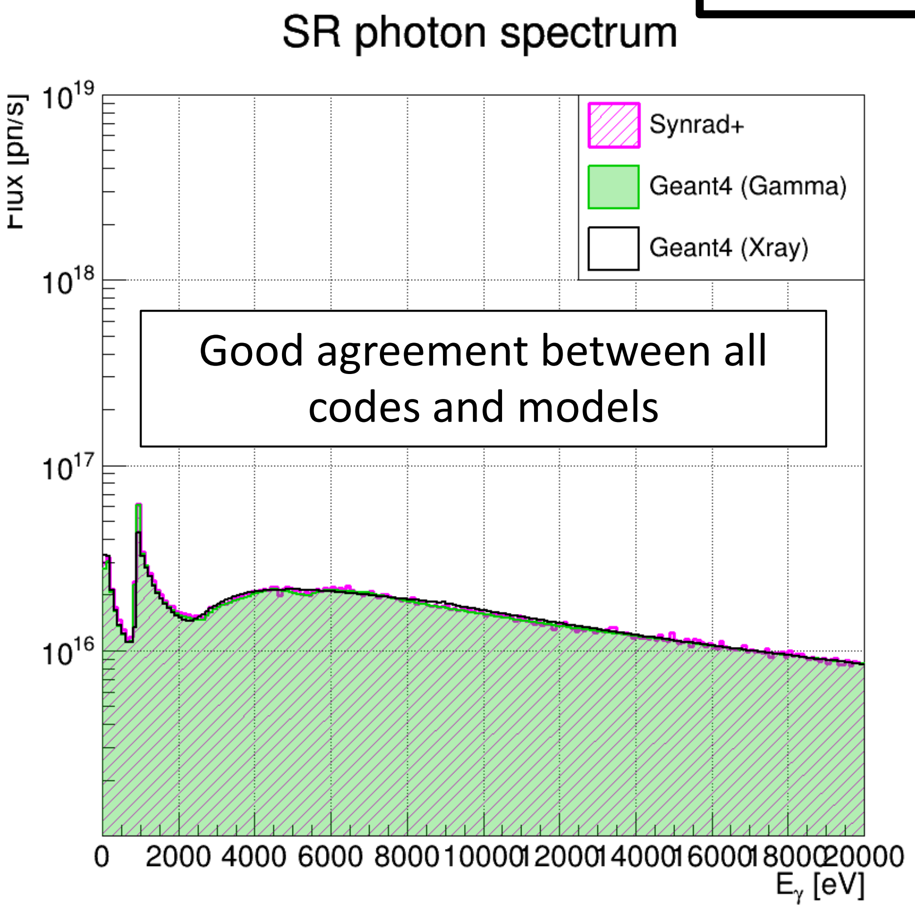
X-ray reflection process in Geant4 (updates)

- Since X-ray reflection as a standard gamma process was missing in Geant4, the Geant4 developers have recently (Dec. 2023) implemented this process; see #50 FCC-ee MDI meeting
  - They use the same material reflection database (like Synrad+) prepared by B.L. Henke et al.
  - Unfortunately, they consider **only specular** (mirror-like) reflection with an attenuation factor to include surface roughness
- Compare the following codes developed for X-ray reflection
  1) Synrad+ (after recent discussions, bugfixes and new features have been implemented by the developers; see 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) Custom-built Geant4 code
     a) With the **Debye-Waller** attenuation factor (similar to the geant4-release) – specular reflection
     b) With the reflection **surface normal random tilt** (similar to the old model in Synrad+) – diffuse reflection
  3) Geant4 release with the **Névot-Croce** attenuation factor – specular reflection

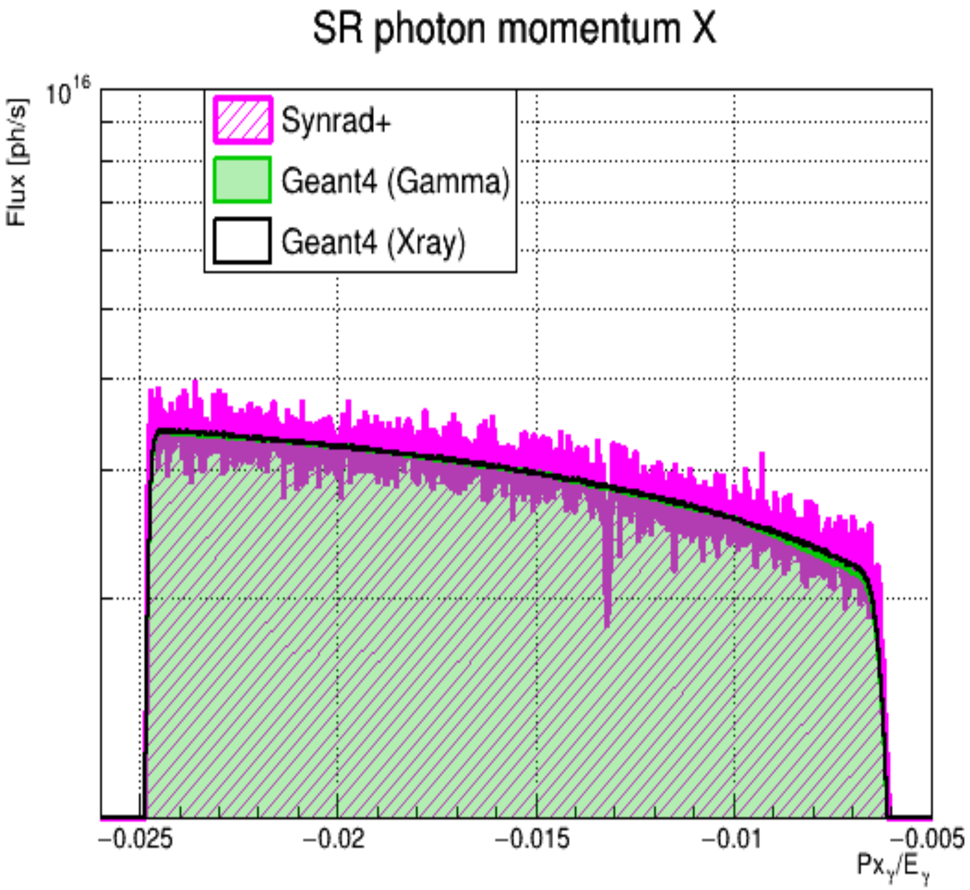
X-ray reflection process benchmark:

Synrad+ (v1.4.33/v1.4.34 bugfix) vs **Geant4** (Gamma, custom-built) vs **Geant4** (Xray, adobted from geant4-release-11.2.0)

Surface roughness RMS = 0 nm

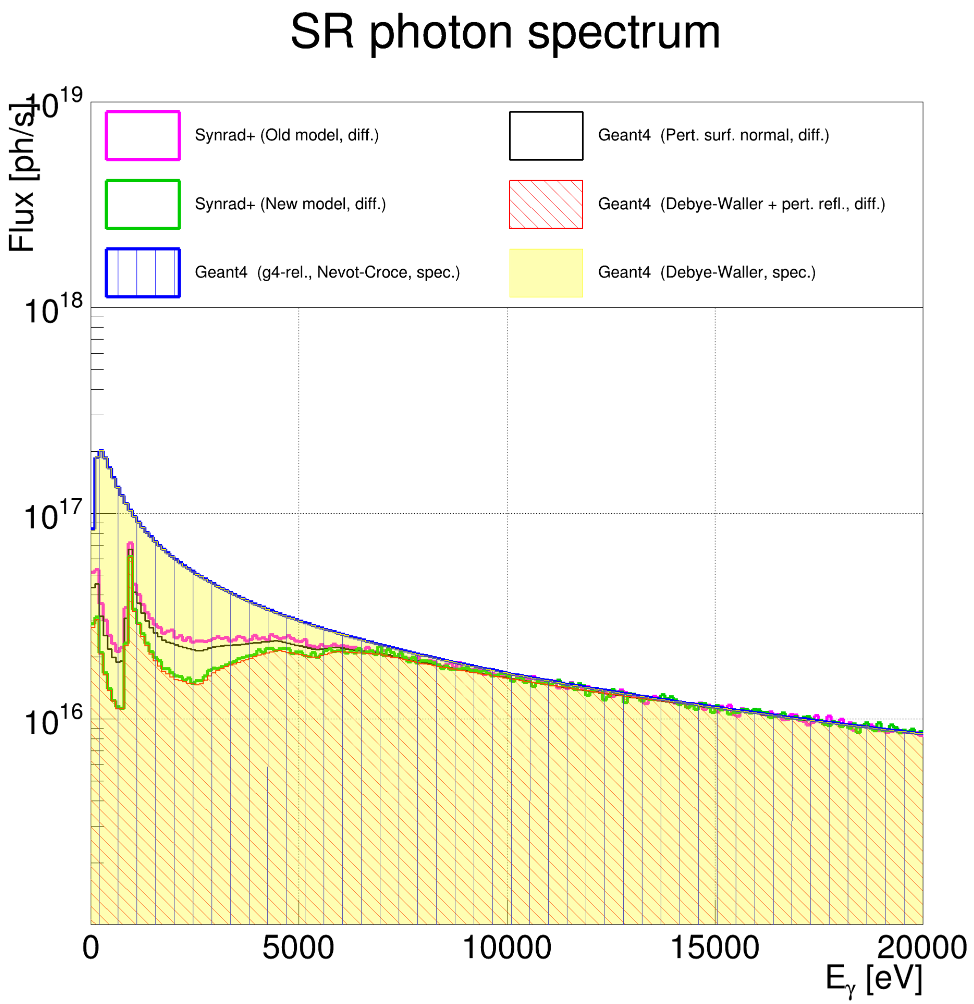


Good agreement between all codes and models



X-ray reflection process benchmark:

Synrad+ (v1.4.33/v1.4.34 bugfix) vs **Geant4** (Gamma, custom-built) vs **Geant4** (Xray, adobted from geant4-release-11.2.0)



Surface roughness RMS = 50 nm

Good agreement

- between Geant4 codes for specular reflection

  (blue and yellow)

- old model Synrad+ vs Geant4 code for diffuse reflection

  (magenta vs black)

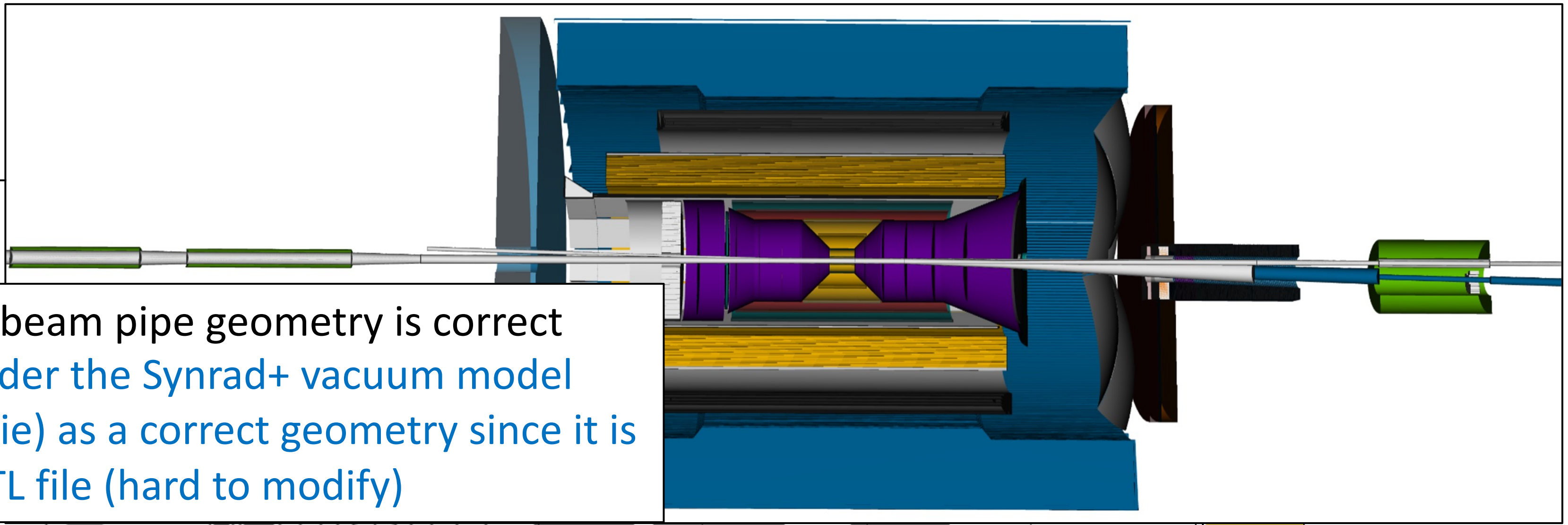
- new model Synrad+ vs Geant4 code for diffuse reflection

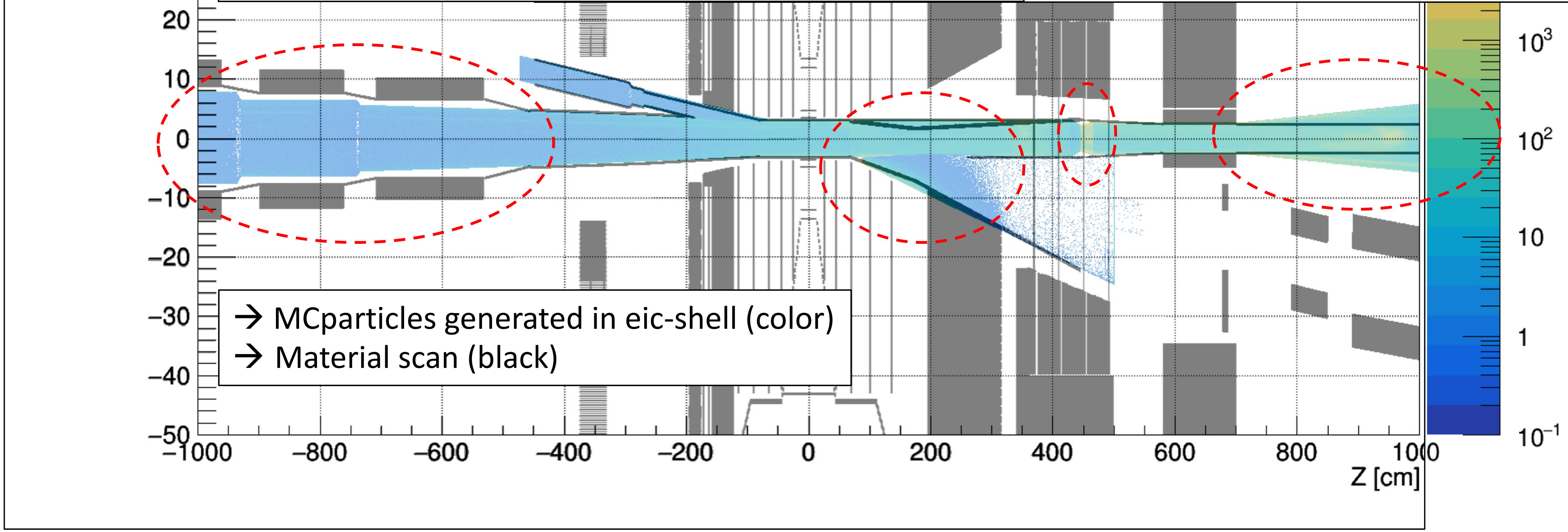
  (green vs red)

More plots are in Backups

Beam pipe geometry

Beam pipe geometry inconsistency

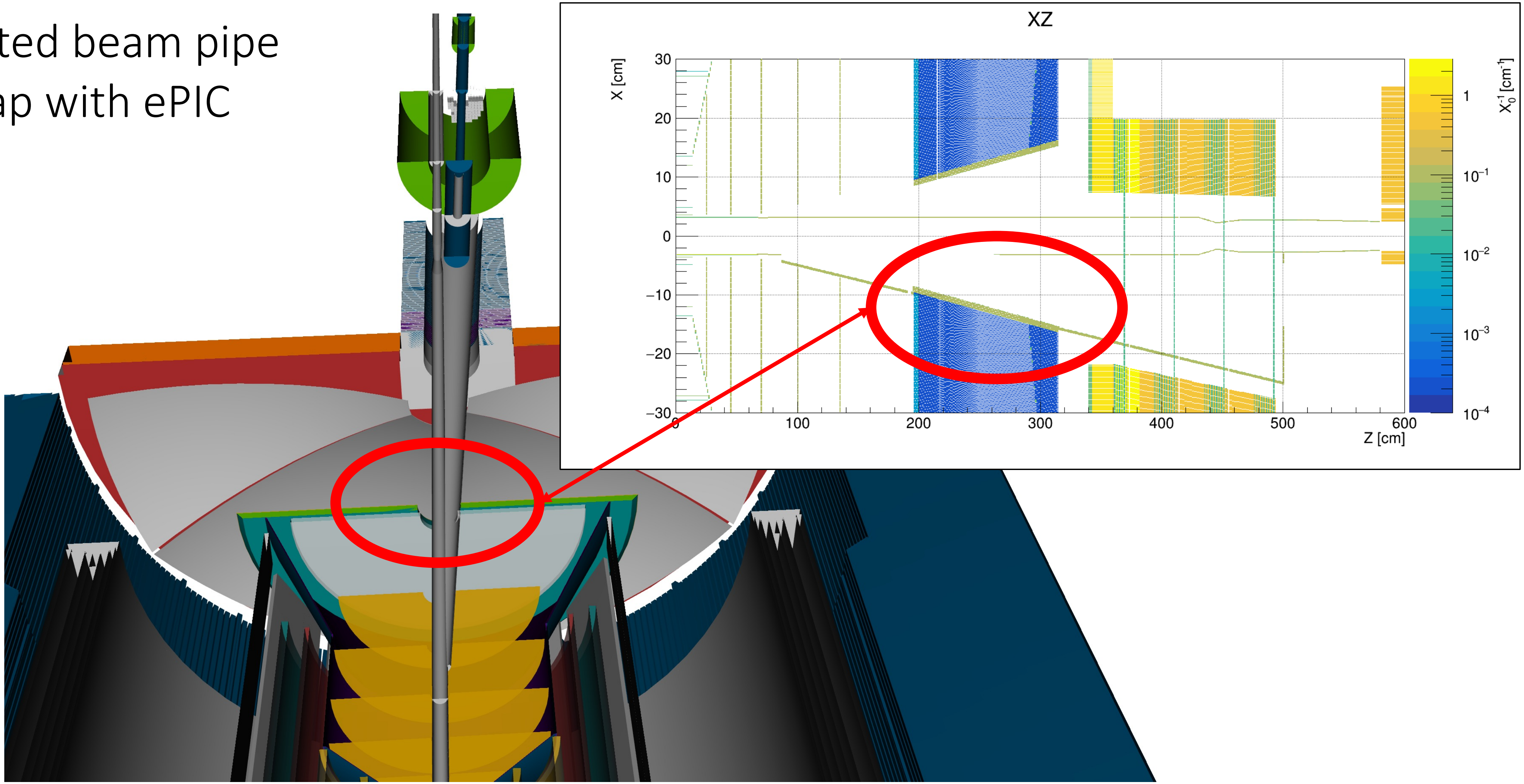




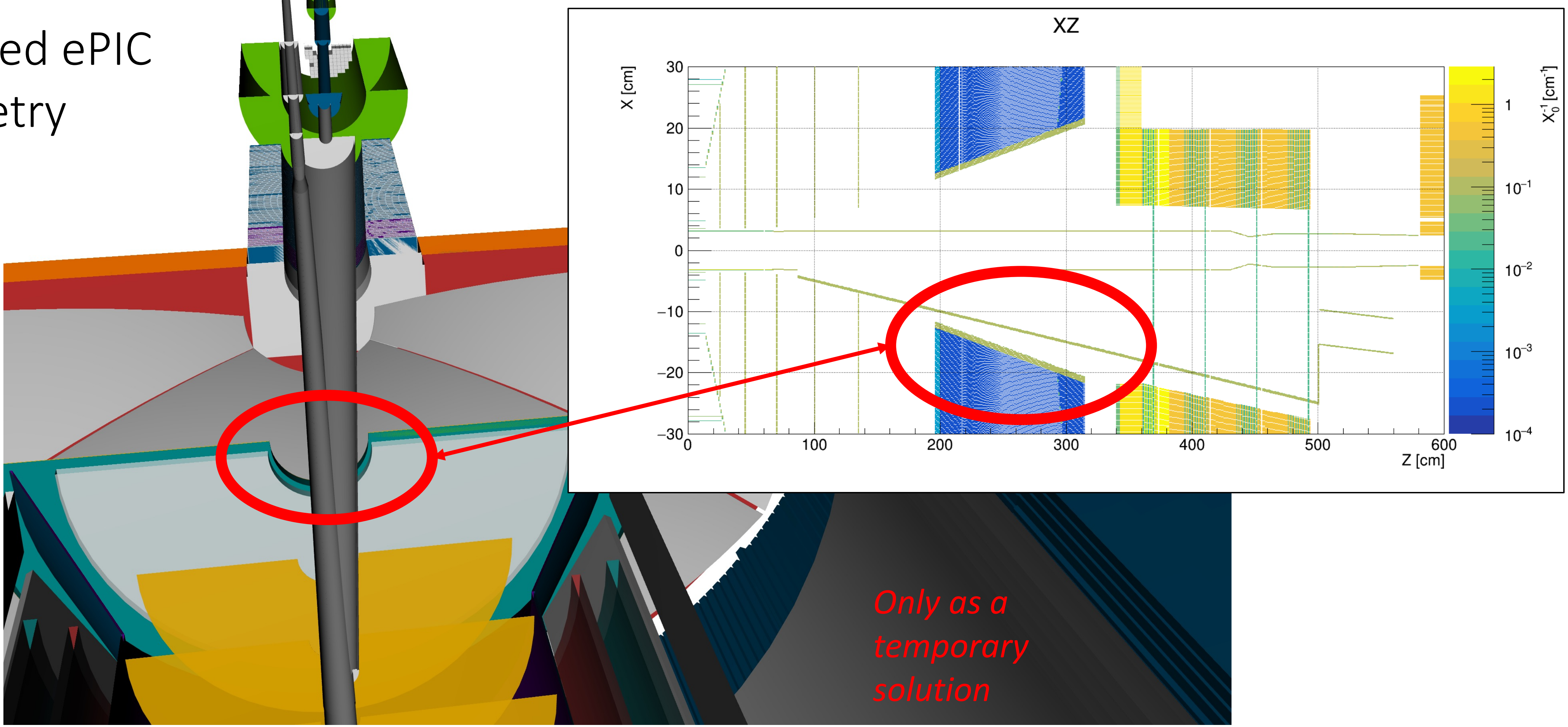
- It is unclear which beam pipe geometry is correct
- **Assumption:** consider the Synrad+ vacuum model (prepared by Charlie) as a correct geometry since it is given as a single STL file (hard to modify)

→ MCparticles generated in eic-shell (color)
→ Material scan (black)

Adjusted beam pipe overlap with ePIC



Adjusted ePIC geometry



compact/definitions.xml

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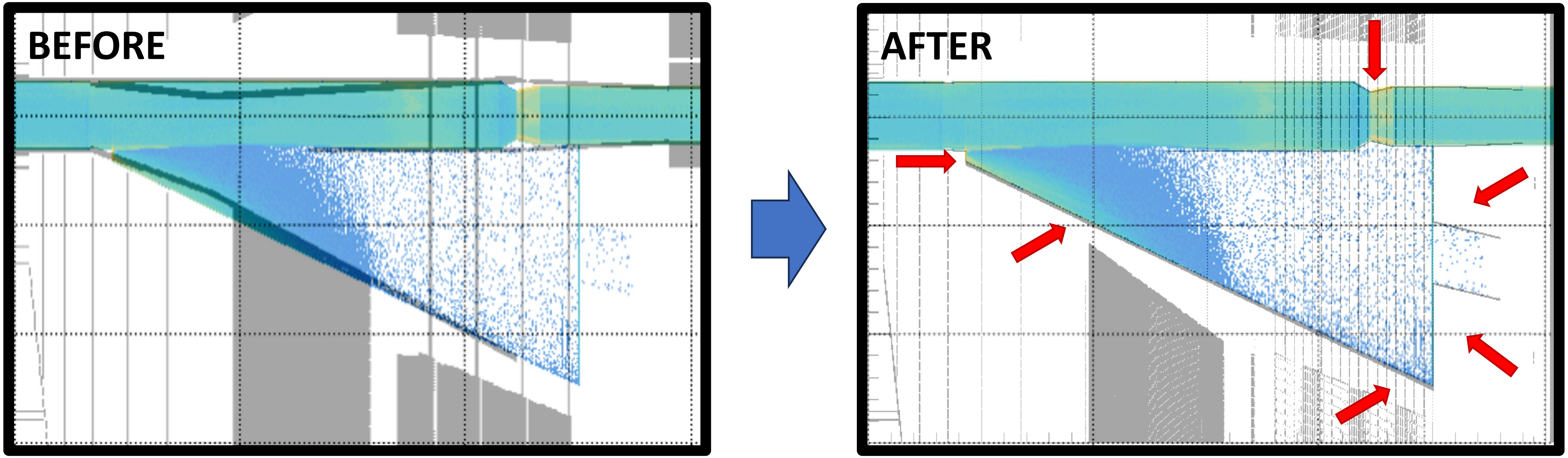
compact/tracking/definitions.xml

<constant name="ForwardTOFRegion_minR" value="~~8~~ 13*cm" />

Beam pipe geometry modification

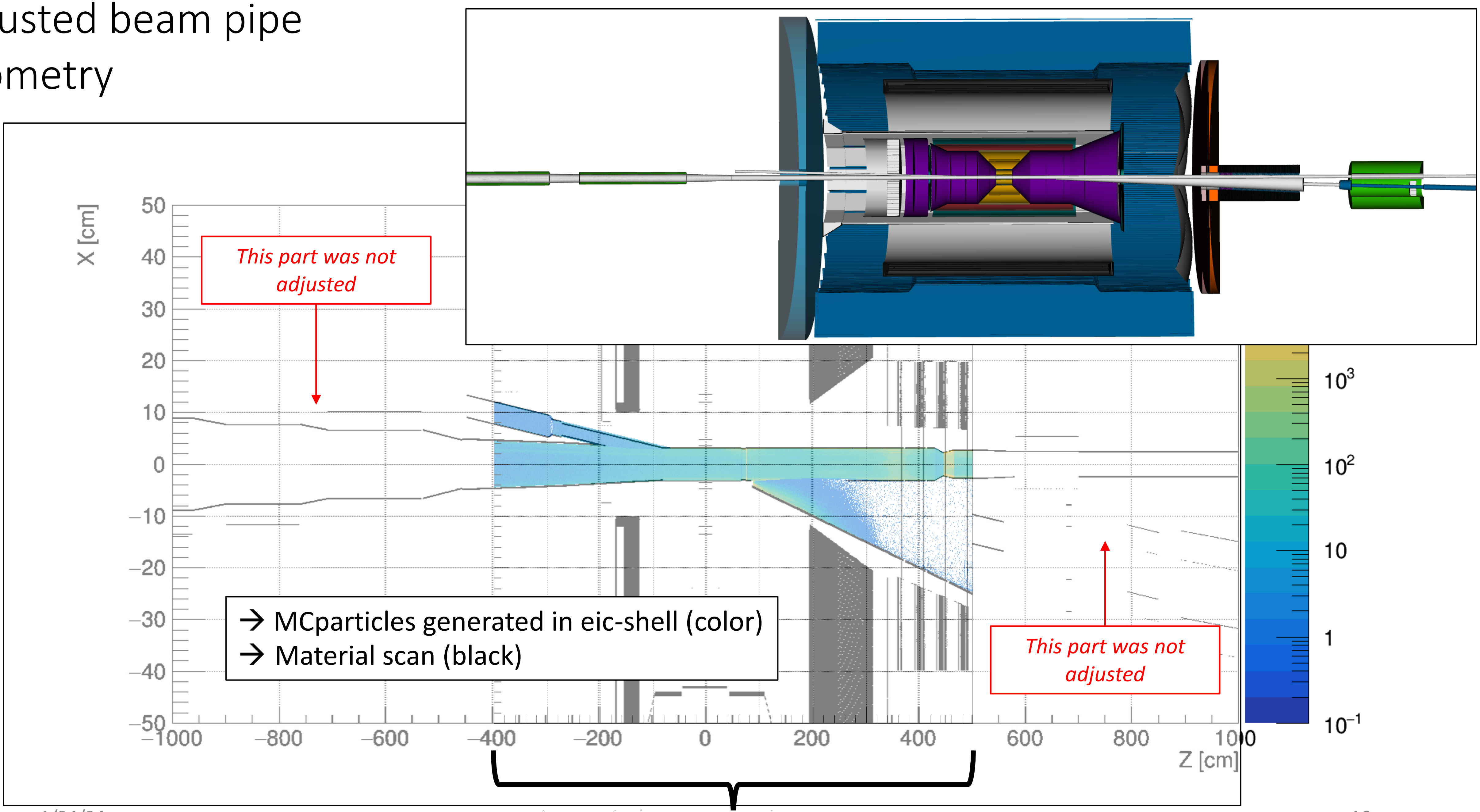
- The new beam pipe modeling is now much closer to the Synrad+ geometry.
- Although it might not be the final/recent beam pipe geometry, we define it as a reference to compare the simulated SR impact on the detector background.



→ MCparticles generated in eic-shell (color)
→ Material scan (black)

More plots are in Backups

Adjusted beam pipe geometry

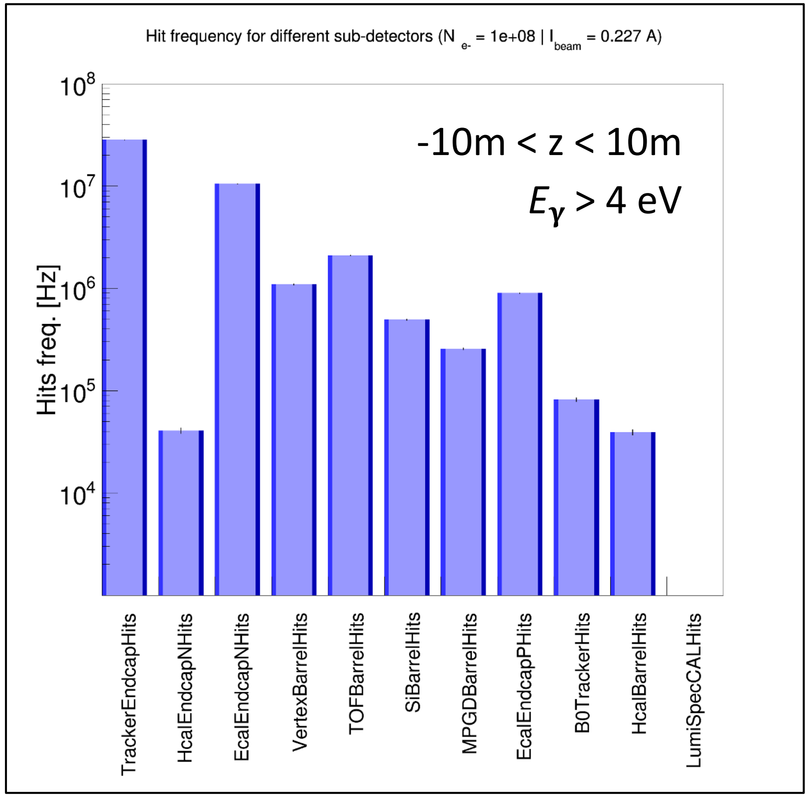


Used for the ePIC SR background simulation

SR background simulation

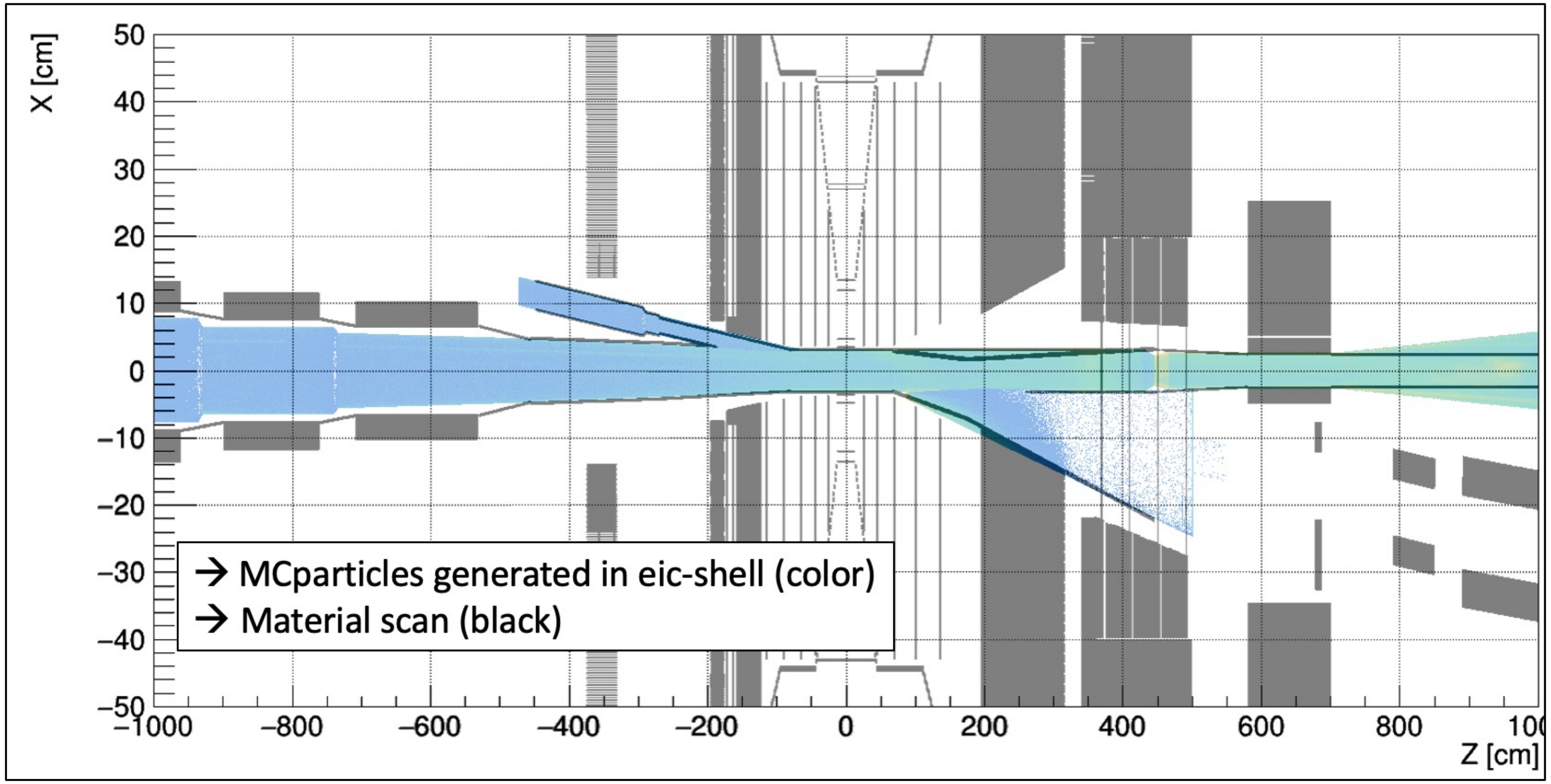
ePIC SR background: Rates with inconsistent geometries

High SR background rates (> 1 MHz) due to generated SR photons outside the vacuum beam pipe



First custom-built Geant4 SR model (contained bugs)

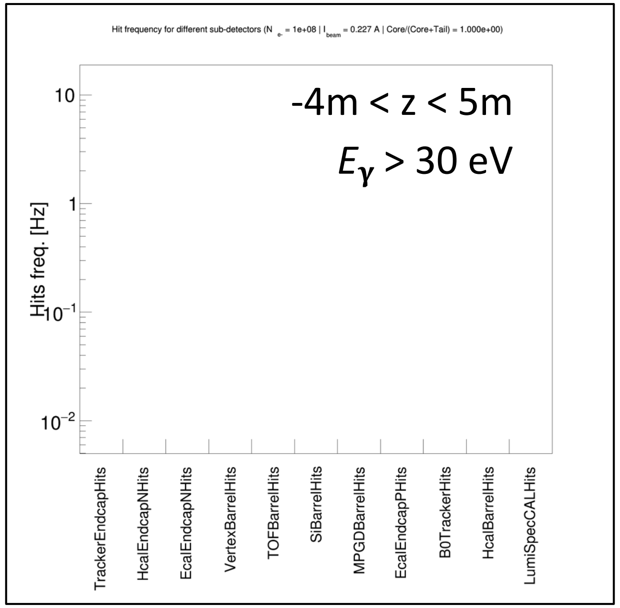
[From Dec. 2023 meeting]



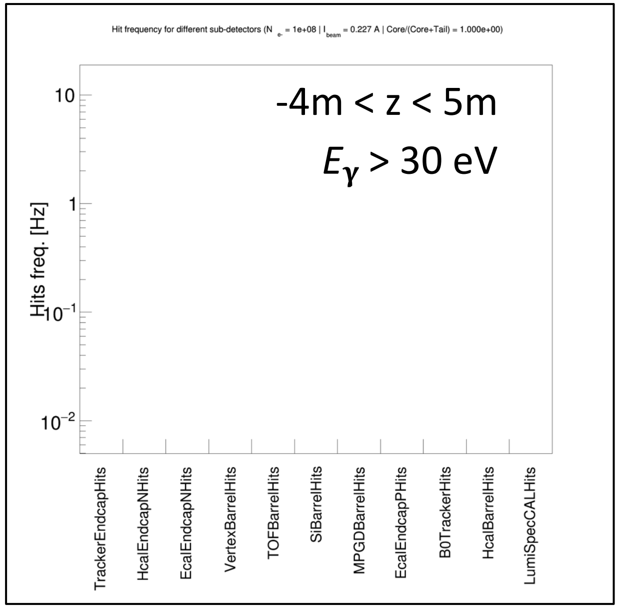
ePIC SR background: Rates with adjusted geometries

Improving the X-ray reflection process and tuning the beam pipe in the eic-shell to the CAD/STL model make the SR background in the ePIC detector **more realistic with diffuse reflection**, i.e., SR background rates ~ 0.1 MHz (e.g., electron beam-gas rates ~3 MHz [ref.])

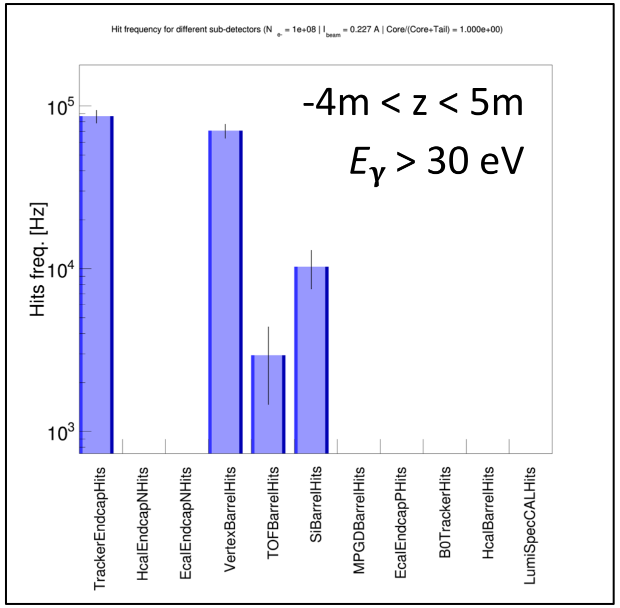
Custom-built Geant4 (X-ray, Névot-Croce, adopted from geant4-release-11.2.0)
Specular reflection



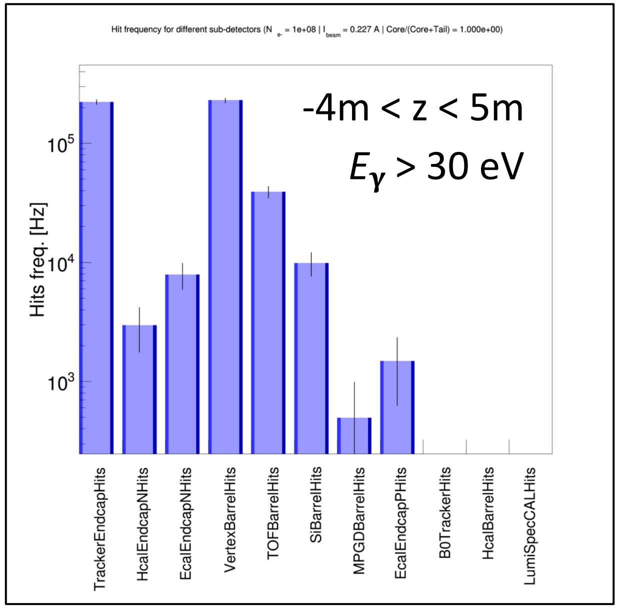
Custom-built Geant4 (Gamma, Debye-Waller)
Specular reflection



Custom-built Geant4 (Gamma, surf. normal tilt, like the old Synrad+ model)
Diffuse reflection



Custom-built Geant4 (Gamma, Debye-Waller + perturbed reflection direction, like the new Synrad+ model)
Diffuse reflection



Beam tail modeling

Overview

- The realistic/actual beam tail distribution modeling is a challenging task
  - Usually, one has to include all possible beam-scattering processes with beam dynamics in the machine lattice, possible machine errors, and collimators
- So far, we do not have a reliable multi-turn particle tracking code for the EIC
  - Therefore, we have to rely on some assumptions and approximations

- Christoph Montag's model [optimistic]: ← *first trial; see* Dec. 2023 meeting
  - **Non-gaussian tails** caused by beam-beam and beam-gas scattering events
  - Enhancement of the electron beam population at large amplitude (beam tails) occurs predominantly in the vertical plane
  - The core of the model – parametrized simulated beam tails
    - No tails in the horizontal plane at E_{e-} = 18 GeV
    - The vertical beam tail integral is about 10^{-8} of the beam core

- Mike Sullivan's model [conservative]: ← *next step*
  - **Gaussian beam tails** as an equilibrium between beam lifetime (beam particles are scattered out of the core into the tails) and SR damping (beam tail particles are pulled back to the core)
    - Especially true for the horizontal plane
  - The integral of beam tails should not exceed a certain value to avoid luminosity degradation
    - Arbitrary threshold: the tail integral is < 5% of the core integral

Summary

- Last time, we reported on the first developments of SR photon reflection in Geant4.
- Since then, several improvements and features to the code have been implemented.
  - Solenoid field using MARCO magnetic field map.
  - Spectral and diffuse reflection processes based on the recently released Geant4 and documented old/new Synrad+ models were implemented in the custom-built Geant4 code for the SR simulation.
- Furthermore, we have identified significant inconsistencies in the vacuum electron beam pipe geometry between the eic-shell (used for the ePIC background rate simulation) and the custom-built Geant4 (CAD/STL drawings imported from Synrad+).
  - Since the correct beam pipe geometry is unclear, we adjusted eic-shell modeling following CAD/STL drawings. → **We need correct, up-to-date vacuum beam pipe drawings.**
  - This temporary solution allowed us to study the ePIC SR background rates for different X-ray reflection models.
- According to the findings:
  - Diffuse reflection based on old and new Synrad+ algorithms works well and gives a realistic estimation of the detector's SR background level (~0.1 MHz).
  - We still need to understand which model is the best for our application; each model has pros and cons.
- Several Synrad+ code updates (new features and bugfixes) were triggered during the new custom-built Geant4 code development; see the following slides.

Next steps

Beam tails

- The first optimistic model with non-Gaussian tails was tested with a very low beam halo intensity.
- A more aggressive model with Gaussian tails will be tested next.

New machine lattice

- Recently, we have received a new machine lattice v6.2
- Questions and subjects to be studied with the SR simulation in Geant4
  - *Do we need to update the masks in front of ePIC?*
  - *What photons pass and hit the beam pipe?*
  - *Updated SR background rates?*
  - *SR photon files?*

- For the review of the ancillary detectors in February:
  - *What are the SR background rates for the low-Q^2 tagger and the Luminosity monitor?*
    - This item requires backward beam pipe geometry modification in both eic-shell and custom-built Geant4.

Synrad+ updates

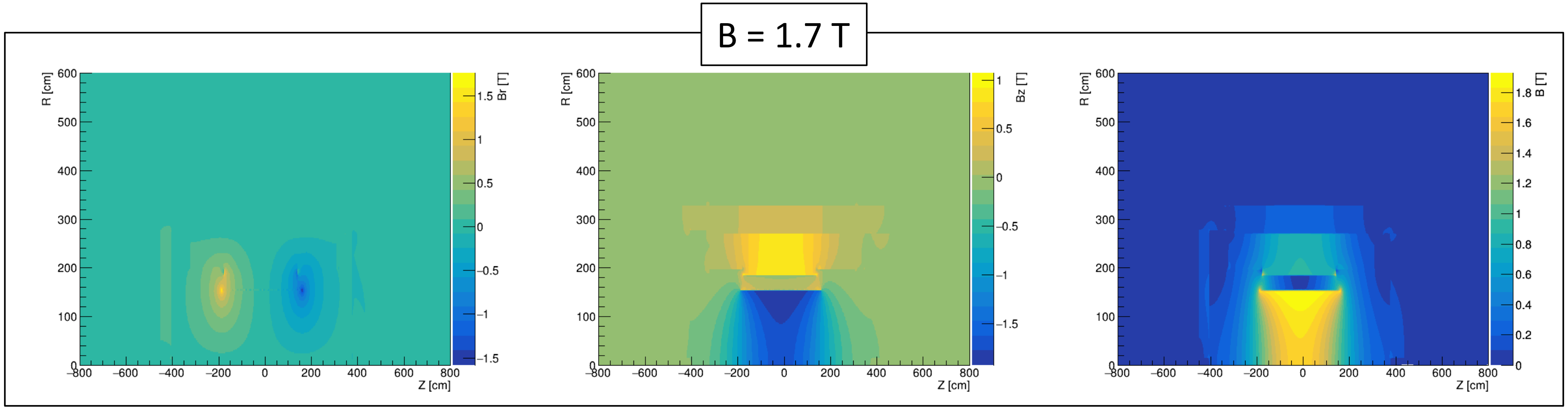
The new custom-built Geant4 code development triggered a few updates to the official Synrad+ software.

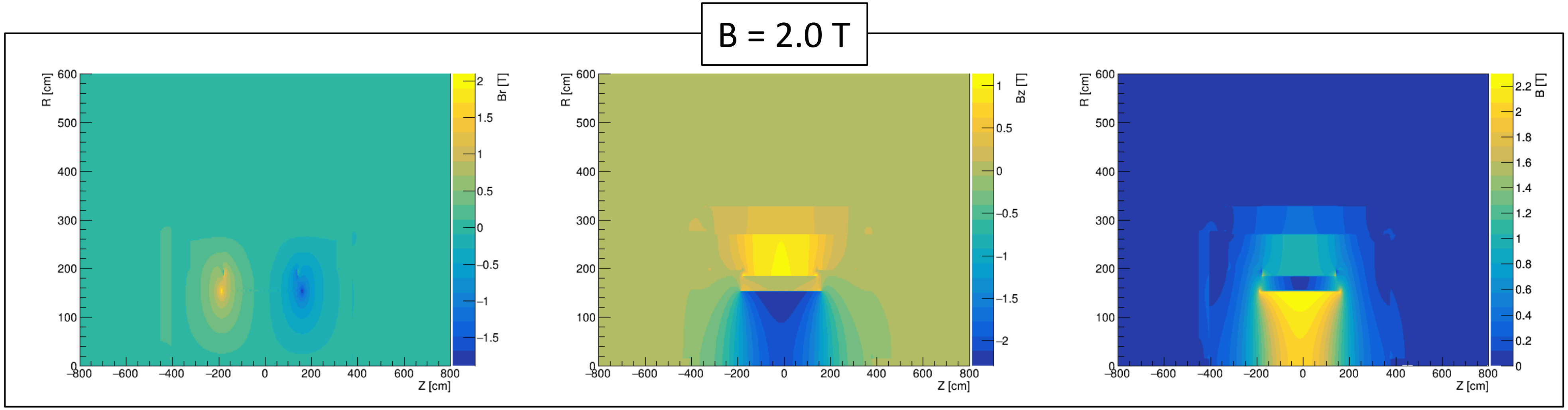
1. An option to log absorbed particles by a given facet is now available.
2. The logged particle flux is now correctly normalized using the correct number of simulation scans.
3. Due to a bug in the code, the switch for the new reflection model did not work correctly in the GUI. Now, through global settings, one can switch between old and new reflection models with one click, and it will be correctly prepared to the simulation.

For more details, please refer to the Synrad+/Molflow+ Forum:
All features and bugfixes from above are implemented in the new release v1.4.34

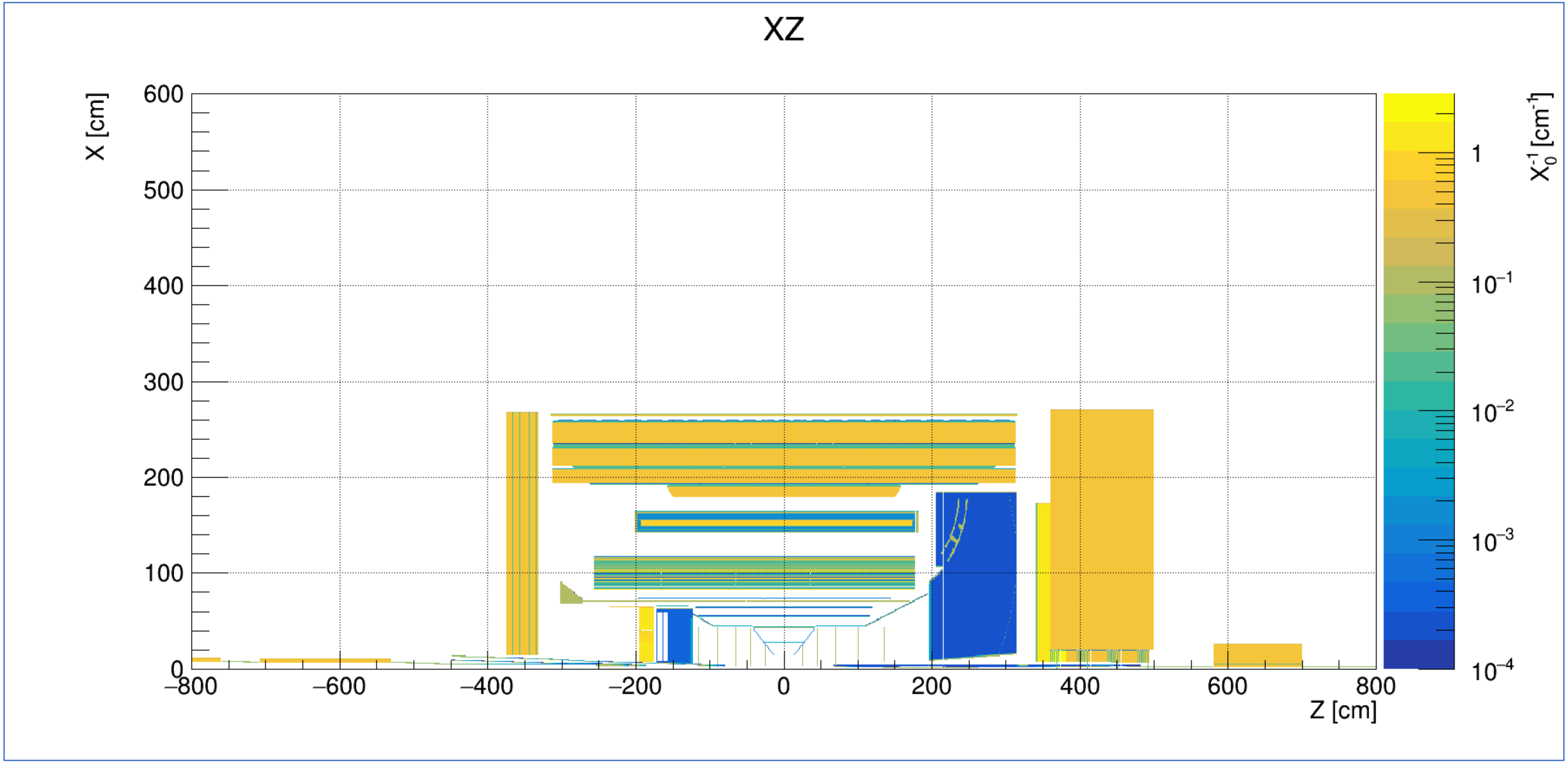
Backup

Solenoid field

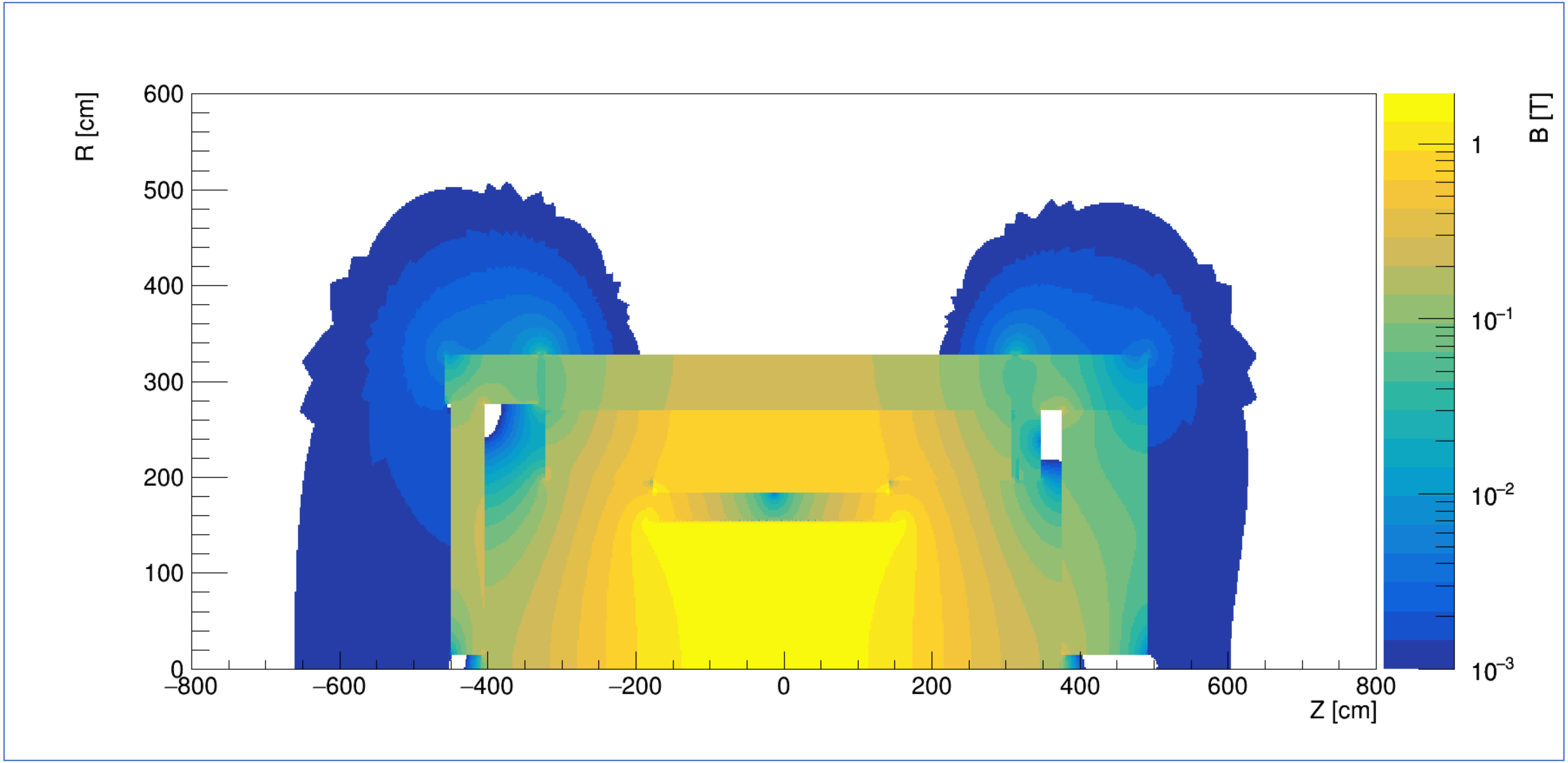


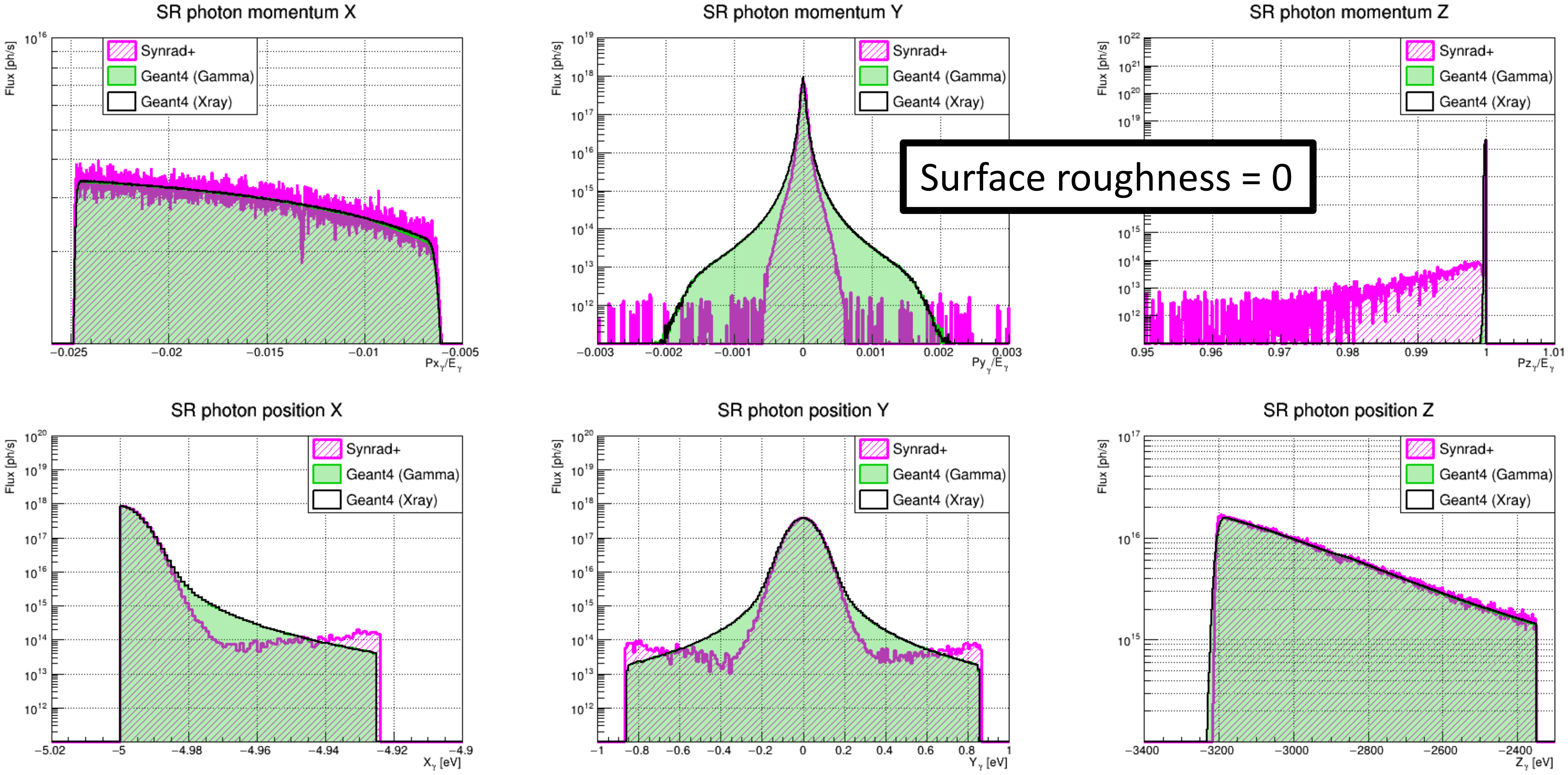


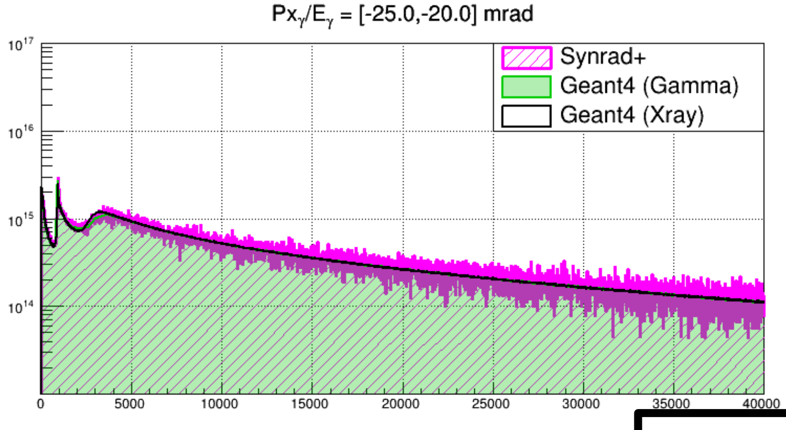
Material scan

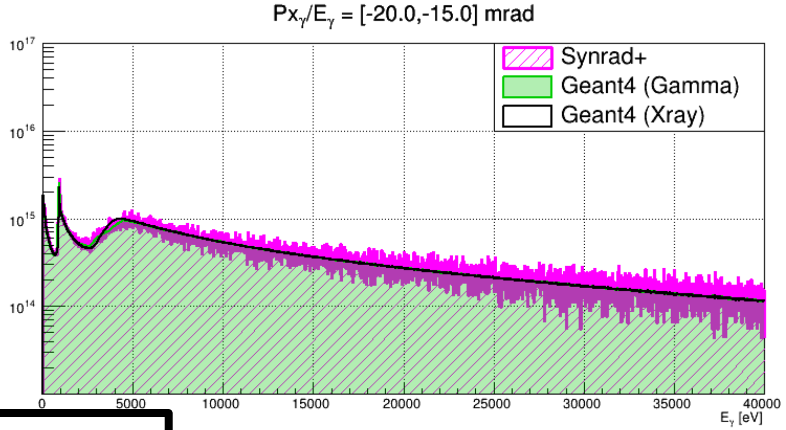


Solenoid field (1.7 T)

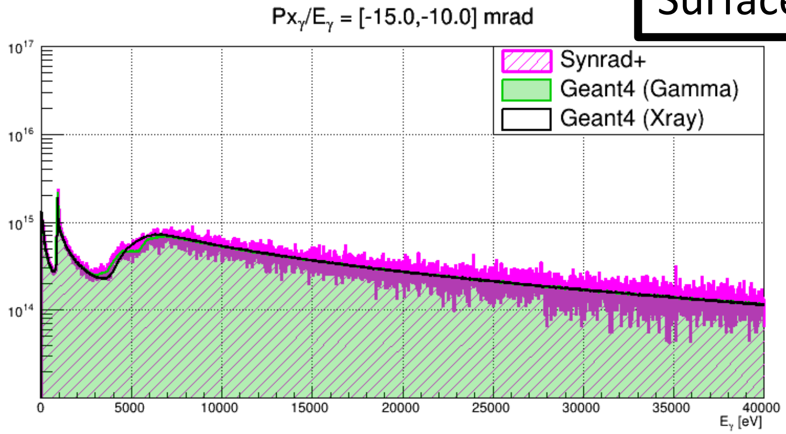


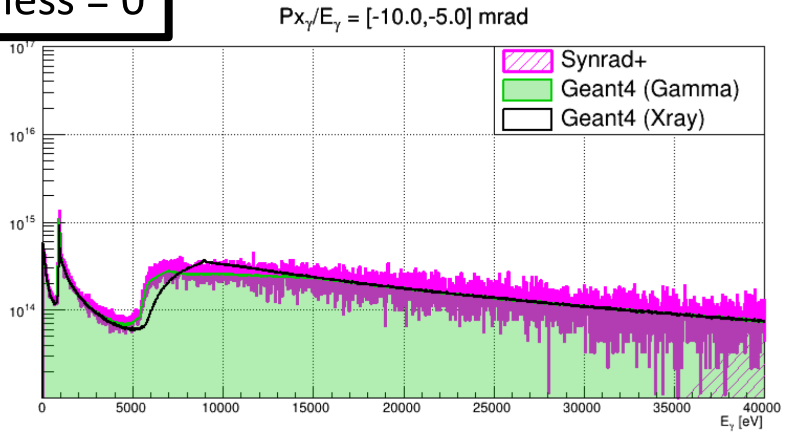

SR photon momentum X
SR photon momentum Y
SR photon momentum Z
Surface roughness = 0
SR photon position X
SR photon position Y
SR photon position Z
Synrad+
Geant4 (Gamma)
Geant4 (Xray)
Flux [ph/s]



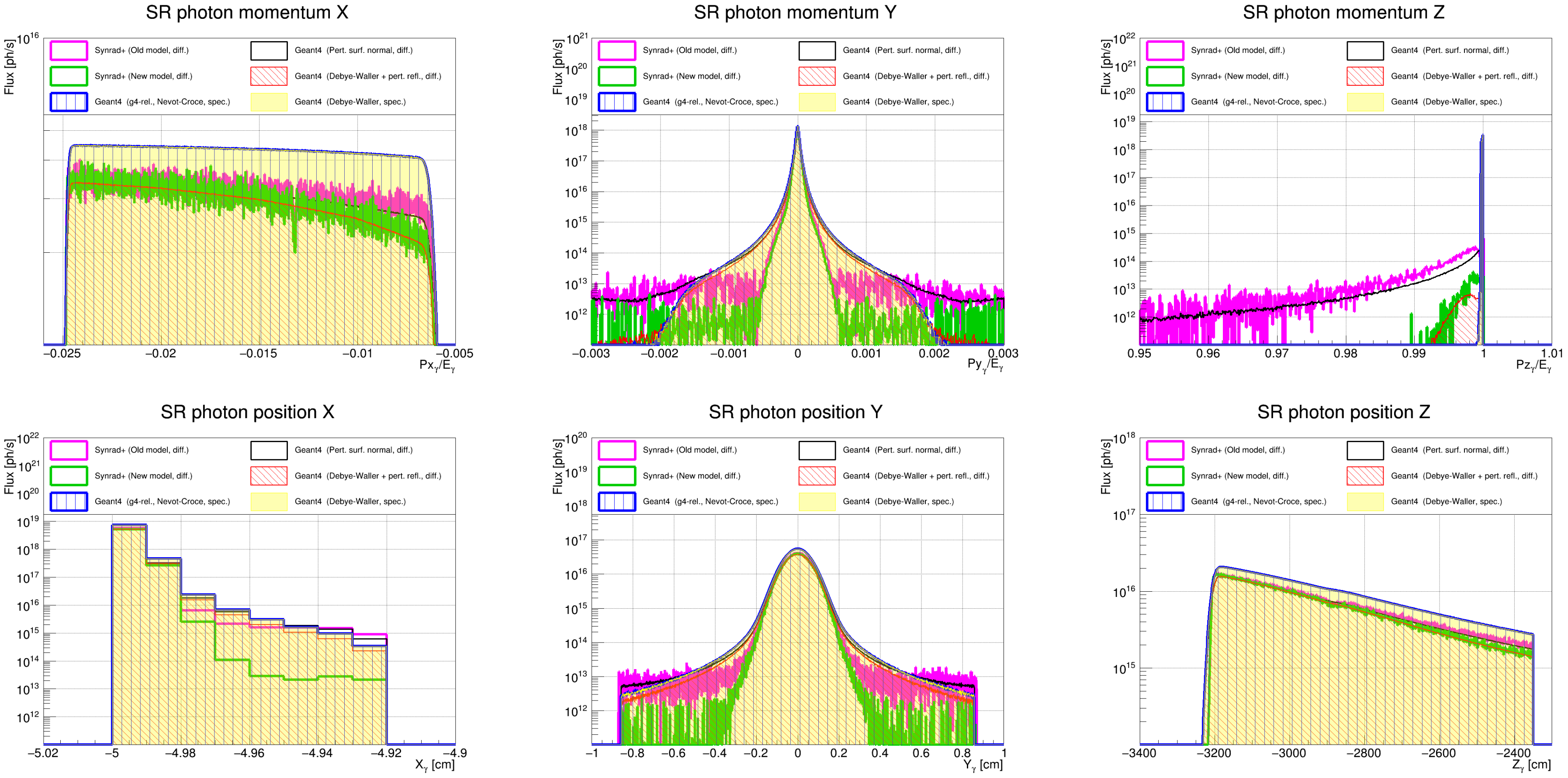


Surface roughness = 0

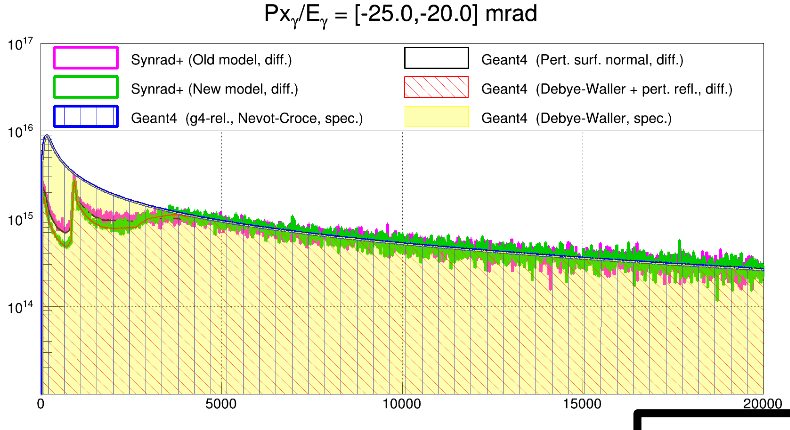


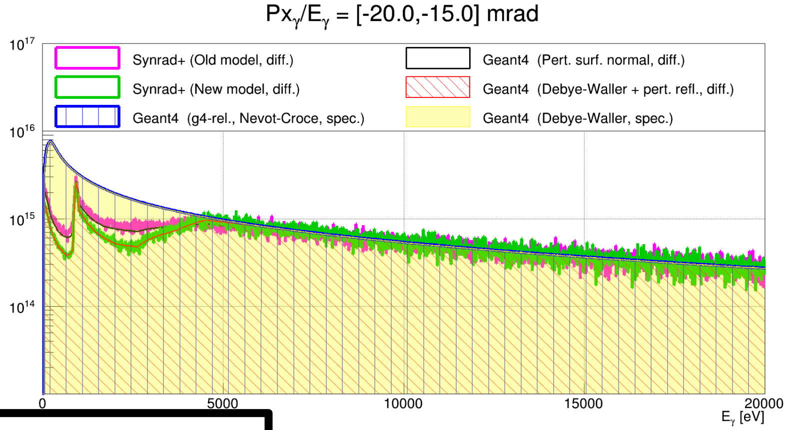


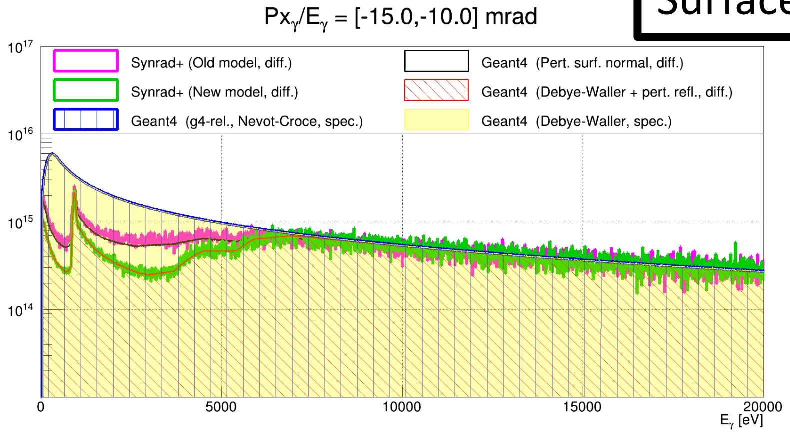
Surface roughness = 50 nm

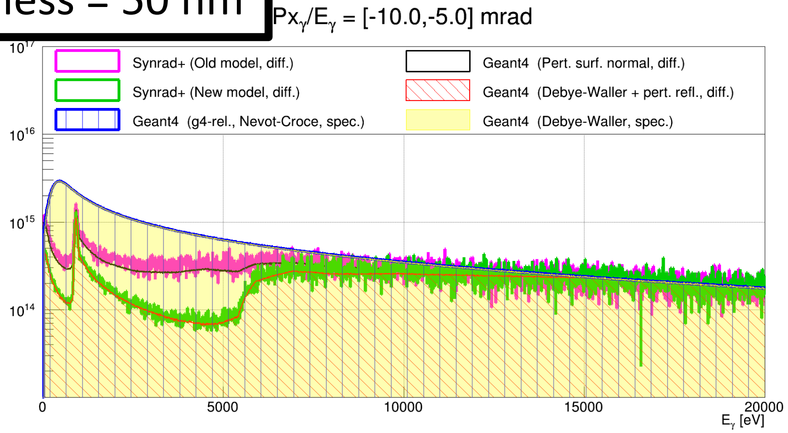


Surface roughness = 50 nm

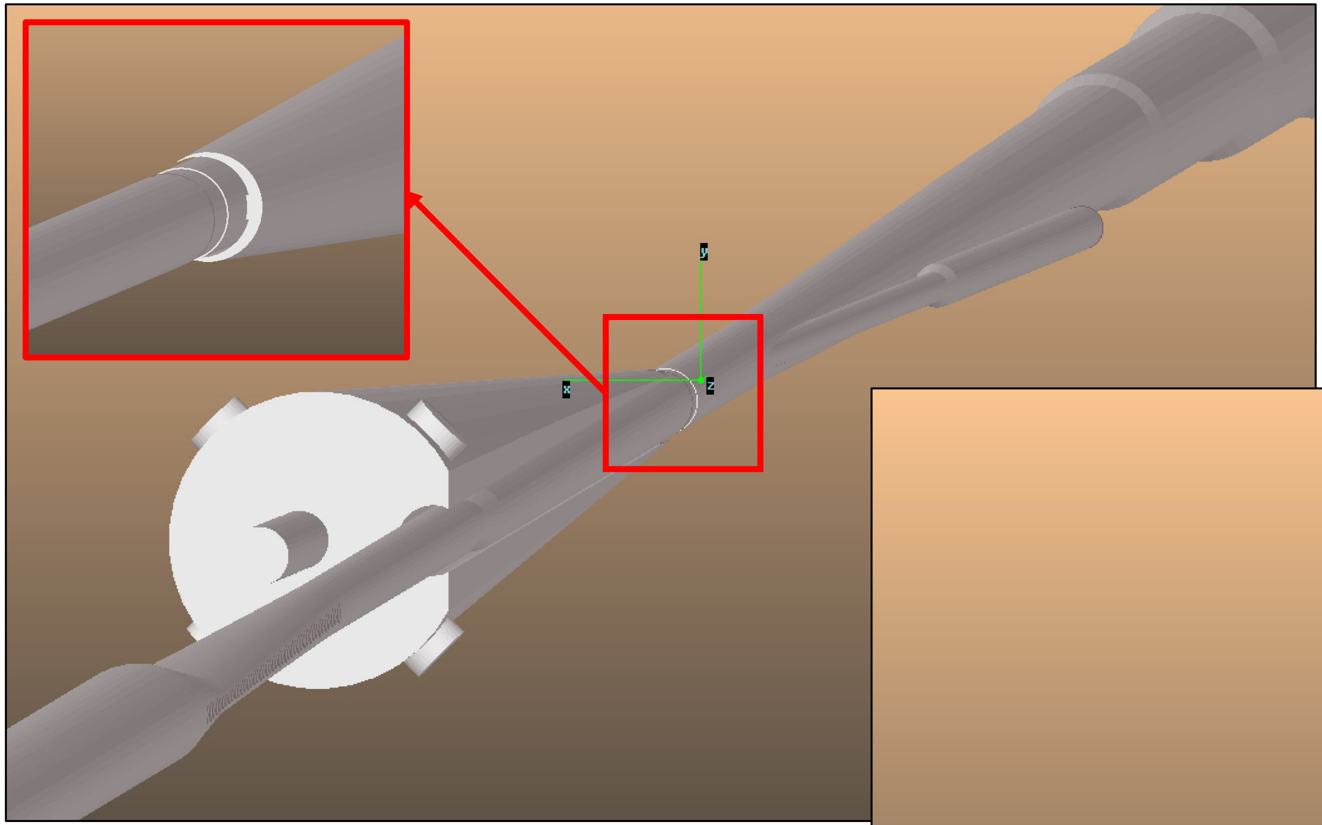


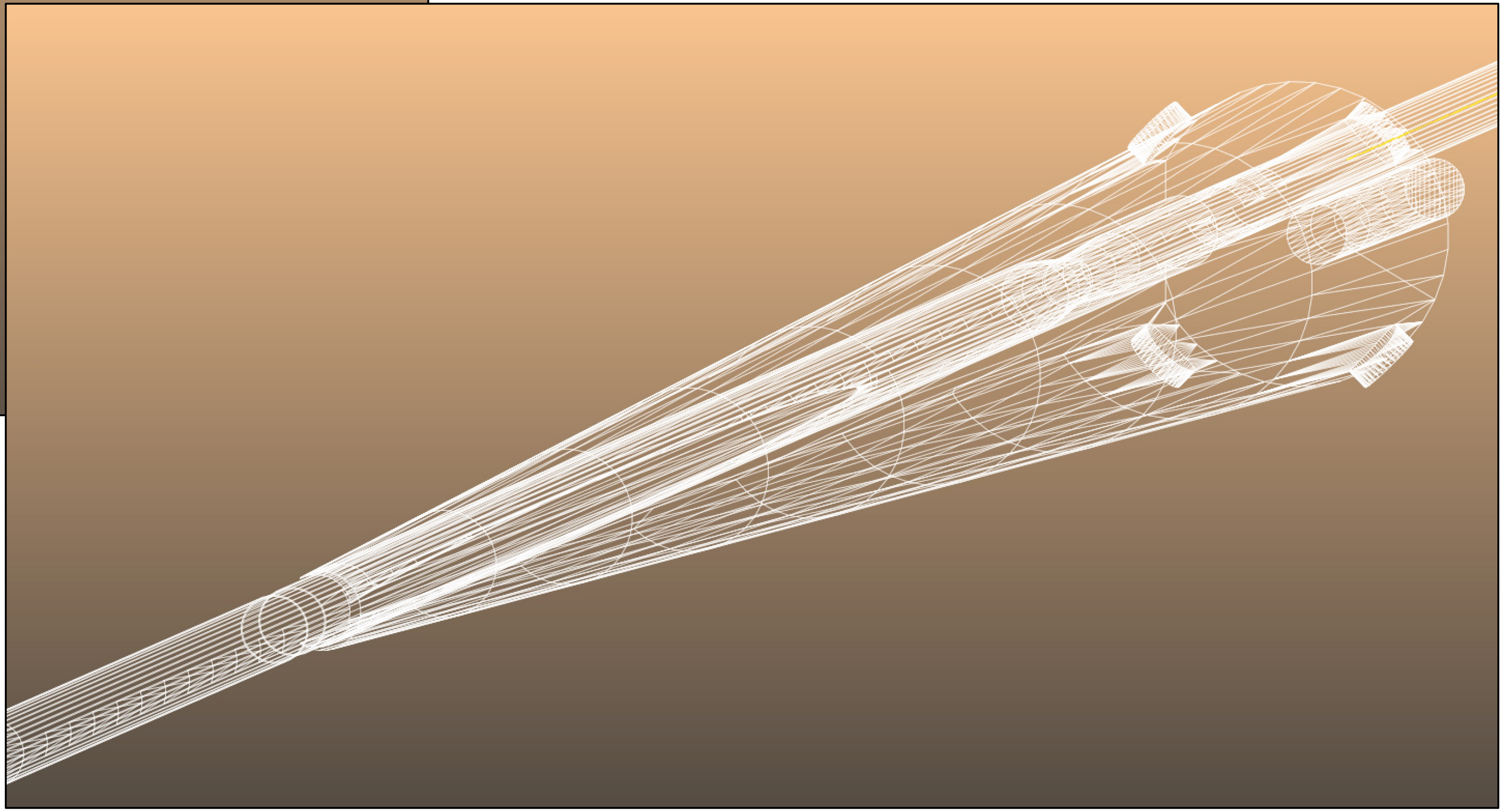




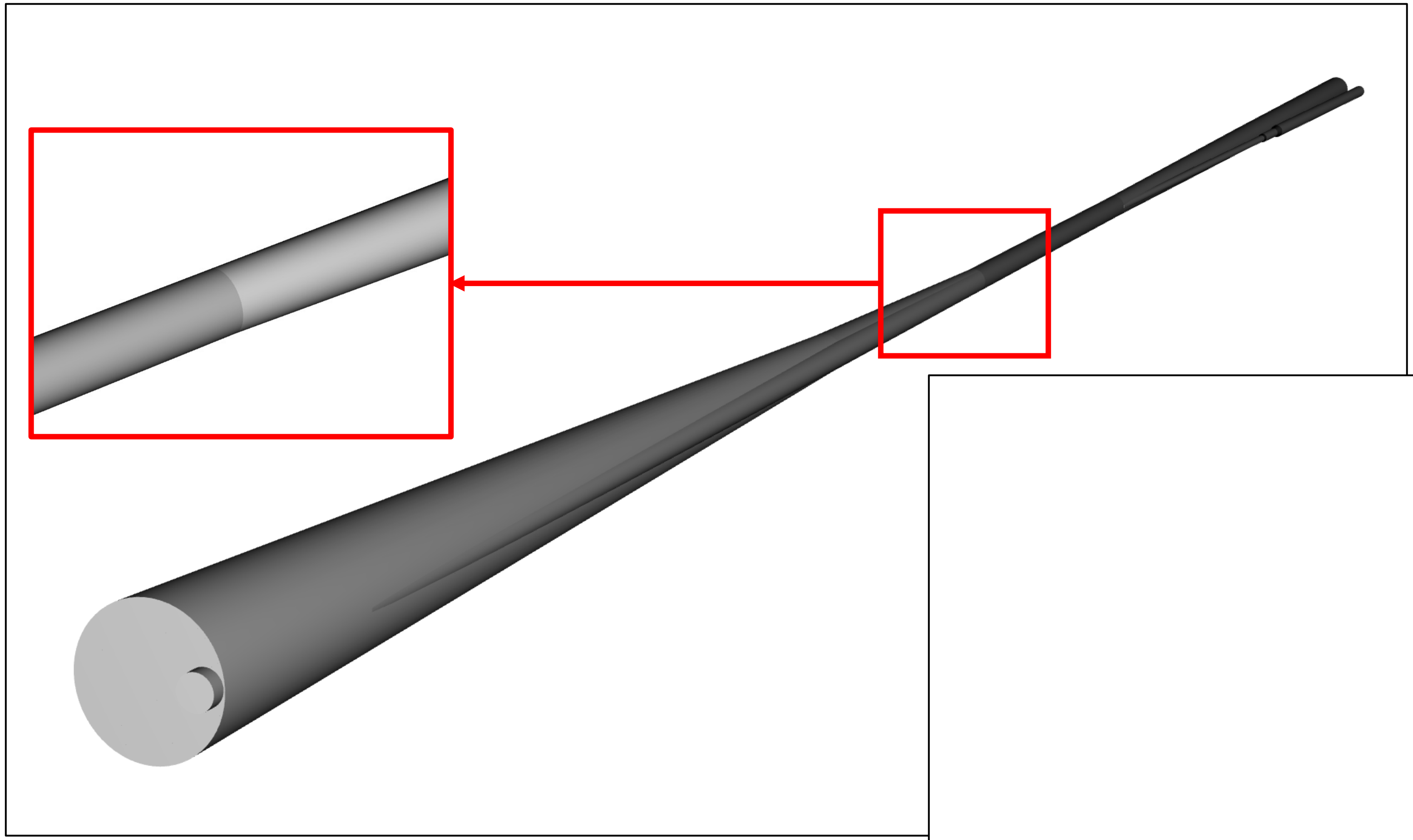


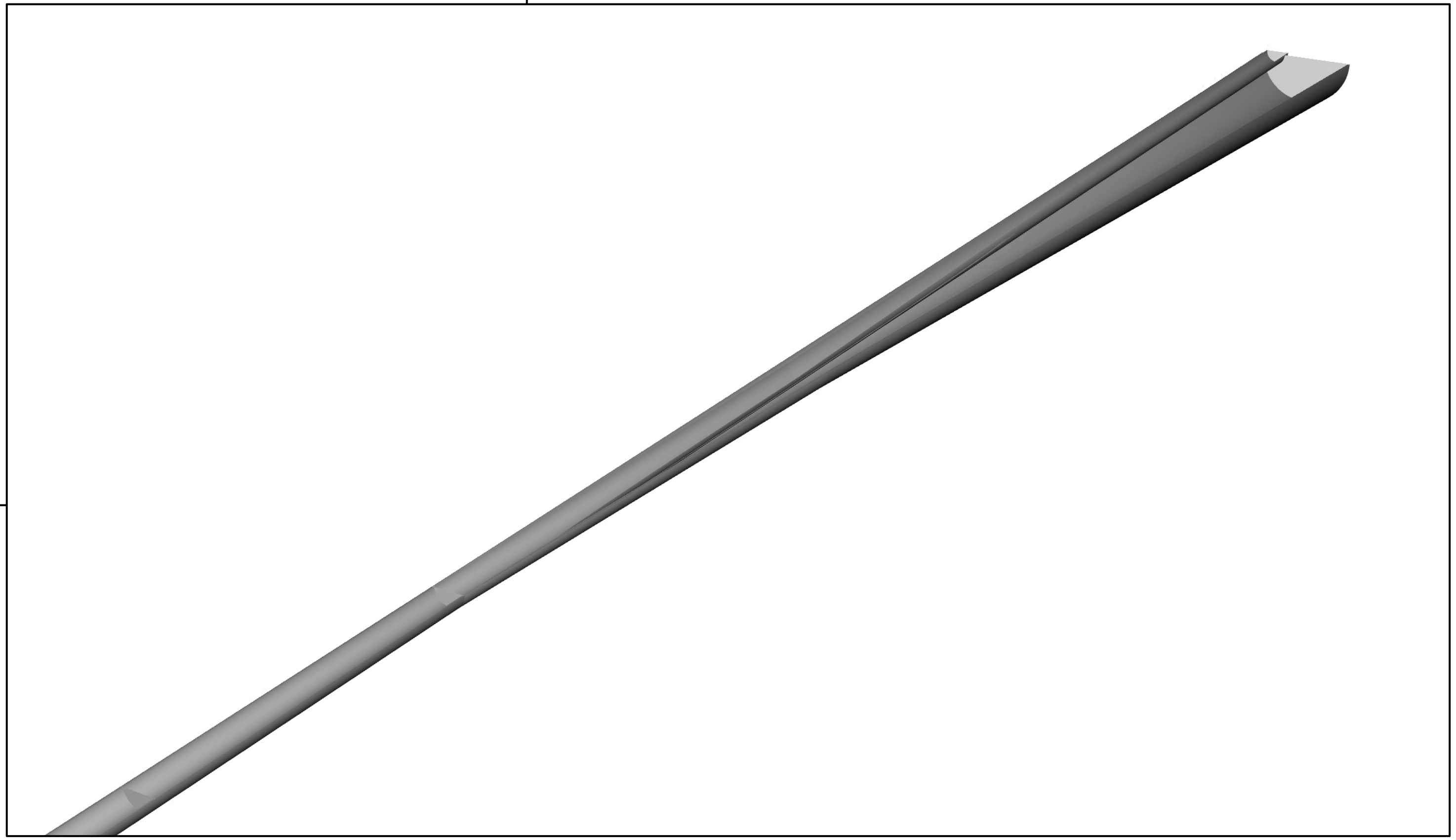
Synrad+ beam pipe geometry



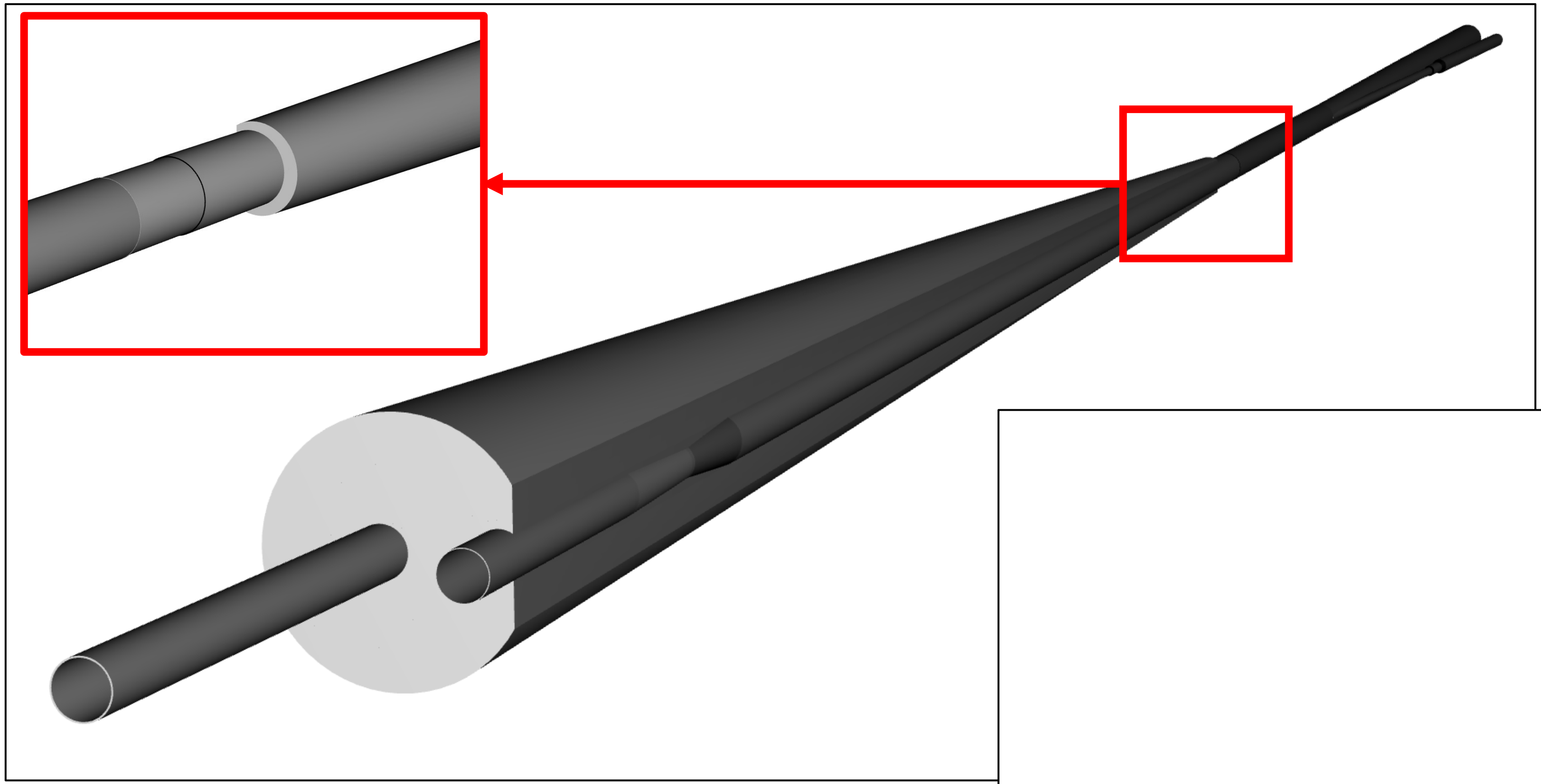


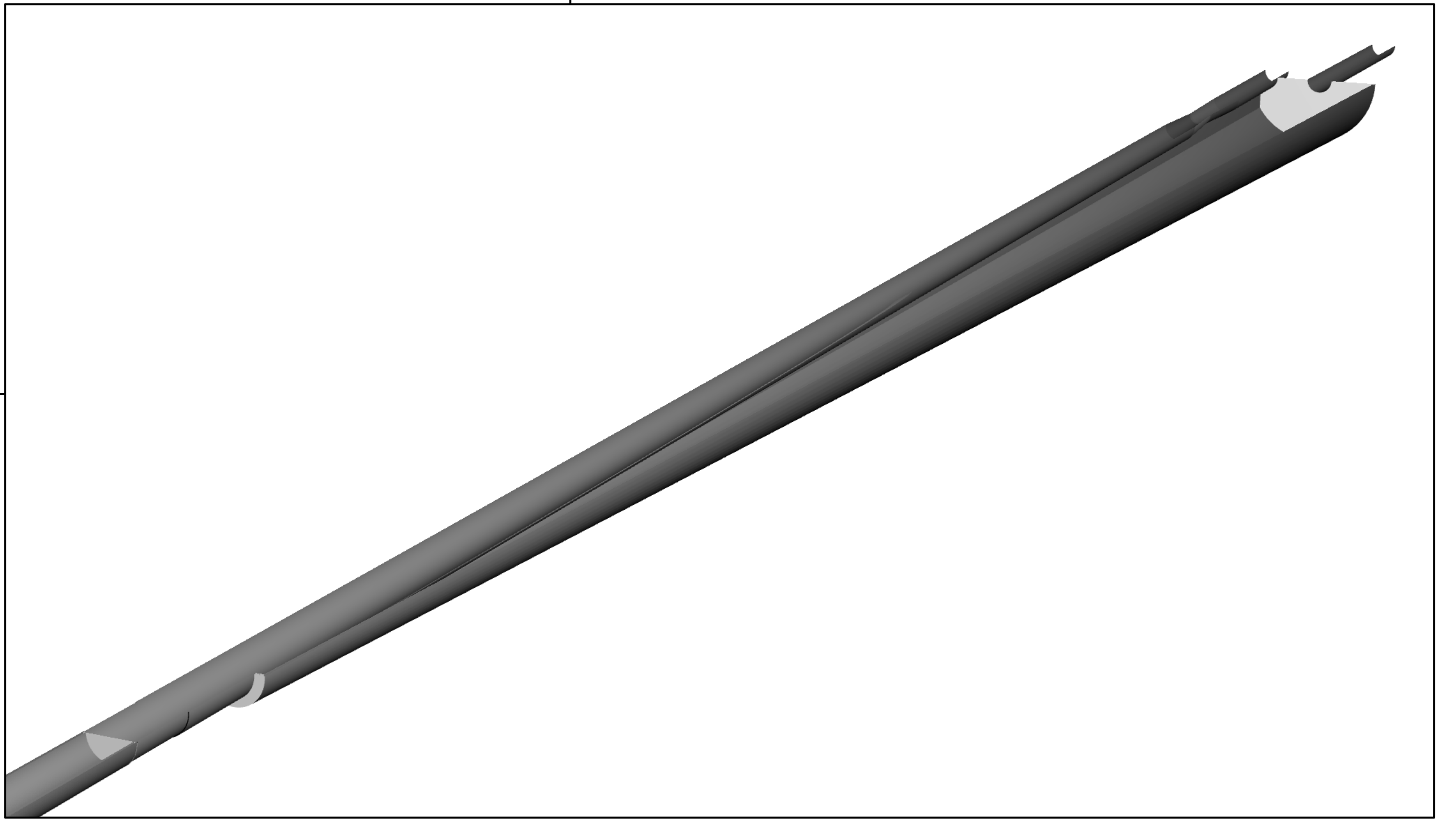
Default beam pipe geometry





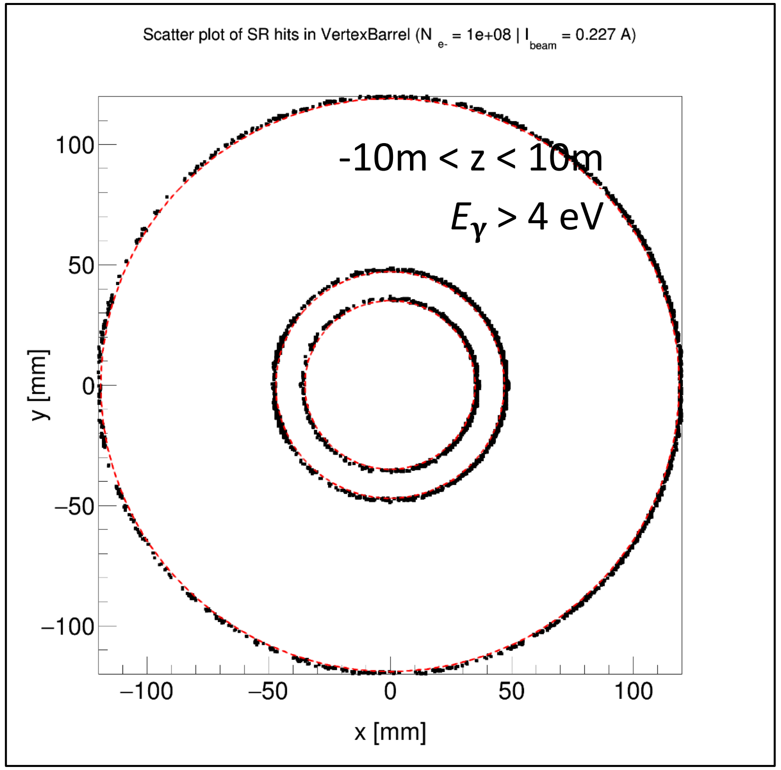
Adjusted beam pipe geometry



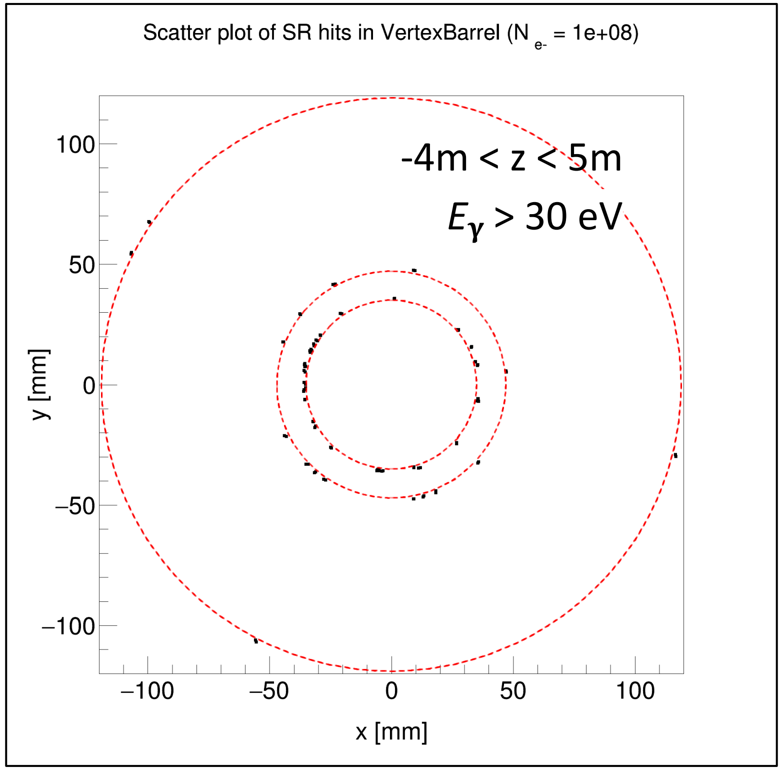


ePIC SR background: Vertex Barrel detector hits

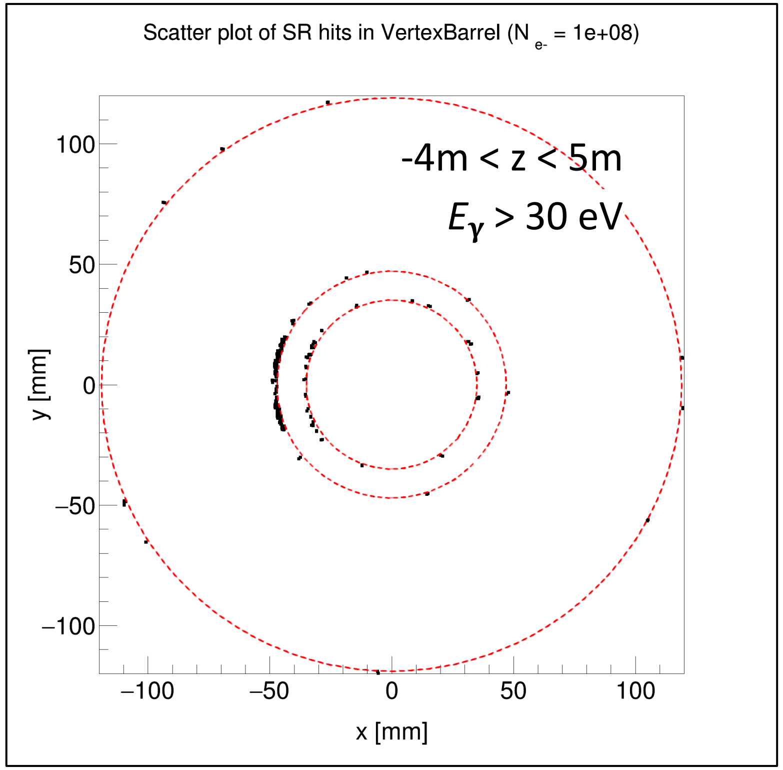
First custom-built Geant4 SR model
(contained bugs)
From Dec. 2023 meeting



Custom-built Geant4
(like the old Synrad+ model)



Custom-built Geant4
(like the new Synrad+ model)



Optimistic model

From Dec. 2023 meeting

Beam tail model

Transverse Beam Tails and Beam Lifetime in the EIC Electron Storage Ring

Christoph Montag

July 1, 2021

Abstract

For most storage ring design purposes it is sufficient to assume a Gaussian distribution of the electrons in a bunch. However, a more detailed knowledge of the population in the transverse tails beyond a few sigma is necessary to predict the beam lifetime and the synchrotron radiation load in the interaction region due to beam-gas scattering and the beam-beam interaction. This report presents simulations to determine the required vacuum level as well as to serve as input data for detailed synchrotron radiation simulations.

5 Fitting the Distribution

To serve as input data for synchrotron radiation simulation codes, the resulting distribution was fitted to an analytical expression. As Figure 4 shows, the non-Gaussian tail distribution is very well described as

$$\rho_{\mathrm{tail}}(r) = K_r \cdot r^{-3}, \quad (3)$$

with $r = x$ or $r = y$. The entire distribution therefore consists of a Gaussian core and a non-Gaussian tail,

$$\rho_{\mathrm{total}}(r) = \rho_{\mathrm{core}}(r) + \rho_{\mathrm{tail}}(r) \quad (4)$$

$$= \exp\left(-\frac{r^2}{2\sigma_r^2}\right) + K_r \cdot r^{-3}. \quad (5)$$

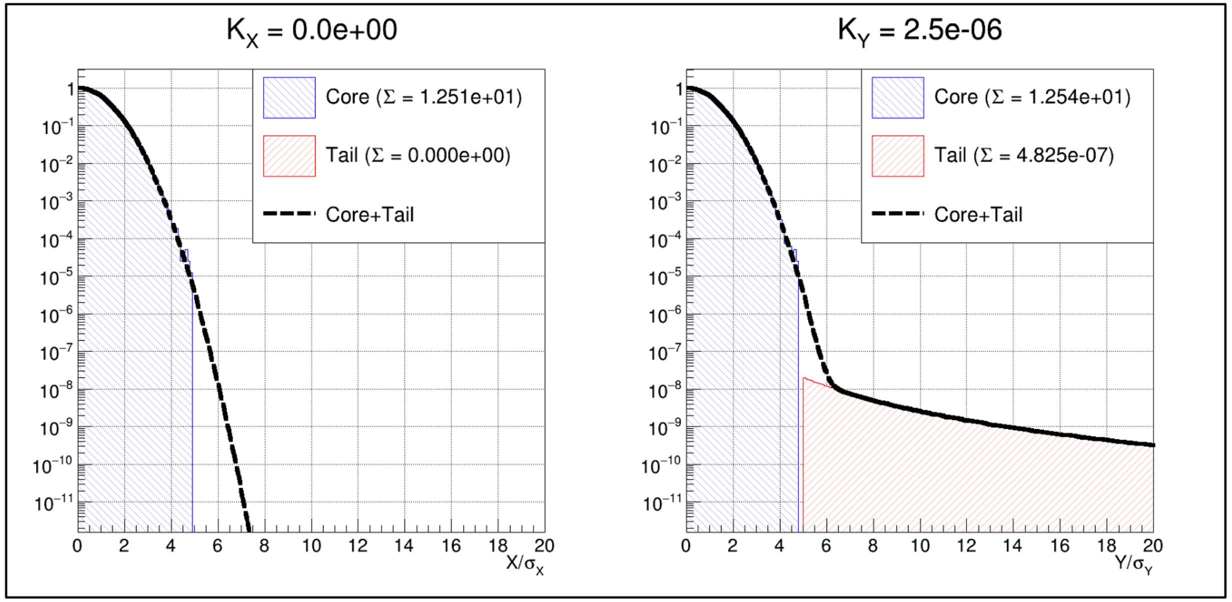
Note that the total number of electrons in the bunch is irrelevant for our purposes, and for simplicity the normalization of the Gaussian distribution is defined such that $\rho_{\mathrm{core}}(0) = 1$.

Table 4 lists the fit parameters K_x and K_y for the tail distributions for different beam energies and vacuum pressures.

Table 4: Fit parameters for different beam energies and vacuum pressures

E [GeV]	P [ntorr]	K_x $[10^{-7}]$	K_y $[10^{-7}]$
5	5	190	3125
5	10	380	6250
10	1.25	6.25	110
10	2.5	12.5	220
10	5	25	450
10	10	50	900
18	10	0	25

18 GeV electron beam | P = 10 nTorr



$$\rho_{\mathrm{total}}(r) = \rho_{\mathrm{core}} + \rho_{\mathrm{tail}} = exp\left(-\frac{r^2}{2\sigma_{\mathrm{r}}^2}\right) + K_{\mathrm{r}} \cdot r^{-3}$$

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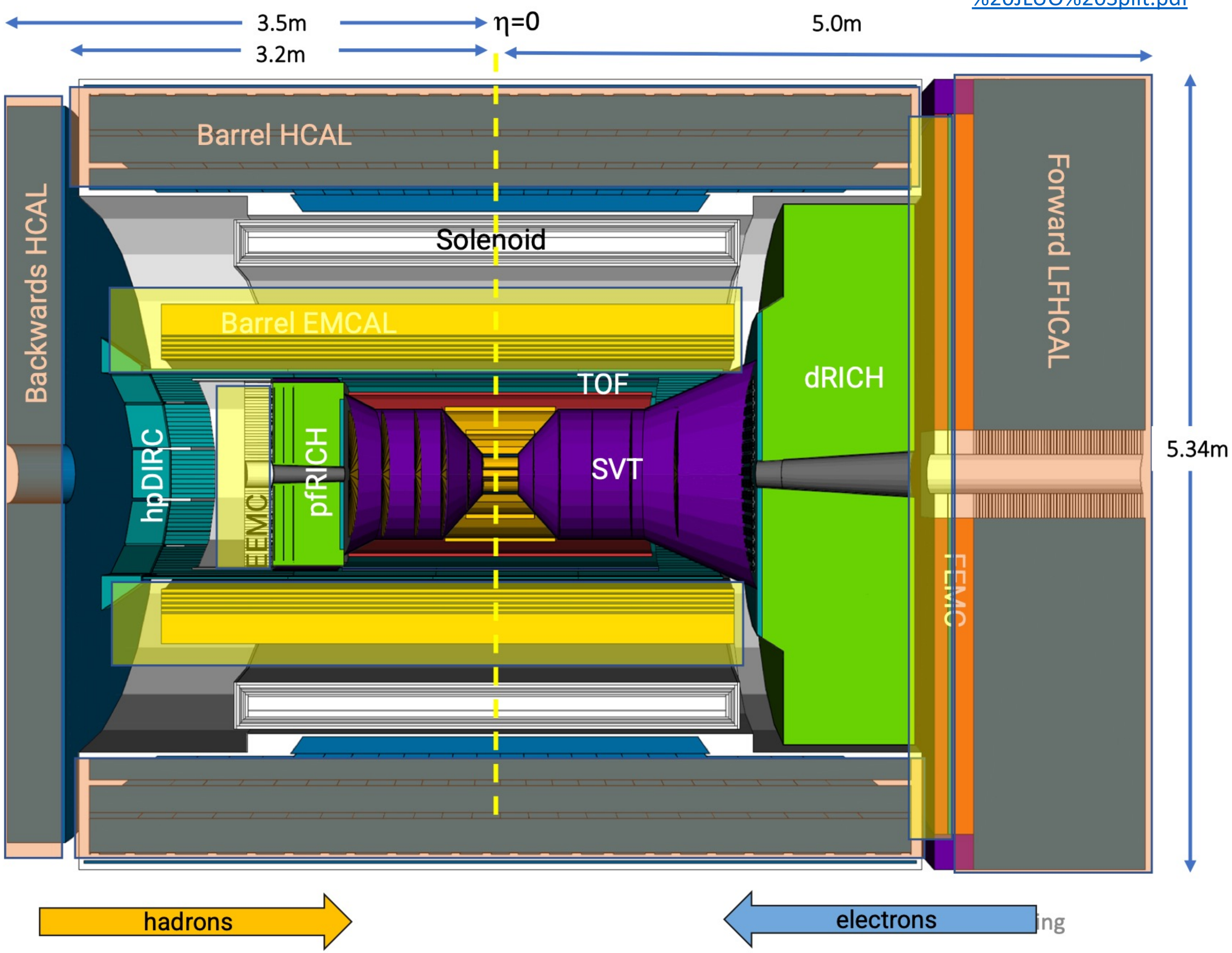
- No tails in the horizontal plane
- The vertical beam tail integral is about 10^{-8} of the beam core

ePIC Detector Design

https://indico.jlab.org/event/714/contributions/12568/attachments/9944/14673/The%20ePIC%20Experiment%20-%20JLUO%20Split.pdf



Tracking:

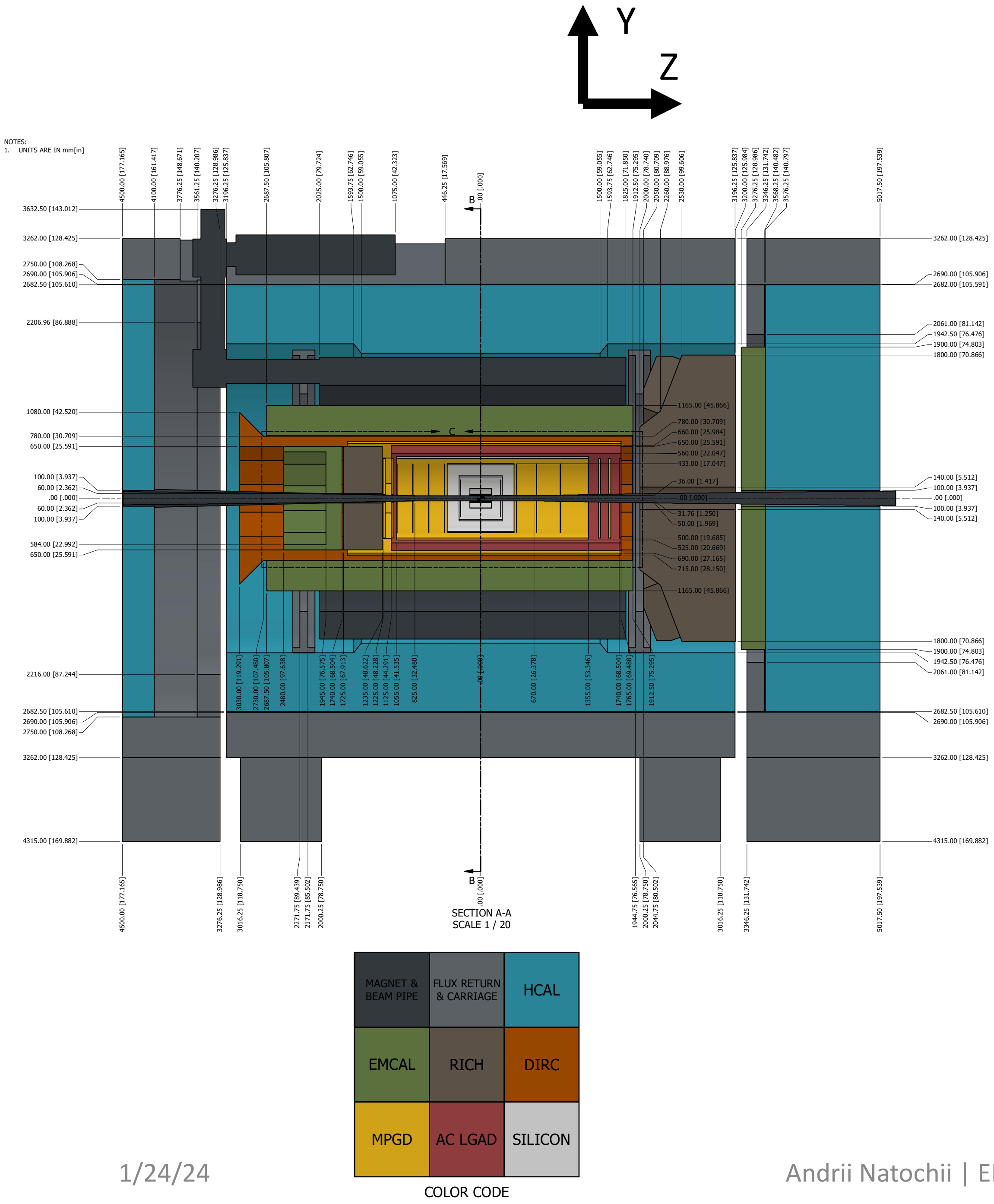
- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

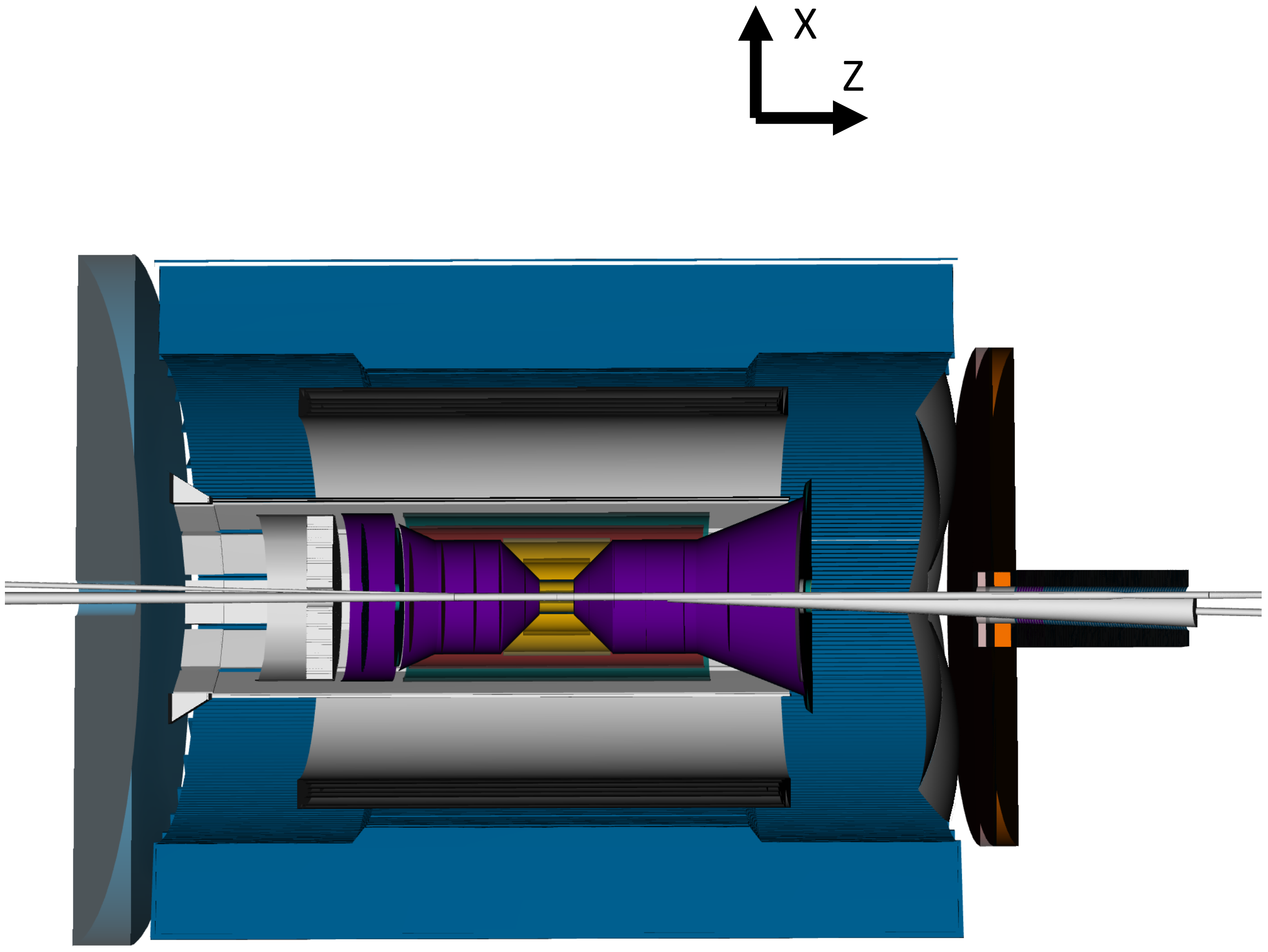
PID:

- hpDIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:

- Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)





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