Synchrotron radiation (SR) data production and analysis scheme

Vacuum calculation
output: pressure profile data

Calculate the gas pressure profile using `molflow+`

SR photon production
output: .csv file with photons

Event generation
output: .hepmc file with events

Detector simulation
output: .root file with hits

Reconstruction and analysis
output: .root file with ntuples

Produce "technical" single photons (vertexes, momentums, and rate) using `synrad+`

Read `synrad+` output files and prepare events that contain SR photons within the integrated time window (e.g., 100 ns) using photons' weights (rates)

Run `ddsim` (actually `npsim`) using the input .hepmc file with generated SR photon events and the default ePIC detector geometry

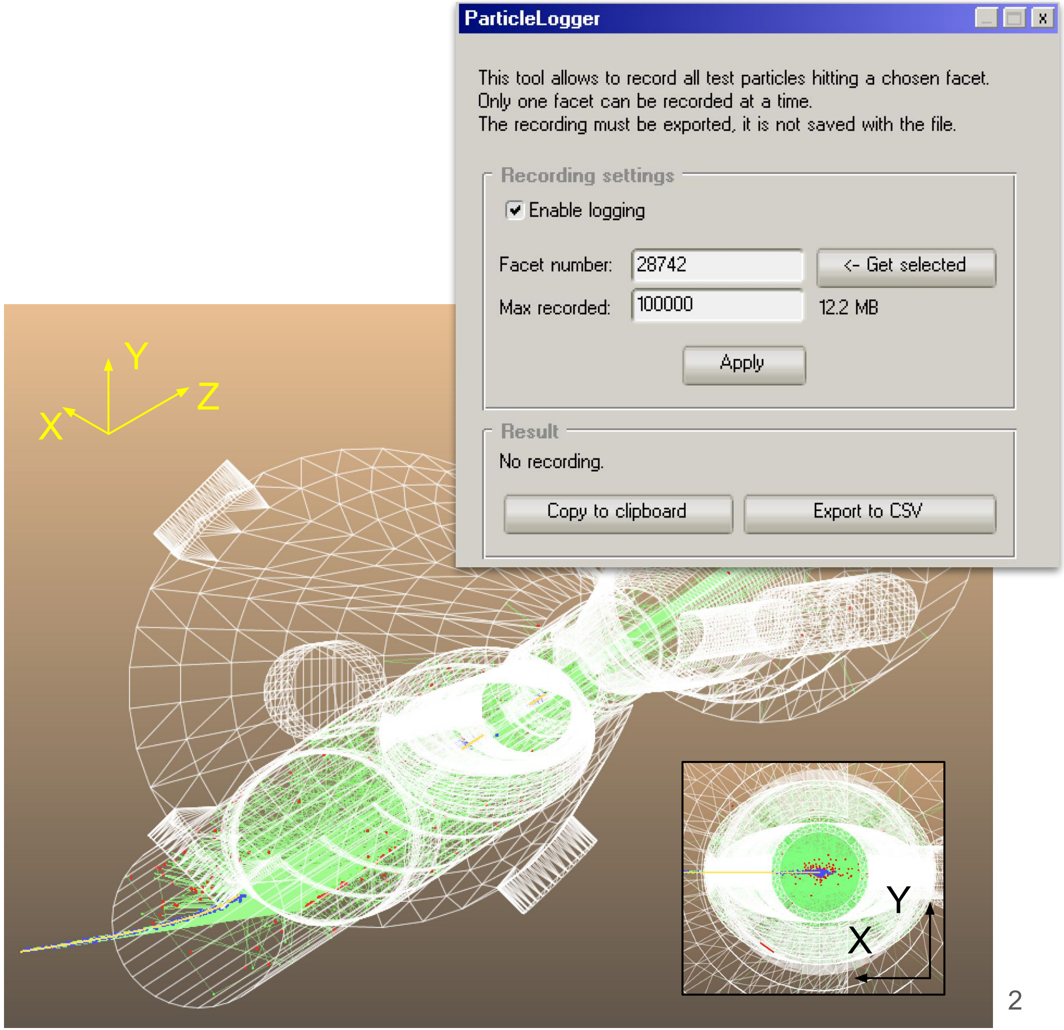
Create a dedicated `eicrecon` plugin to store ntuples and histograms with the detector hit information

Plot the final figures

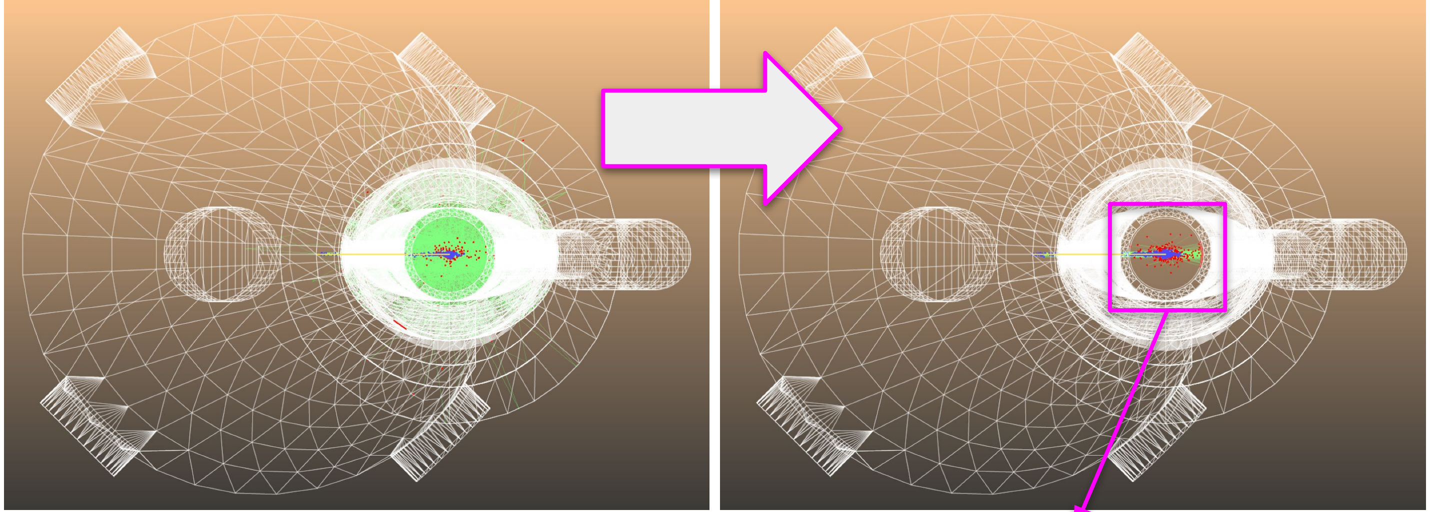
Let's focus on this step

Synrad+ GUI limitation

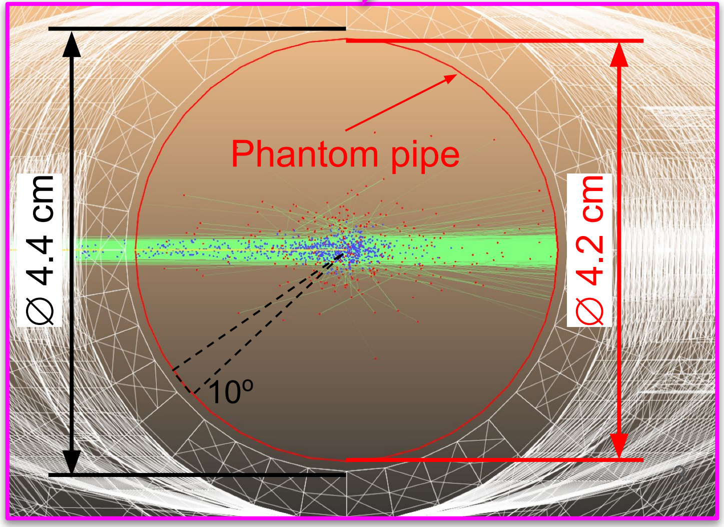
- The geometry (beam pipe) is made of an assembly of **~29k facets** (triangles and rectangles) imported from 3D CAD
- Unfortunately, the GUI allows to store the information about the photons hitting the beam pipe only for one facet at a time
- Although, only up to 1k facets are hit by photons, it is extremely time consuming procedure to store this information for each of them (to type facet's ID, run simulation, export data to csv)



Possible solution



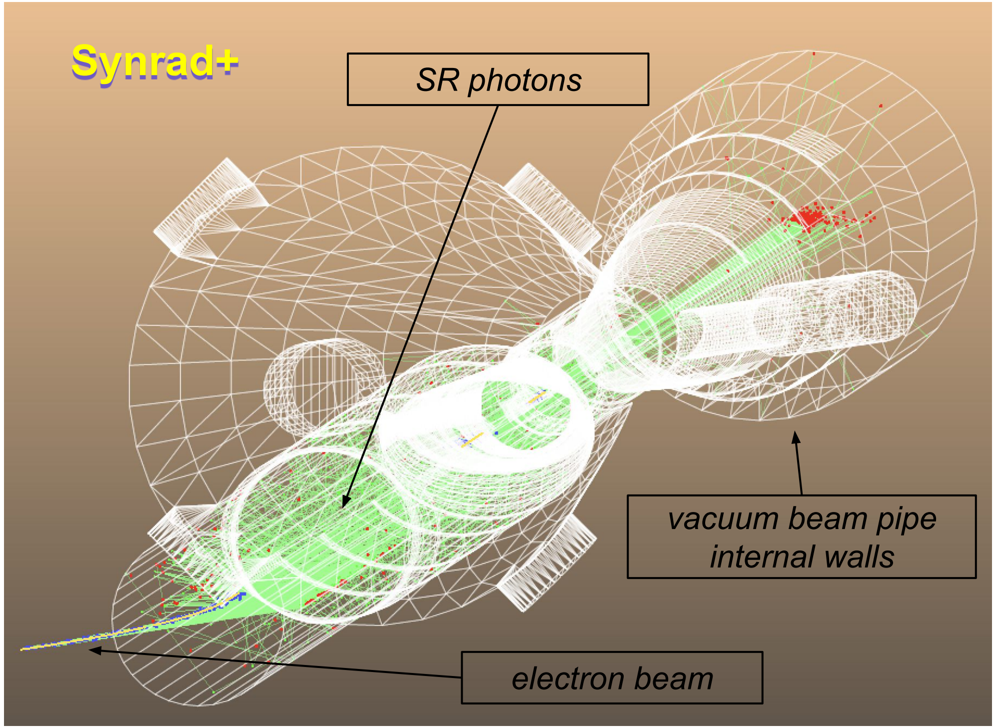
Instead of collecting photon data from **~1k facets**, we can create a phantom beam pipe with a simple geometry inside the real pipe and collect the data. The phantom pipe is an ideal absorber.



- **Pros**
  - Only **36 facets** → easy to store the data (~40min)
- **Cons**
  - Detailed information about scattered photons is lost
- **Proposal**
  - `Synrad+` → `Geant4` transition for the SR simulation

Steps to be done

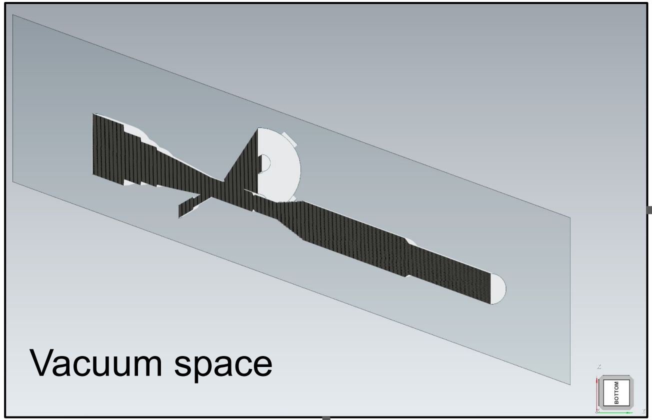
1. Convert vacuum beam pipe structure into the Geant4 model
2. Create magnetic regions
   a. 3 dipoles + 2 quadrupoles
3. Implement SR photon reflection from the vacuum-metal interface
4. Collect absorbed photon hits

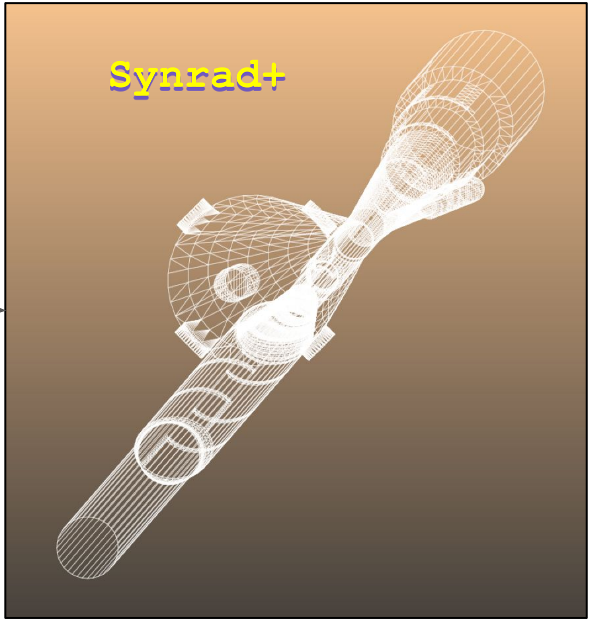


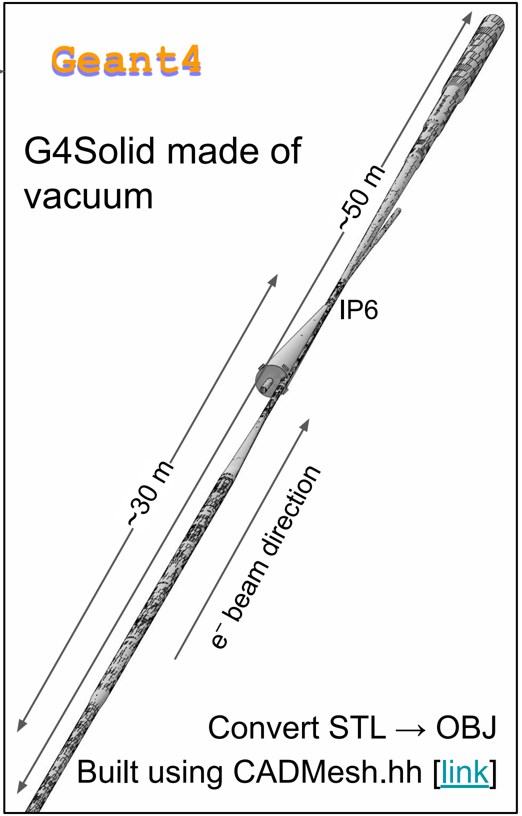
Vacuum modelling in Geant4

From Charlie:

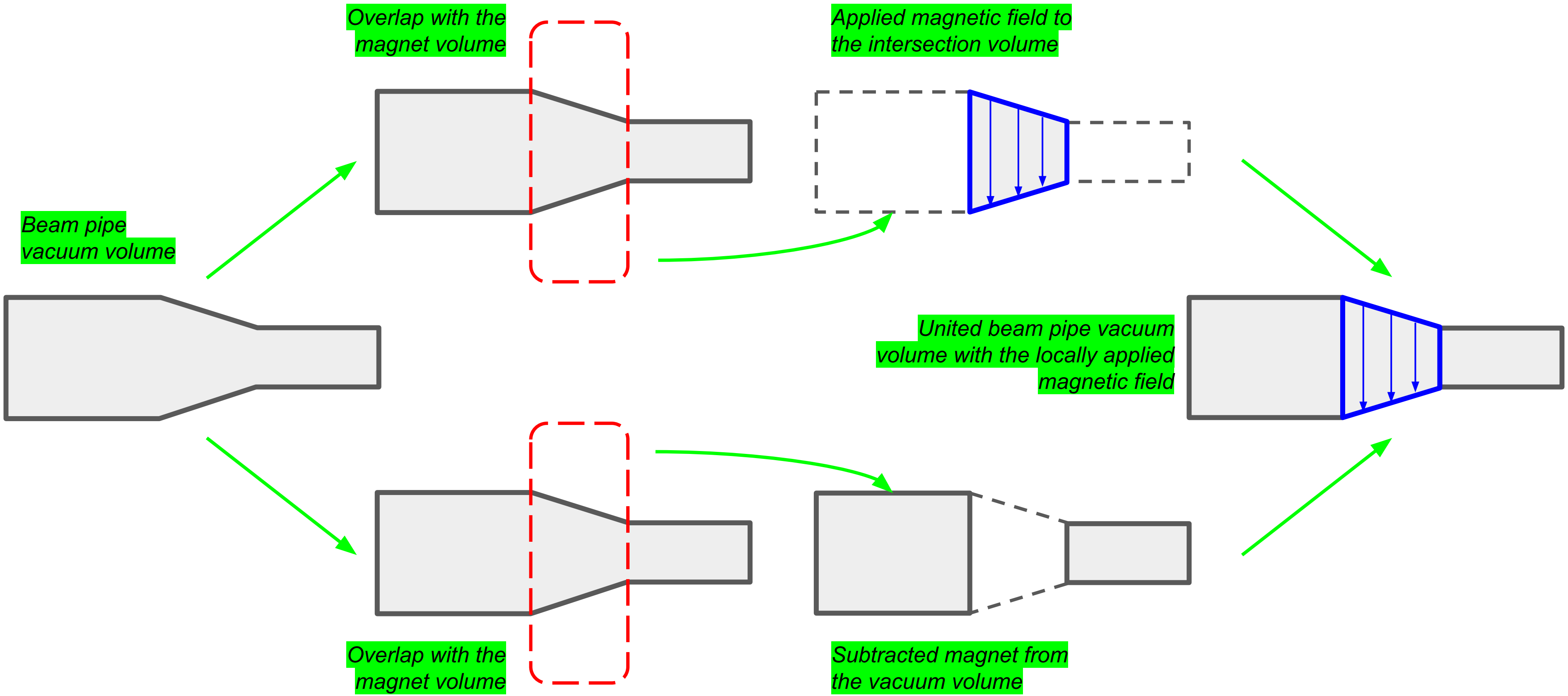
"Detector chamber 211004 mm.stl"







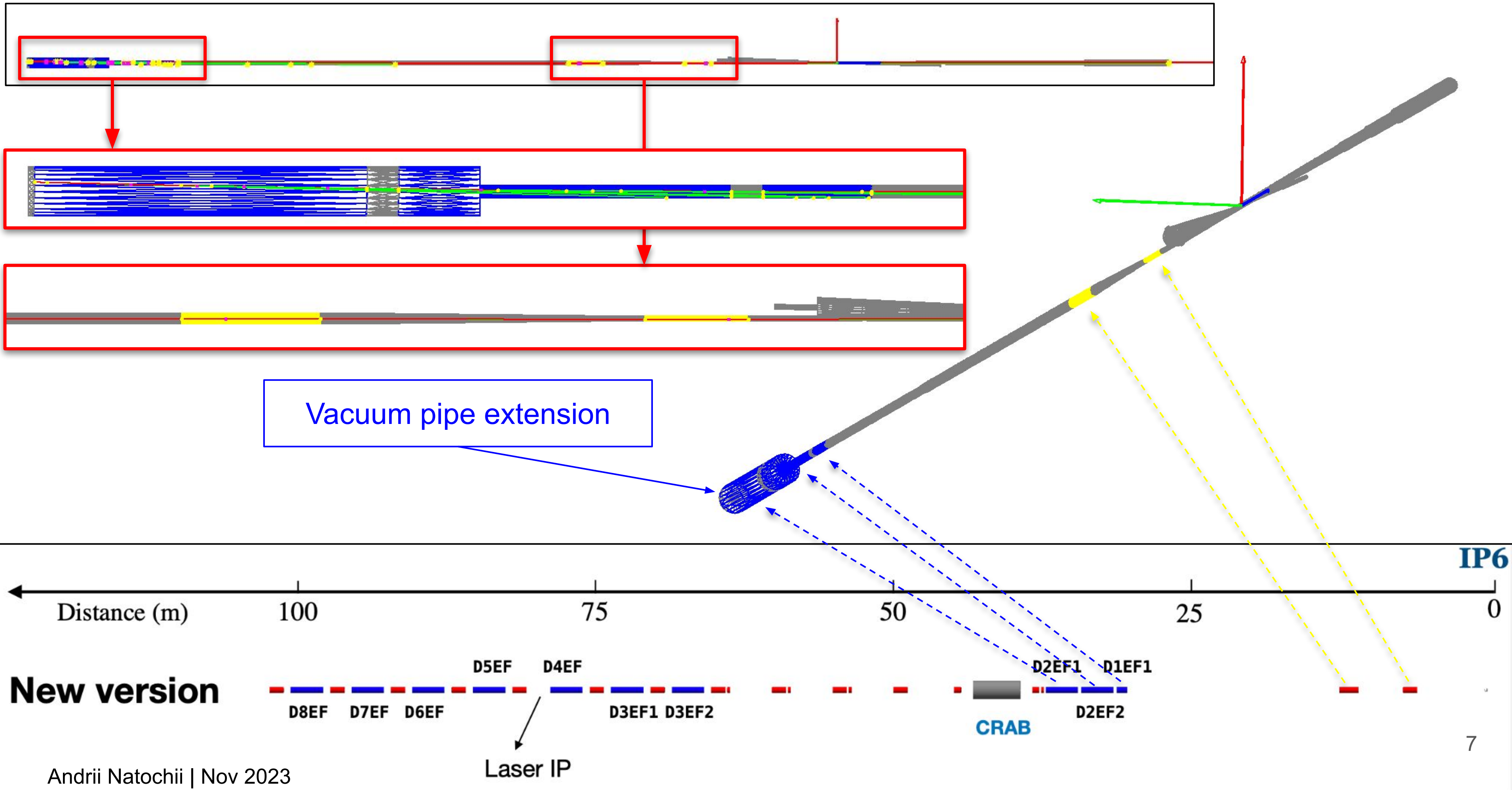
Magnetic field implementation



- In Geant4, the EM-field can be associated only with a logical volume (describes the element properties)
  → Assign the magnetic field to a part of the vacuum (locally)

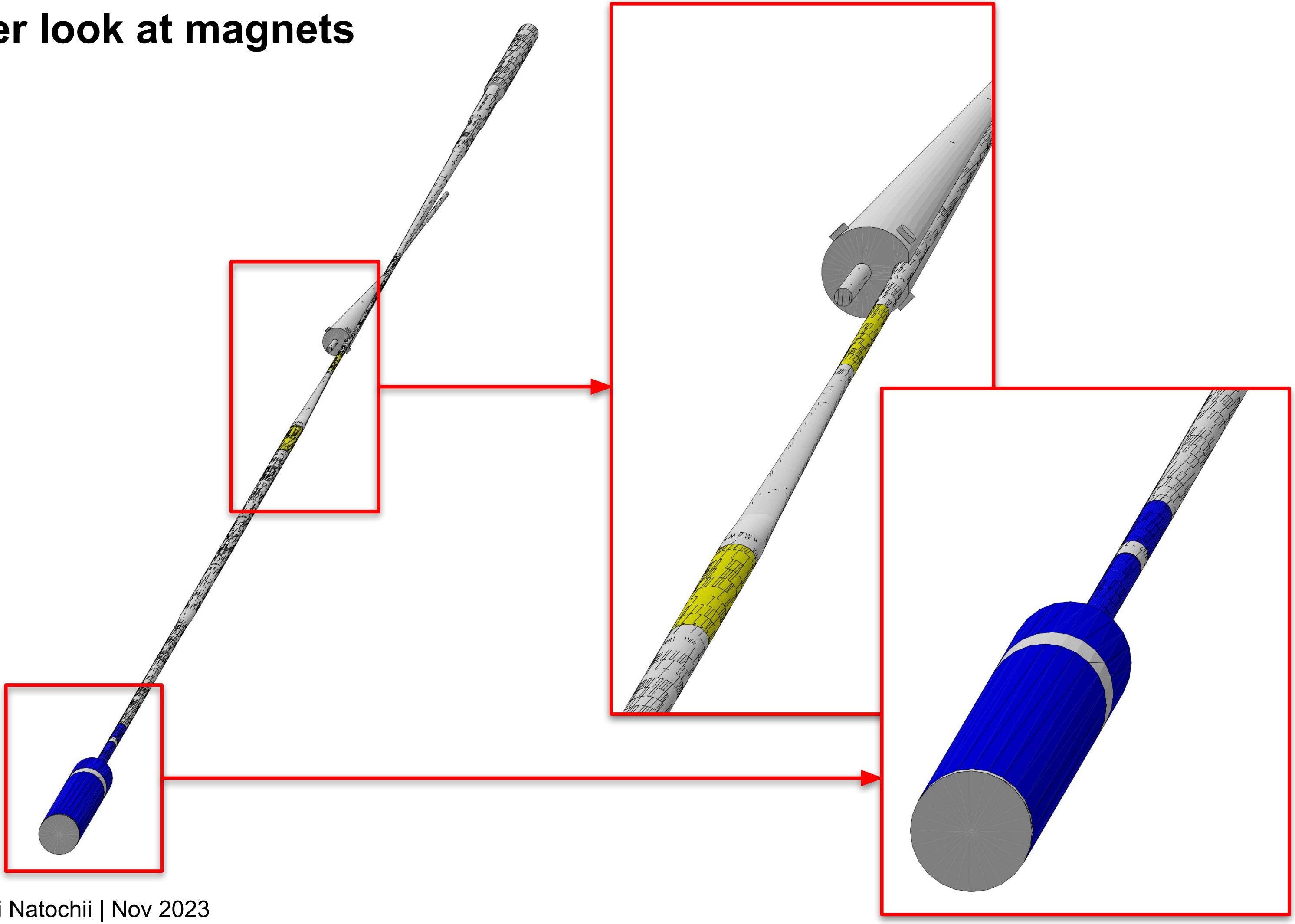
Magnetic field implementation (2)

Geant4



Closer look at magnets

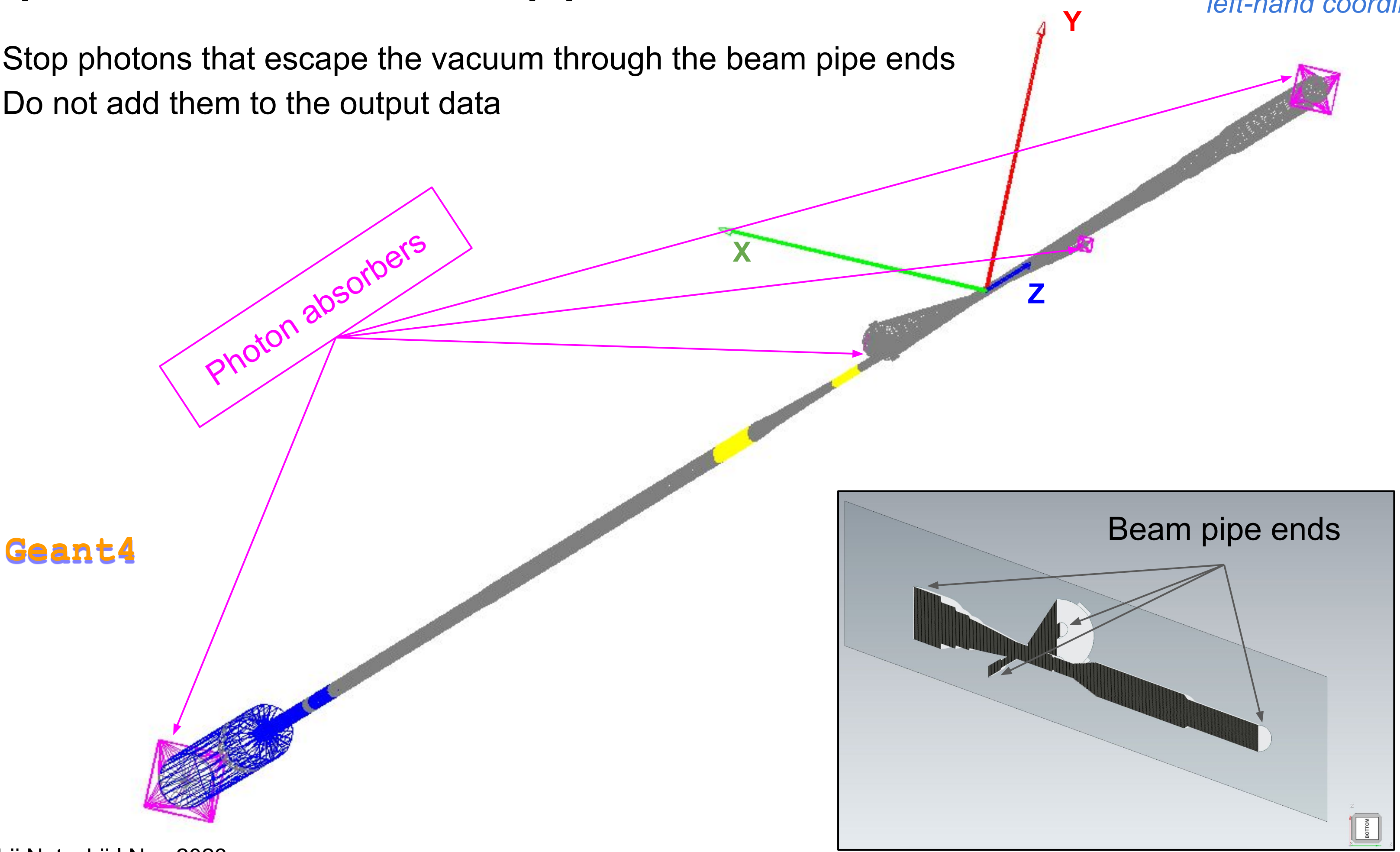
Geant4



Stop photons at the end of the pipe

The geometry is visualized in the left-hand coordinate system

- Stop photons that escape the vacuum through the beam pipe ends
- Do not add them to the output data



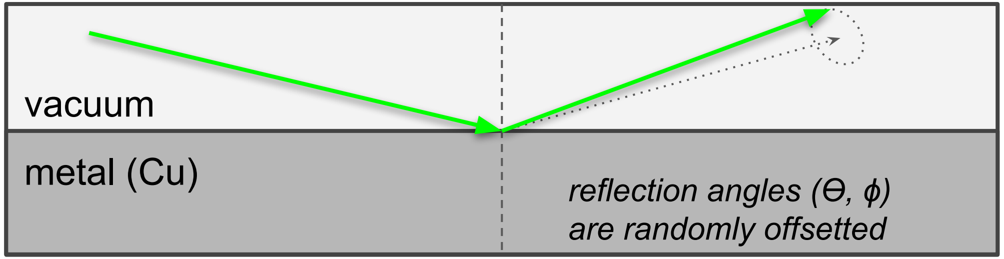
SR scattering process

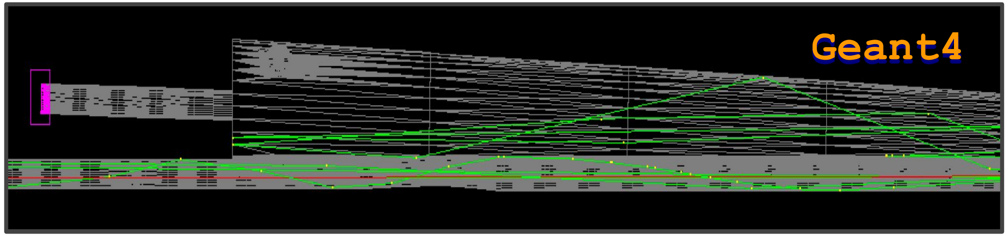
- SR scattering process is not implemented in Geant4
  - It is available only for optical photons

Task:

Create “new physics” for SR gamma rays

- Fresnel formulas for reflection probability
  - Use an extended CSV table from `Synrad+`
- Specular reflection (mirror-like) including surface roughness [link]





EXPLANATION OF TABLES continued

TABLE III. Specular Reflectivity for Mirrors: Be, C, Al, Al_2O_3, SiO_2, Ni, Cu, Mo, Pt, and Au

Line, E — As in Table I

θ — Grazing incidence angle in milliradians

$P(\%)$ — $100 \times I(\theta)/I_0$, the reflection intensity ratio calculated by Eqs. (54), (55), (56), and (57) for *unpolarized* incident radiation; this quantity is listed below each θ and plotted vs photon energy

https://doi.org/10.1006/adnd.1993.1013

TABLE III. Specular Reflectivity for Mirrors

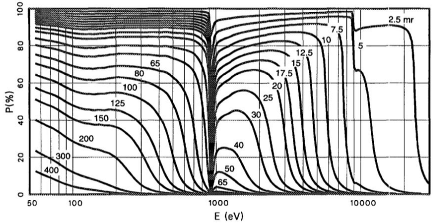
See page 211 for Explanation of Tables

Copper (Cu)

$\rho = 8.96$ gm/cm^3

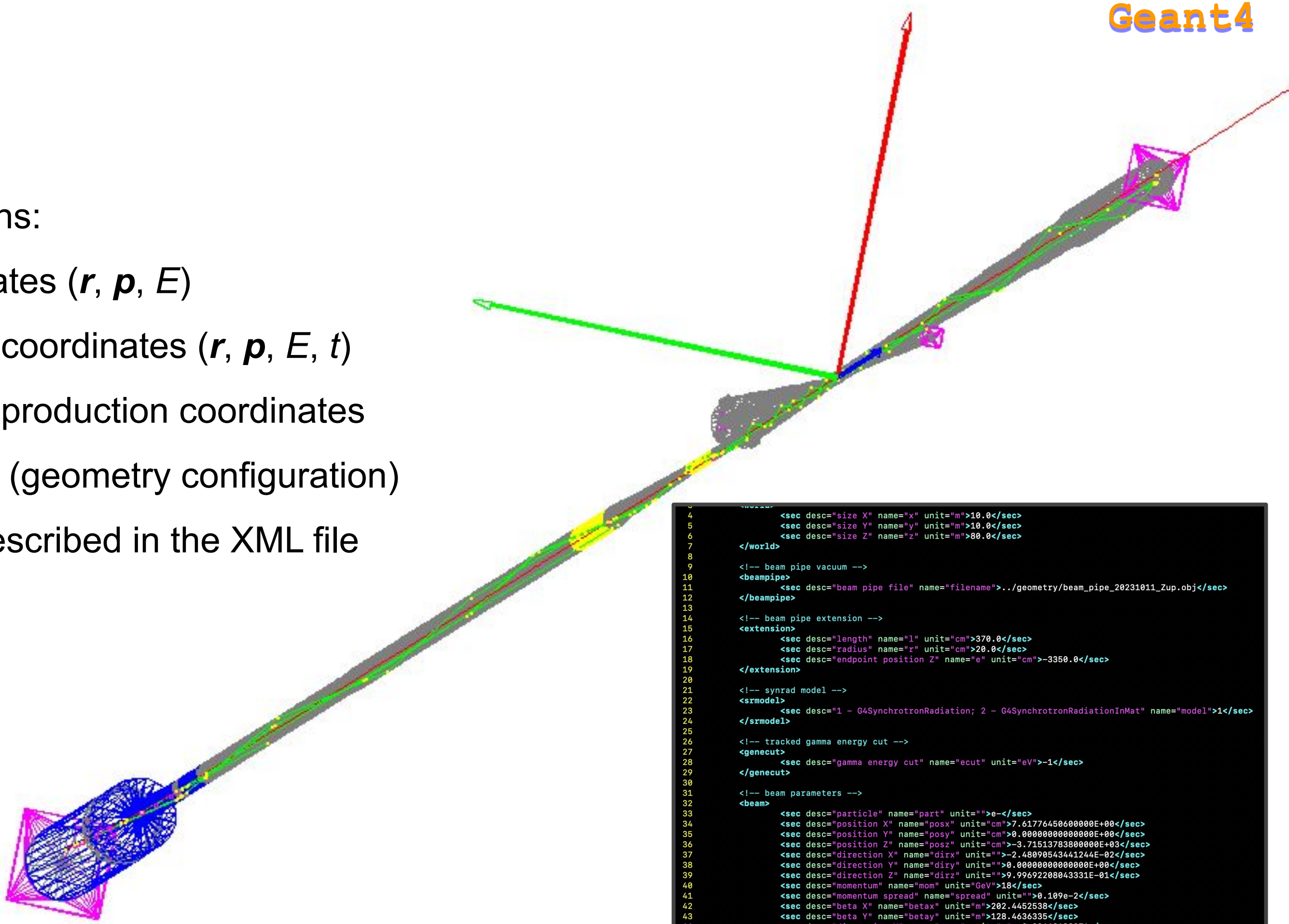
Grazing Incidence Angle, θ (milliradians)

Line		E(eV)	5 mr	10 mr	15 mr	20 mr	30 mr	50 mr	80 mr	125 mr	200 mr	400 mr
Al	$L_{2,3}$	72.4	97.6	95.3	93.0	90.8	86.5	78.5	67.7	53.9	35.7	8.51
Si	$L_{2,3}$	91.5	97.3	94.7	92.2	89.7	85.0	76.2	64.5	49.6	30.5	5.23
Be	K	108.5	97.2	94.4	91.7	89.1	84.1	74.8	62.5	47.0	27.3	3.74
Zr	Mζ	151.1	97.1	94.3	91.6	89.0	83.9	74.4	61.8	45.6	24.0	1.96
B	Kα	183.3	97.2	94.6	91.9	89.4	84.5	75.2	62.6	45.7	21.7	1.13
C	Kα	277.0	97.3	94.8	92.2	89.7	84.9	75.6	61.9	40.3	7.49	.226
N	Kα	392.4	97.4	94.8	92.2	89.7	84.8	74.7	57.8	20.0	1.38	5.40E-2
Ti	Lα	452.2	97.4	94.9	92.4	89.9	84.9	74.5	54.5	9.01	.696	2.98E-2
O	Kα	524.9	97.3	94.7	92.2	89.6	84.4	72.8	45.3	3.58	.341	1.56E-2
Cr	Lα	572.8	97.3	94.7	92.1	89.5	84.1	71.6	35.2	2.16	.226	1.07E-2
F	Kα	676.8	97.3	94.6	91.9	89.2	83.3	67.7	10.4	.837	9.92E-2	4.91E-3
Co	Lα	776.2	96.9	93.9	90.8	87.7	80.6	55.8	3.30	.359	4.59E-2	2.34E-3
Ni	Lα	851.5	96.3	92.6	88.8	84.7	75.2	25.9	1.34	.169	2.26E-2	1.18E-3
Cu	Lα	929.7	71.4	50.7	35.7	24.8	11.6	2.62	.452	7.64E-2	1.13E-2	6.18E-4
Zn	Lα	1011.7	87.0	75.5	65.0	55.4	38.1	11.9	1.50	.209	2.85E-2	1.49E-3
Mg	Kα	1253.6	89.8	80.3	71.2	62.3	44.0	9.37	.880	.121	1.66E-2	8.74E-4
Al	Kα	1486.7	91.2	82.9	74.5	65.8	44.9	4.80	.460	6.57E-2	9.16E-3	4.85E-4
Si	Kα	1740.0	92.1	84.3	76.1	66.9	39.1	2.19	.237	3.51E-2	4.97E-3	2.65E-4
Zr	Lα	2042.4	92.8	85.4	77.2	66.6	21.0	.996	.119	1.83E-2	2.61E-3	1.40E-4
Cl	Kα	2622.4	93.7	86.7	77.3	58.1	3.94	.310	4.11E-2	6.50E-3	9.42E-4	5.08E-5
Ag	Lα	2984.3	94.1	87.2	76.1	32.1	1.90	.173	2.38E-2	3.80E-3	5.53E-4	2.99E-5
Ca	Kα	3691.7	94.7	87.4	62.3	5.62	.648	6.82E-2	9.72E-3	1.57E-3	2.30E-4	1.25E-5
Ti	Kα	4510.8	95.1	86.4	9.99	1.73	.254	2.89E-2	4.21E-3	6.87E-4	1.01E-4	5.48E-6
V	Kα	4952.2	95.3	84.5	5.15	1.07	.167	1.94E-2	2.85E-3	4.67E-4	6.87E-5	3.73E-6
Cr	Kα	5414.7	95.5	78.9	2.98	.685	.112	1.33E-2	1.97E-3	3.23E-4	4.75E-5	2.58E-6
Mn	Kα	5898.8	95.6	37.2	1.84	.454	7.71E-2	9.28E-3	1.38E-3	2.26E-4	3.33E-5	1.81E-6
Co	Kα	6930.3	95.7	7.54	.794	.214	3.81E-2	4.68E-3	6.99E-4	1.15E-4	1.70E-5	9.23E-7
Ni	Kα	7478.2	95.7	4.44	.542	.150	2.72E-2	3.37E-3	5.05E-4	8.32E-5	1.23E-5	6.68E-7
Cu	Kα	8047.8	95.5	2.76	.374	.106	1.95E-2	2.43E-3	3.64E-4	6.01E-5	8.87E-6	4.83E-7
Ge	Kα	9886.4	66.5	1.01	.160	4.72E-2	8.87E-3	1.12E-3	1.69E-4	2.79E-5	4.12E-6	2.24E-7
Y	Kα	14988.0	5.35	.171	3.09E-2	9.47E-3	1.83E-3	2.34E-4	3.54E-5	5.85E-6	8.65E-7	4.71E-8
Mo	Kα	17479.0	2.20	8.90E-2	1.64E-2	5.09E-3	9.88E-4	1.27E-4	1.92E-5	3.18E-6	4.70E-7	2.55E-8
Pd	Kα	21177.0	.833	3.97E-2	7.51E-3	2.34E-3	4.57E-4	5.87E-5	8.90E-6	1.47E-6	2.18E-7	1.19E-8
Sn	Kα	25271.0	.365	1.91E-2	3.65E-3	1.14E-3	2.24E-4	2.88E-5	4.37E-6	7.24E-7	1.07E-7	5.86E-9
Xe	Kα	29779.0	.176	9.70E-3	1.87E-3	5.88E-4	1.16E-4	1.49E-5	2.26E-6	3.74E-7	5.53E-8	3.00E-9



Inputs and outputs

- The output ROOT file contains:
  - Initial electron coordinates (***r***, ***p***, *E*)
  - Absorbed SR photons coordinates (***r***, ***p***, *E*, *t*)
  - Absorbed SR photons production coordinates
  - Simulation parameters (geometry configuration)
- Geometry configuration is described in the XML file
  - Magnet settings
  - Beam parameters
  - Absorbers

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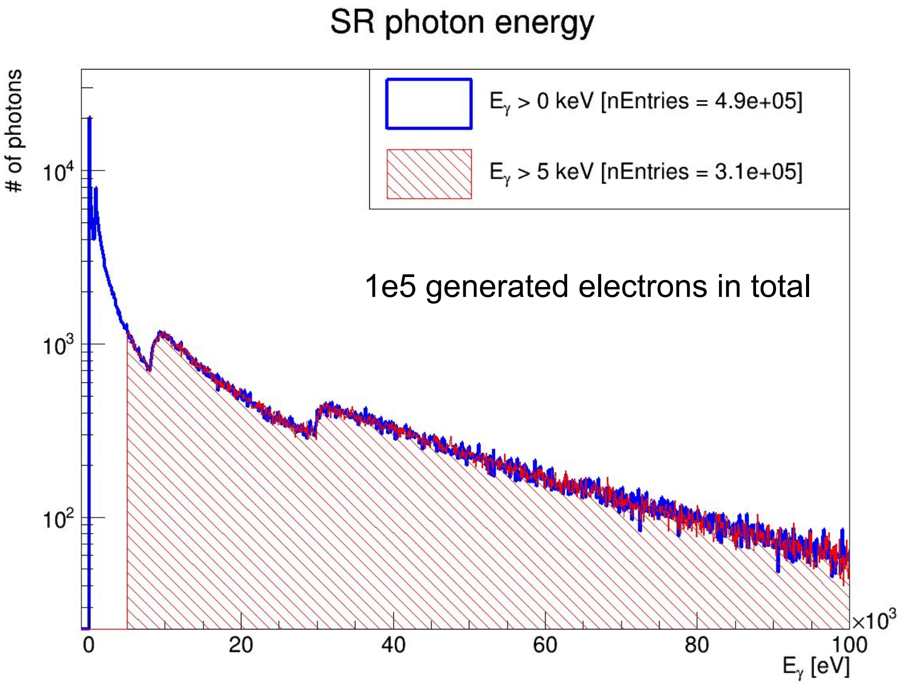
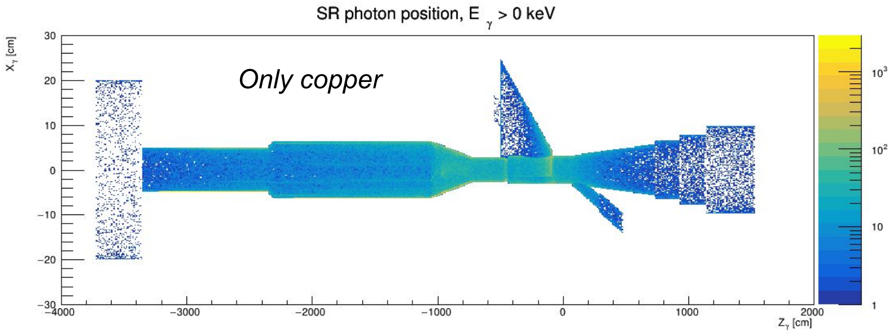
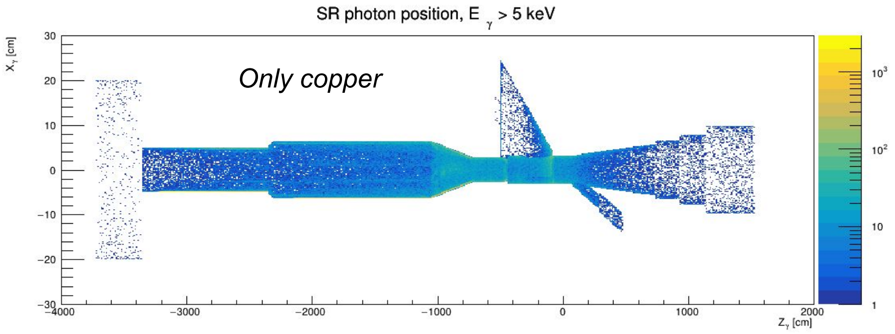
```

SR simulation results

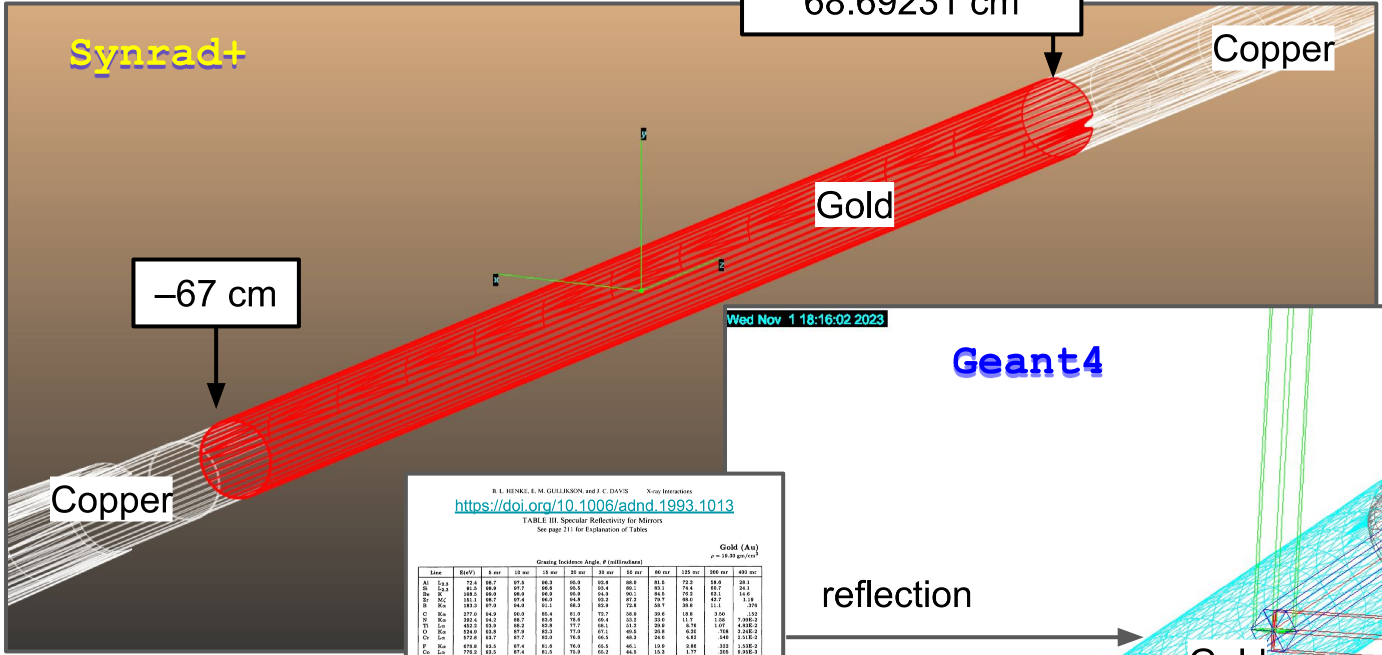
Applying the E_γ cut at 5 keV speeds up the simulation by a factor of 3
Photon tracking is time-consuming

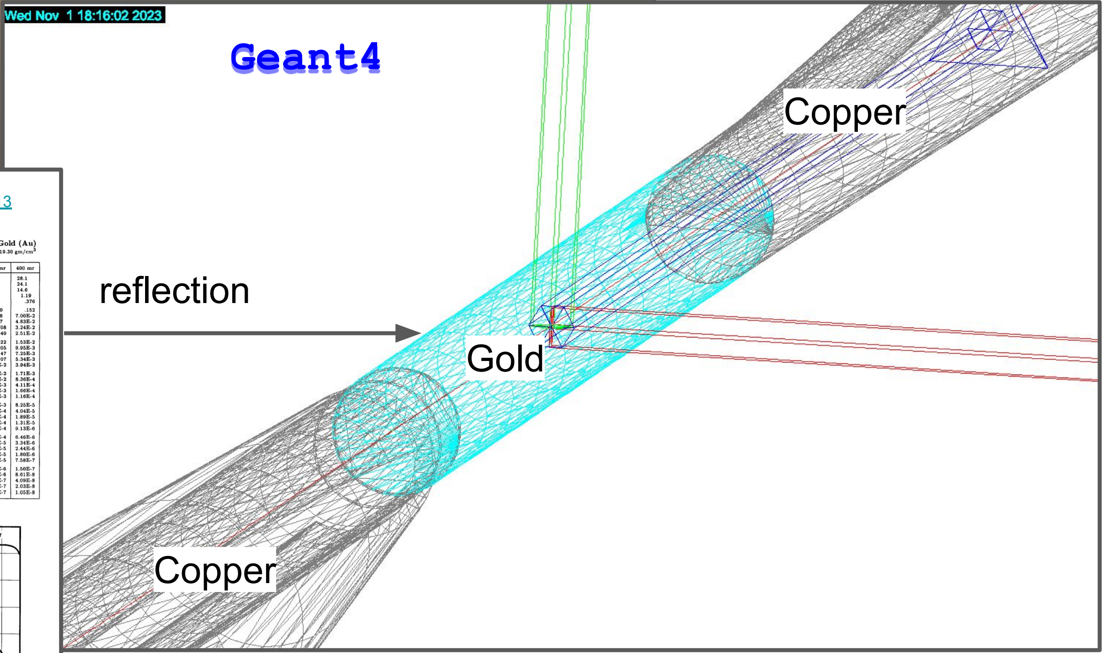






IP beam pipe





B. L. HENKE, E. M. GULLIKSON, and J. C. DAVIS X-ray Interactions

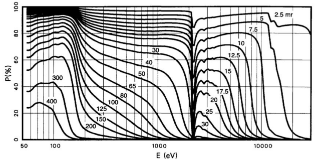
https://doi.org/10.1006/adnd.1993.1013

TABLE III. Specular Reflectivity for Mirrors
See page 211 for Explanation of Tables

Gold (Au)
$\rho = 19.30\ gm/cm^3$

Grazing Incidence Angle, θ (milliradians)

Line		E(eV)	5 mr	10 mr	15 mr	20 mr	30 mr	50 mr	80 mr	125 mr	200 mr	400 mr
Al	$L_{2,3}$	72.4	98.7	97.5	96.3	95.0	92.6	88.0	81.5	72.3	58.6	28.1
Si	$L_{2,3}$	91.5	98.9	97.7	96.6	95.5	93.4	89.1	83.1	74.4	60.7	24.1
Be	K	108.5	99.0	98.0	96.9	95.9	94.0	90.1	84.5	76.2	62.1	14.6
Zr	$M\zeta$	151.1	98.7	97.4	96.0	94.8	92.2	87.2	79.7	68.0	42.7	1.19
B	$K\alpha$	183.3	97.0	94.0	91.1	88.3	82.9	72.8	58.7	38.8	11.1	.376
C	$K\alpha$	277.0	94.9	90.0	85.4	81.0	72.7	58.0	39.6	18.8	3.50	.152
N	$K\alpha$	392.4	94.2	88.7	83.6	78.6	69.4	53.2	33.0	11.7	1.58	7.00E-2
Ti	$L\alpha$	452.2	93.9	88.2	82.8	77.7	68.1	51.2	29.9	8.76	1.07	4.83E-2
O	$K\alpha$	524.9	93.8	87.9	82.3	77.0	67.1	49.5	26.8	6.20	.708	3.24E-2
Cr	$L\alpha$	572.8	93.7	87.7	82.0	76.6	66.5	48.3	24.6	4.82	.540	2.51E-2
F	$K\alpha$	676.8	93.5	87.4	81.6	76.0	65.5	46.1	19.9	2.86	.322	1.53E-2
Co	$L\alpha$	776.2	93.5	87.4	81.5	75.9	65.2	44.5	15.3	1.77	.205	9.95E-3
Ni	$L\alpha$	851.5	93.5	87.4	81.5	75.8	64.9	43.0	11.7	1.24	.147	7.25E-3
Cu	$L\alpha$	929.7	93.5	87.4	81.5	75.8	64.5	41.1	8.47	.880	.107	5.34E-3
Zn	$L\alpha$	1011.7	93.6	87.5	81.6	75.8	64.3	39.0	5.91	.628	7.82E-2	3.94E-3
Mg	$K\alpha$	1253.6	93.8	87.8	81.9	76.0	63.3	27.7	2.06	.251	3.31E-2	1.71E-3
Al	$K\alpha$	1486.7	93.7	87.7	81.5	75.2	60.1	11.6	.869	.117	1.59E-2	8.36E-4
Si	$K\alpha$	1740.0	93.5	87.1	80.5	73.2	53.0	4.03	.386	5.55E-2	7.75E-3	4.11E-4
Zr	$L\alpha$	2042.4	92.3	84.7	76.3	65.9	26.3	1.22	.143	2.17E-2	3.10E-3	1.66E-4
Cl	$K\alpha$	2622.4	82.9	67.4	52.3	36.7	9.46	.753	9.60E-2	1.49E-2	2.15E-3	1.16E-4
Ag	$L\alpha$	2984.3	83.6	68.3	52.7	35.1	6.56	.519	6.75E-2	1.06E-2	1.53E-3	8.25E-5
Ca	$K\alpha$	3691.7	84.9	69.8	51.8	26.3	2.68	.238	3.23E-2	5.15E-3	7.48E-4	4.04E-5
Ti	$K\alpha$	4510.8	86.4	71.1	46.5	10.2	1.05	.105	1.48E-2	2.39E-3	3.49E-4	1.89E-5
V	$K\alpha$	4952.2	86.9	71.1	38.5	5.74	.677	7.14E-2	1.02E-2	1.65E-3	2.41E-4	1.31E-5
Cr	$K\alpha$	5414.7	87.3	70.6	24.4	3.41	.449	4.91E-2	7.06E-3	1.15E-3	1.68E-4	9.13E-6
Mn	$K\alpha$	5898.8	87.7	69.5	12.8	2.13	.304	3.42E-2	4.97E-3	8.10E-4	1.19E-4	6.46E-6
Co	$K\alpha$	6930.3	88.2	62.9	4.29	.929	.148	1.74E-2	2.55E-3	4.18E-4	6.15E-5	3.34E-6
Ni	$K\alpha$	7478.2	88.4	53.0	2.74	.641	.106	1.26E-2	1.86E-3	3.05E-4	4.49E-5	2.44E-6
Cu	$K\alpha$	8047.8	88.5	30.7	1.82	.451	7.67E-2	9.24E-3	1.37E-3	2.25E-4	3.32E-5	1.80E-6
Ge	$K\alpha$	9886.4	88.3	5.38	.628	.172	3.10E-2	3.84E-3	5.74E-4	9.45E-5	1.39E-5	7.58E-7
Y	$K\alpha$	14988.0	44.7	.627	.104	3.11E-2	5.90E-3	7.49E-4	1.13E-4	1.87E-5	2.76E-6	1.50E-7
Mo	$K\alpha$	17479.0	15.9	.333	5.79E-2	1.76E-2	3.37E-3	4.29E-4	6.48E-5	1.07E-5	1.58E-6	8.61E-8
Pd	$K\alpha$	21177.0	4.28	.147	2.67E-2	8.21E-3	1.59E-3	2.03E-4	3.07E-5	5.09E-6	7.52E-7	4.09E-8
Sn	$K\alpha$	25271.0	1.62	6.96E-2	1.30E-2	4.02E-3	7.83E-4	1.01E-4	1.52E-5	2.52E-6	3.72E-7	2.03E-8
Xe	$K\alpha$	29779.0	.720	3.50E-2	6.63E-3	2.07E-3	4.04E-4	5.20E-5	7.87E-6	1.30E-6	1.93E-7	1.05E-8



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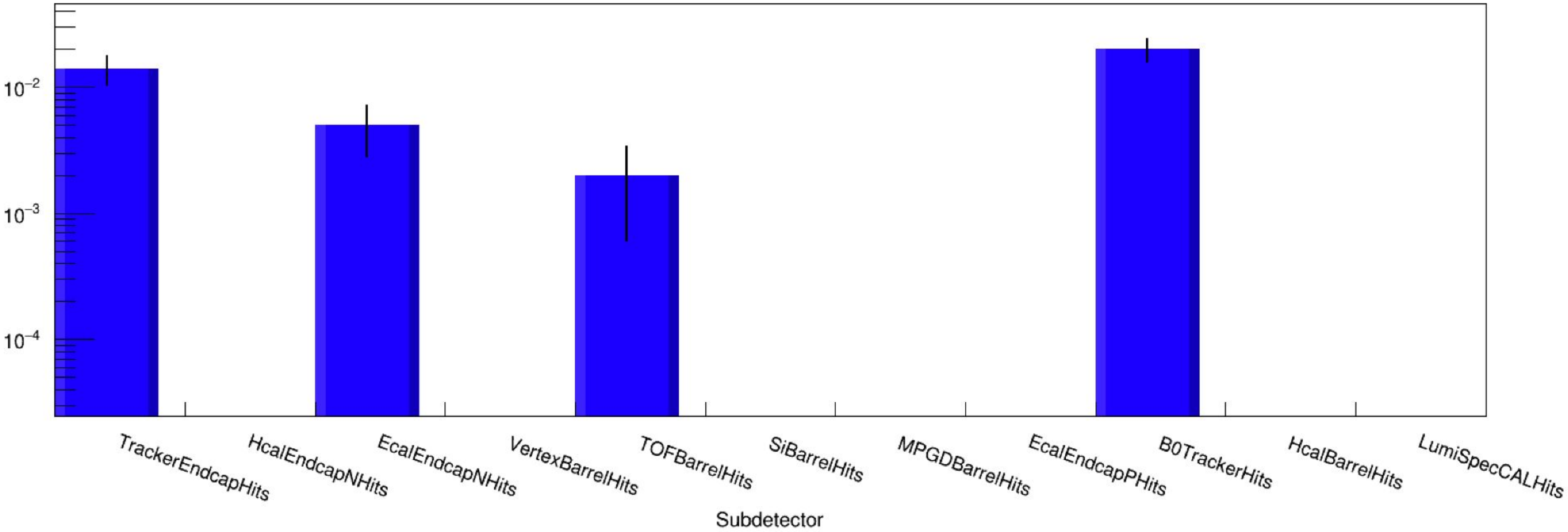
ePIC background (low statistics, for demonstration only)

ePIC hit rate [arb. Units] for only 1000 electrons without the energy cut



A dedicated `EICrecon` analysis plugin was created to analyse the `eic-shell` simulation data

Next

- Benchmark the `Geant4` SR simulation by comparing its results against
  - SR distribution in `Synrad+`
  - Beam pipe geometry in `eic-shell`
- Run the high-stat EIC background simulation using `eic-shell`
  - `EICrecon` analysis is the most time-consuming step (multithreading option is needed)
- Study the contribution of different magnets to ePIC BG rates
- Optimizing the simulation
  - Energy cut (e.g., E_γ > 5 keV or E_γ > 10 keV)
  - SR photon hits within a shorter range (e.g., ±4 m from the IP6)
- SR photon masking
  - Study a possible BG mitigation through the SR mask installation inside the vacuum