FLASH Radiotherapy with hIgh Dose-rate particle beAms

Radioprotection studies @SAFEST 24 MeV linac

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&
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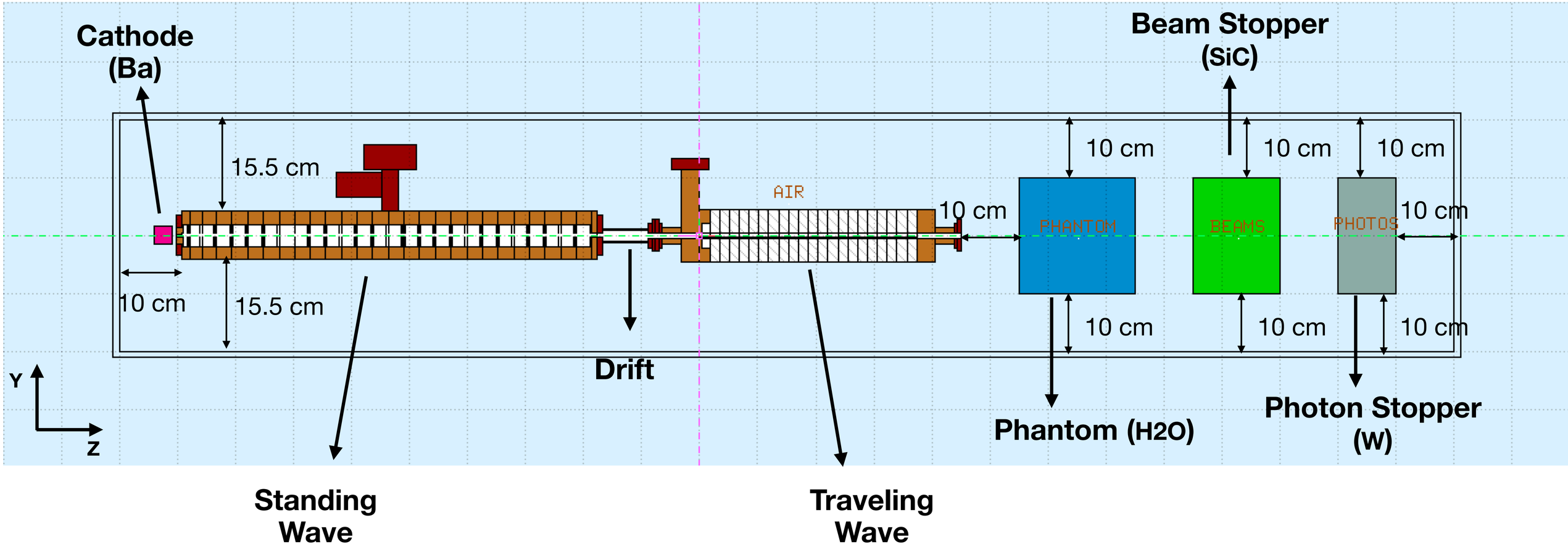
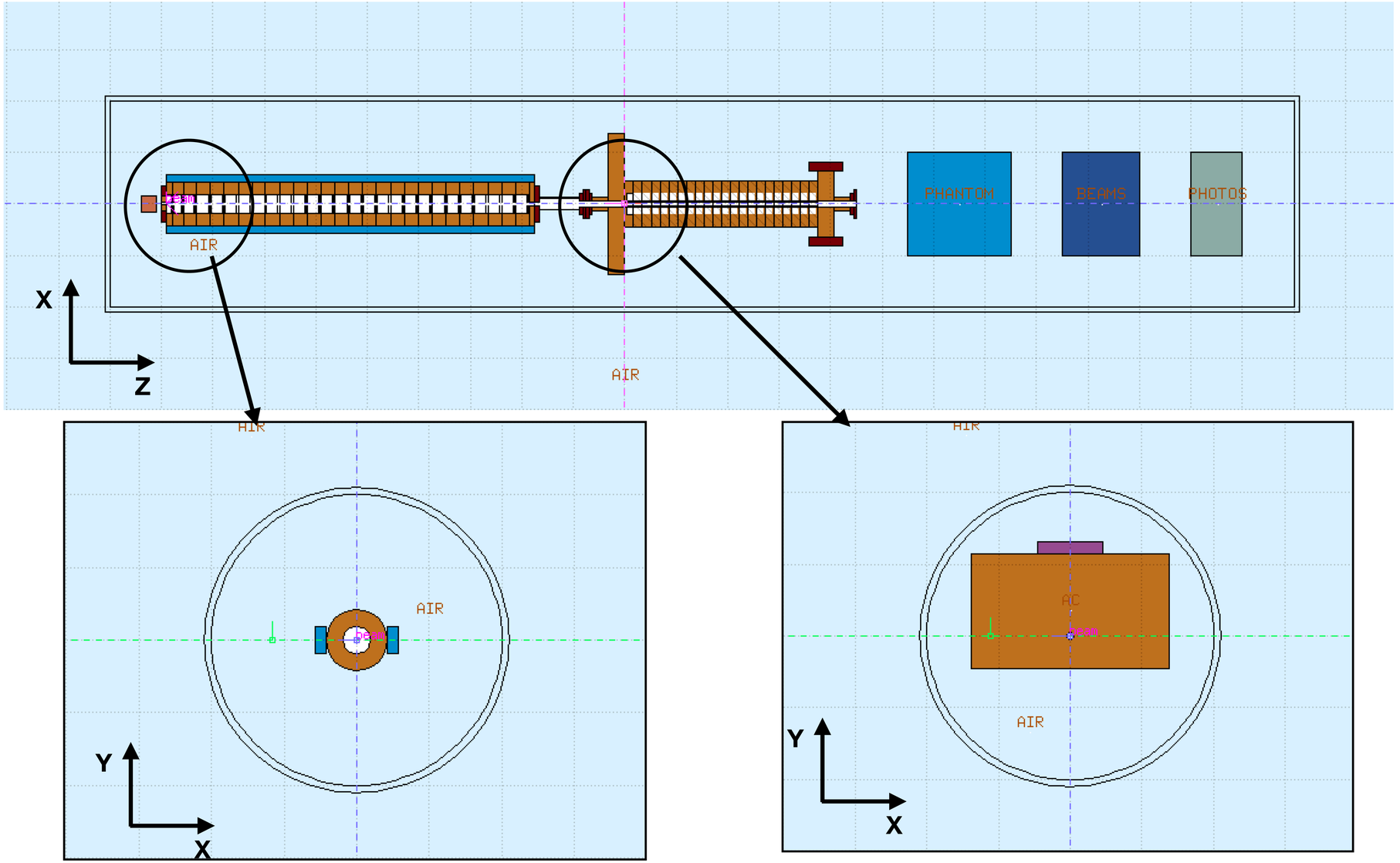
FLUKA geometry

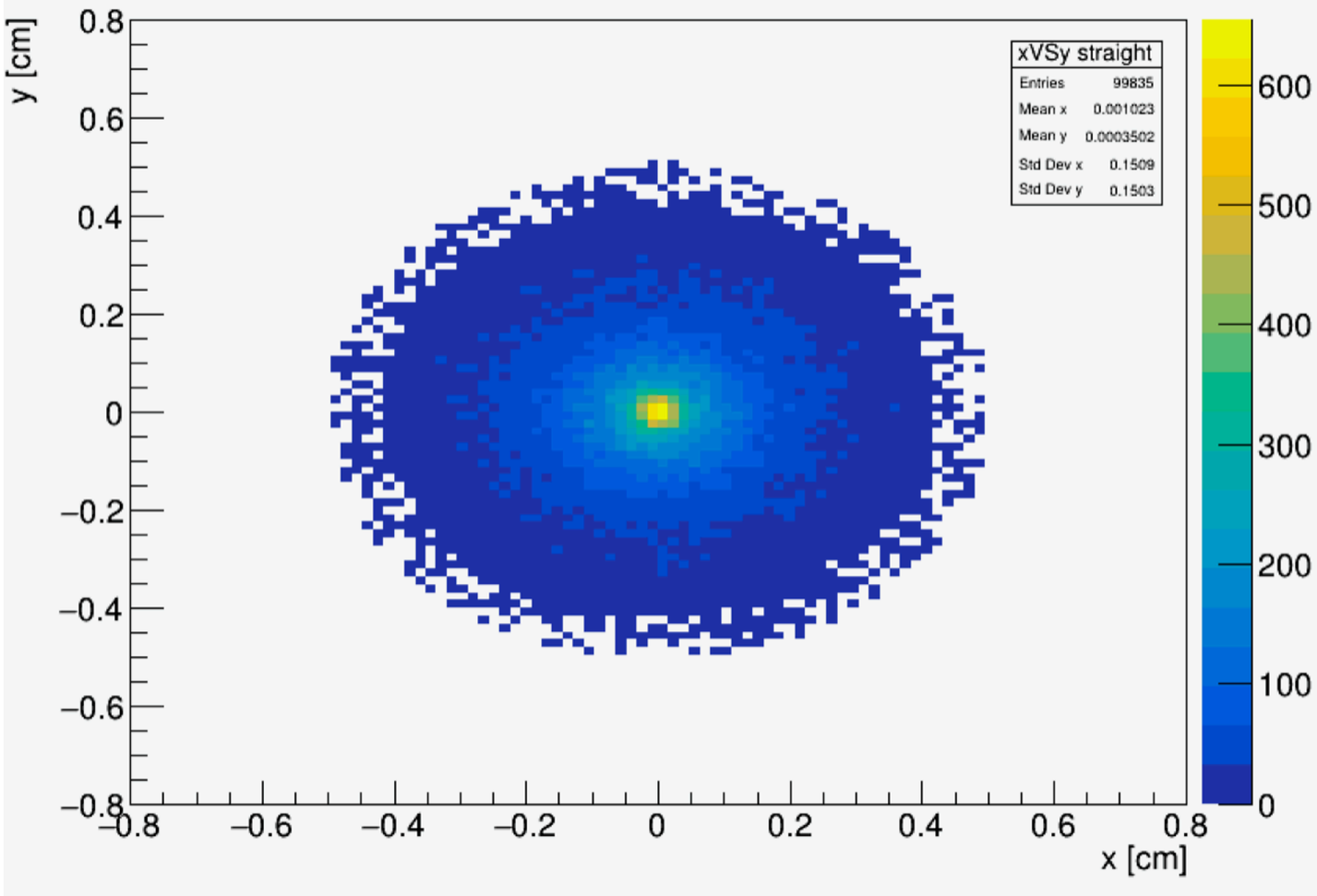
- The full **geometry** (including **materials**) of the accelerator has been implemented **in FLUKA**.



FLUKA geometry: different views



Input file: from Parmela to FLUKA

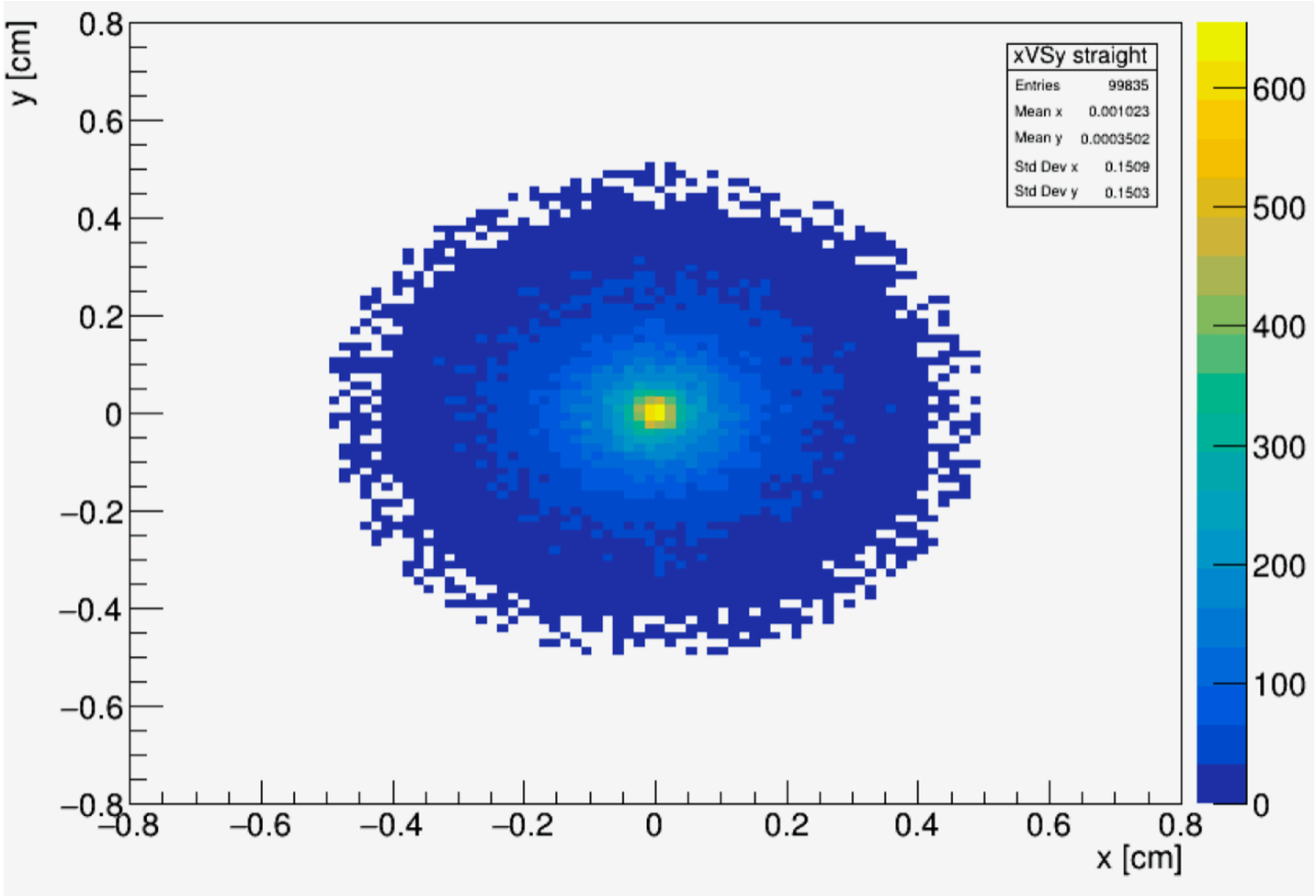


Distribution (x,y) of all particles read from the output file of Parmela.

- The beam dynamic has been evaluated by means of simulations performed with the PARMELA software, which provides the **spatial and energy information of all beam particles subjected to the accelerating electromagnetic fields of the structure**.

The beam interactions with the accelerator passive materials has been simulated with FLUKA using as input the beam kinematic information provided by PARMELA.

Input file: from Parmela to FLUKA



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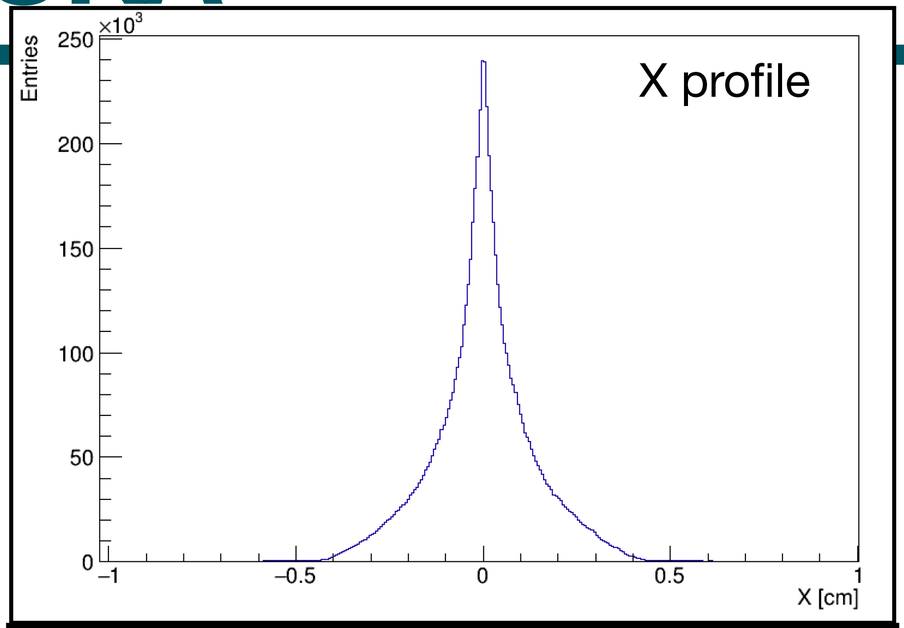
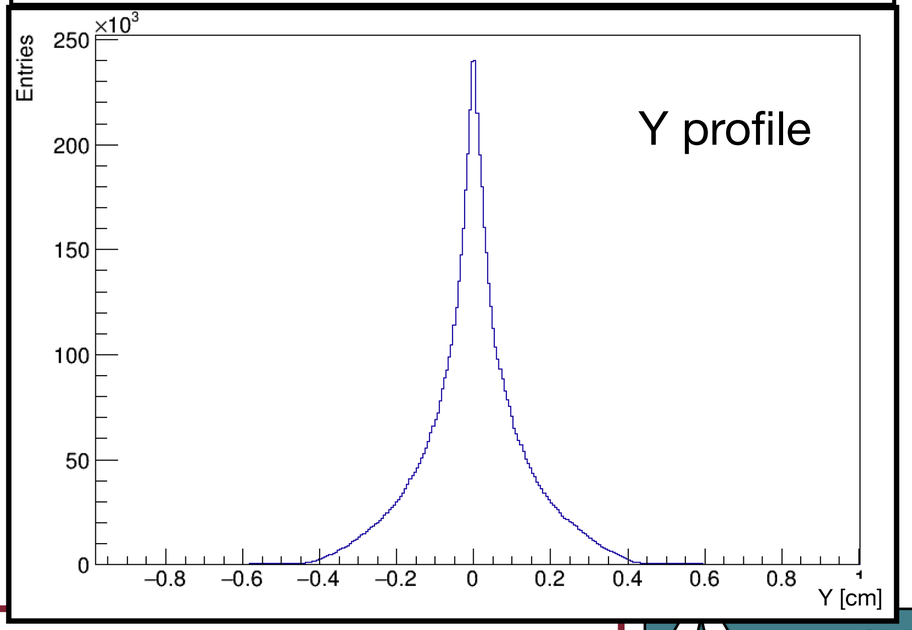
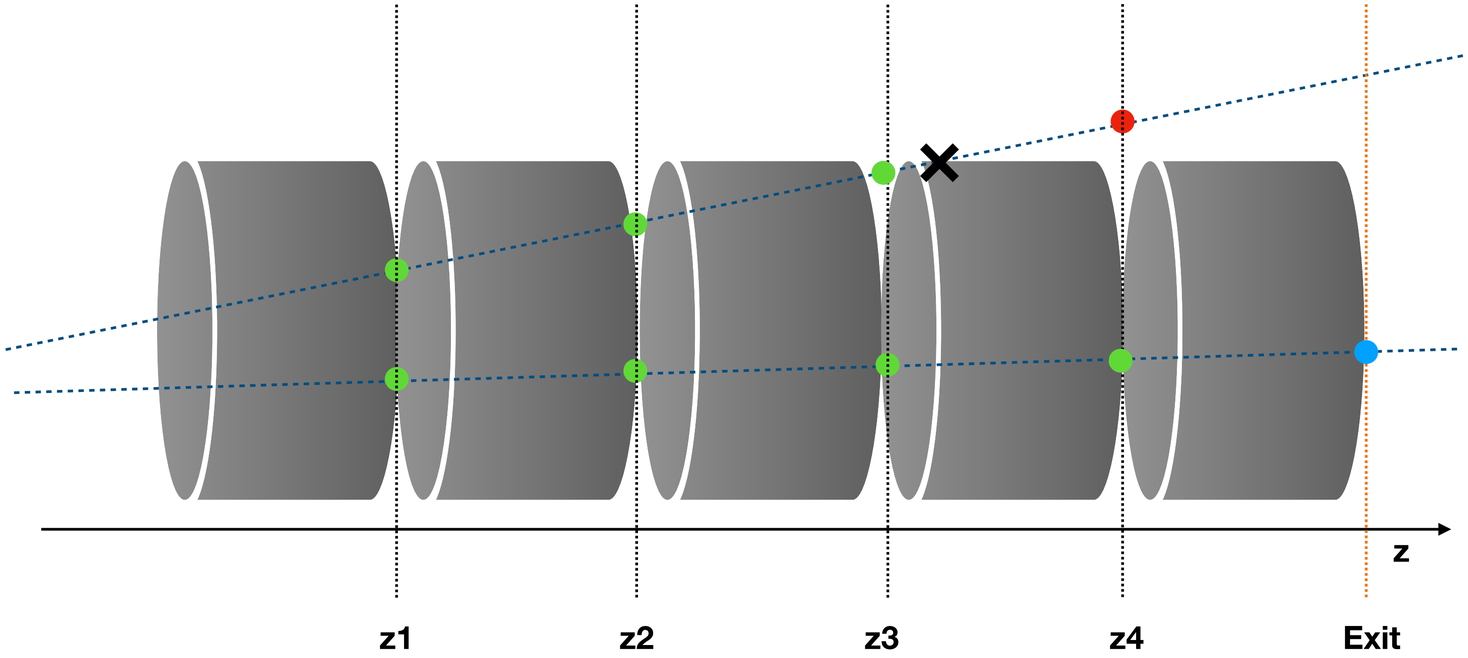




Input file: from Parmela to FLUKA

The PARMELA simulations output consists in the 4-momentum of each individual particle at **discrete z positions along the cavities**. According such dynamic:

- Particles that do not exit from the beam pipe are simulated in Fluka using as starting position the end of the pipe (●)
- Particles that exit from the vacuum pipe along their travel are tracked in FLUKA starting from the **intersection coordinate** between the line describing its direction and the beam pipe cylinder (✕).



Phantom

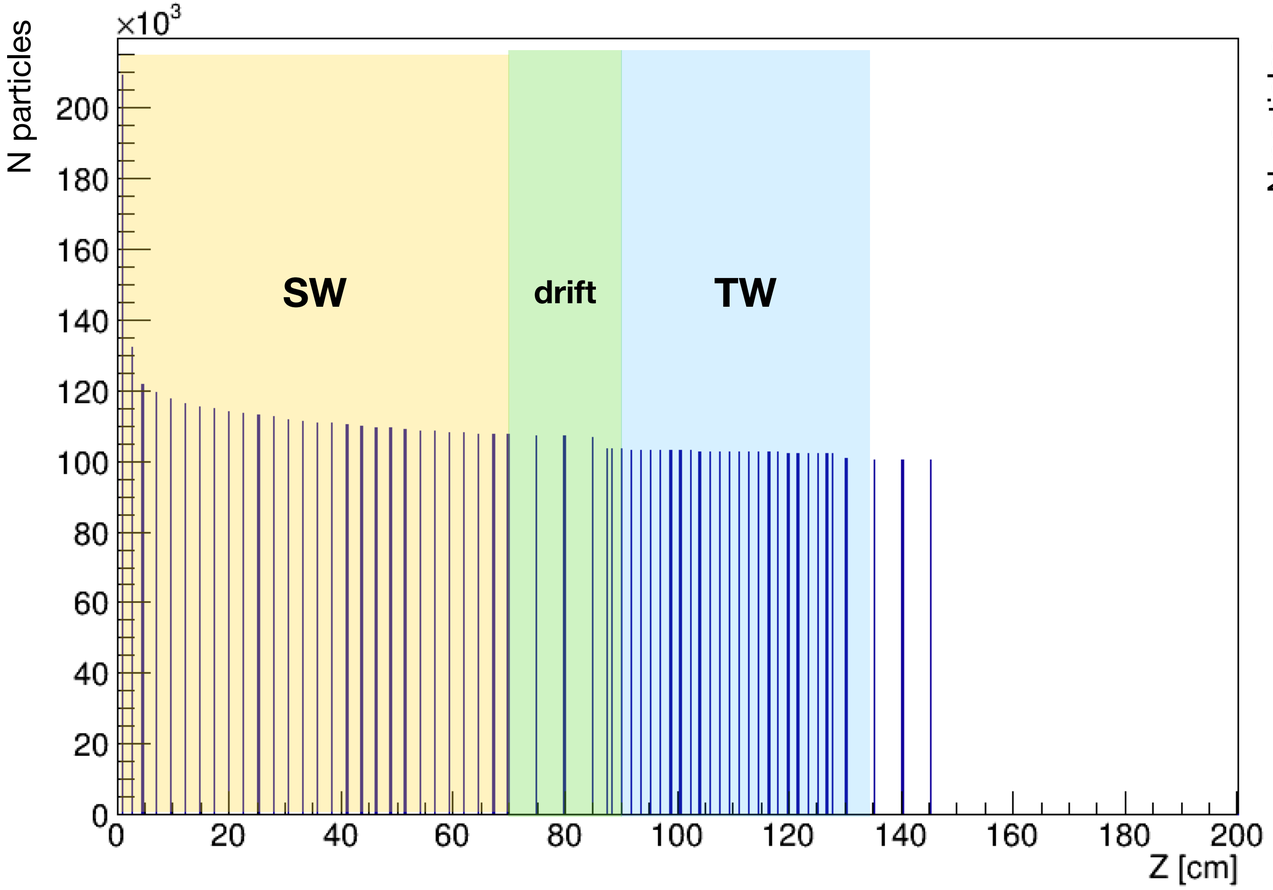
Statistical sample simulated by PARMELA

N total e^-	$2 \cdot 10^5$
N outgoing e^- ●	14790
N straight e^- ●	99835
N backscattered e^-	85375

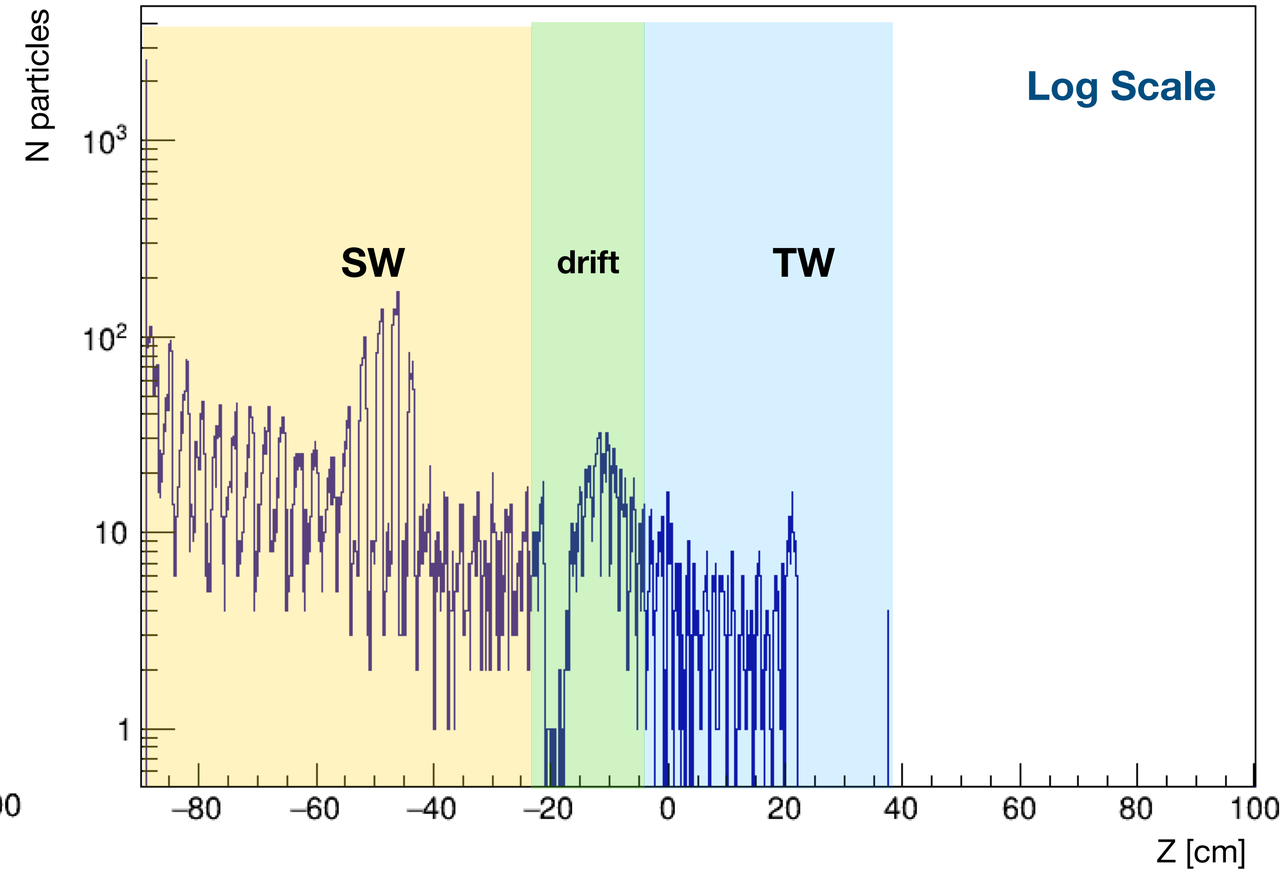
Non tracked by PARMELA

Input file: from Parmela to FLUKA

- Distribution in z of all particles read from the output file of Parmela.



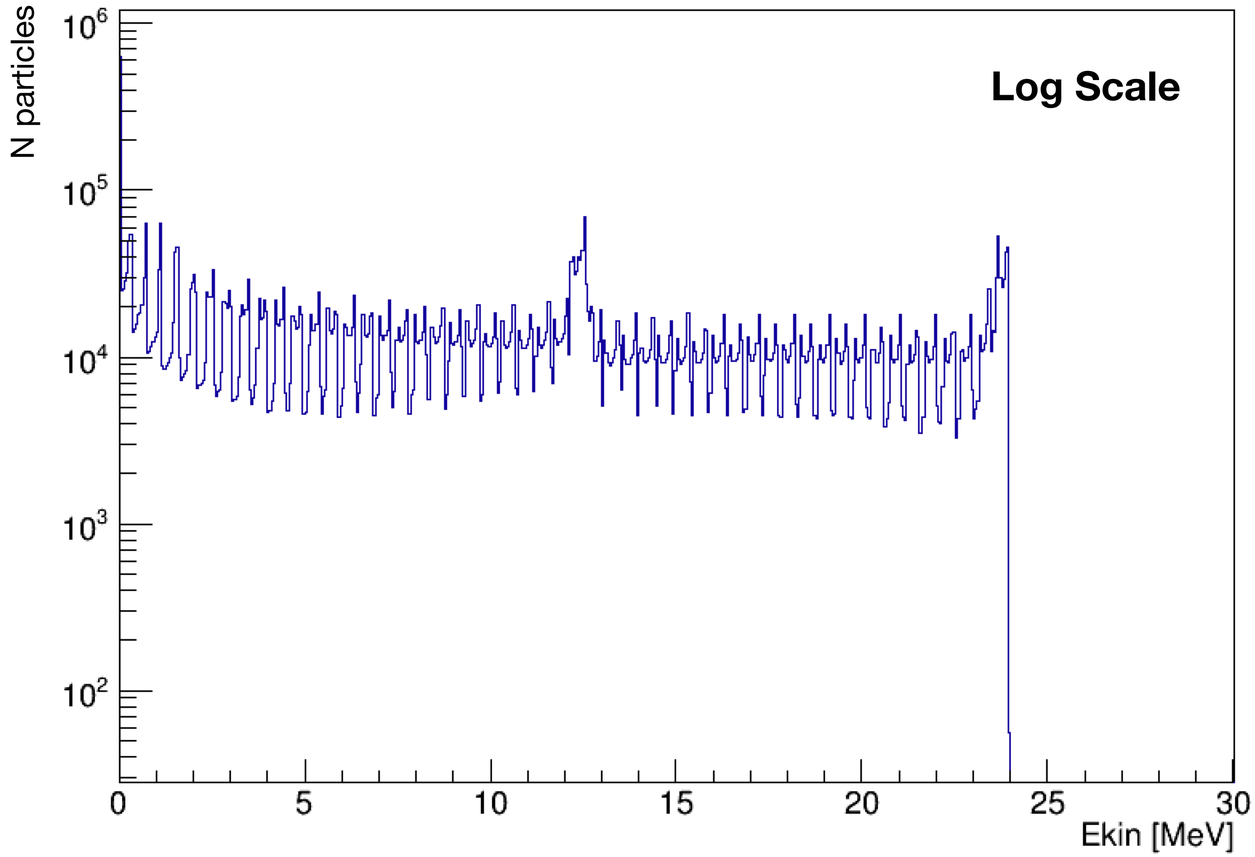
- Distribution in z of all particles exiting the accelerator.



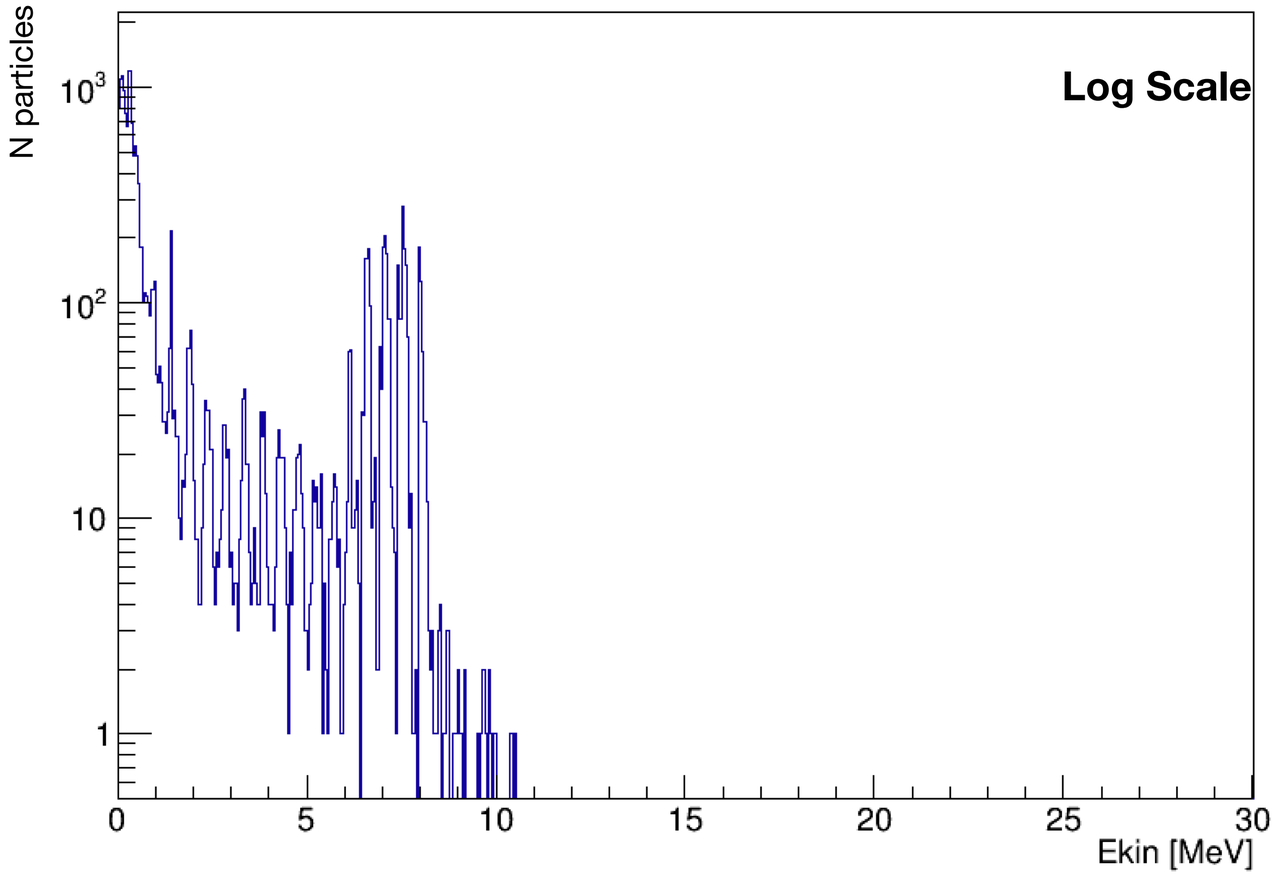
Note: the z axes have two different scales because I shifted the z coordinates to fit the reference system in FLUKA.

Input file: from Parmela to FLUKA

- Distribution in kinetic energy of all particles read from the **output file of Parmela**.



- Distribution in kinetic energy of all particles **exiting the accelerator**.



Analysis of the FLUKA simulation: DISPERSED FLUX

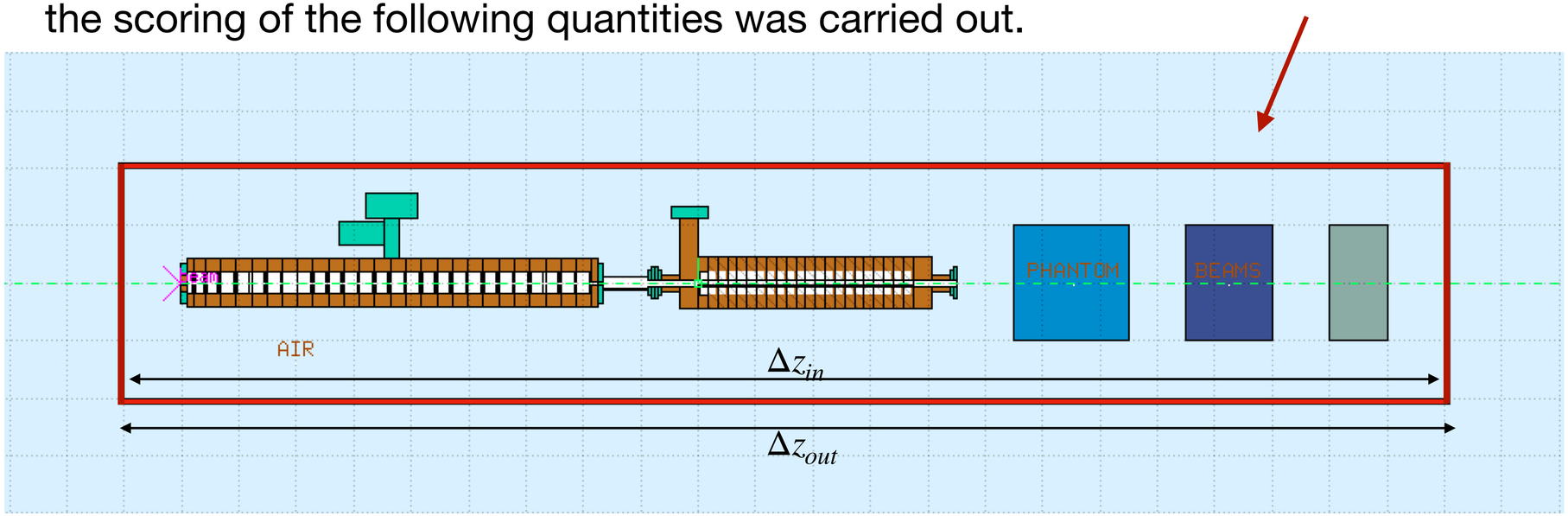
FLUKA number of primaries

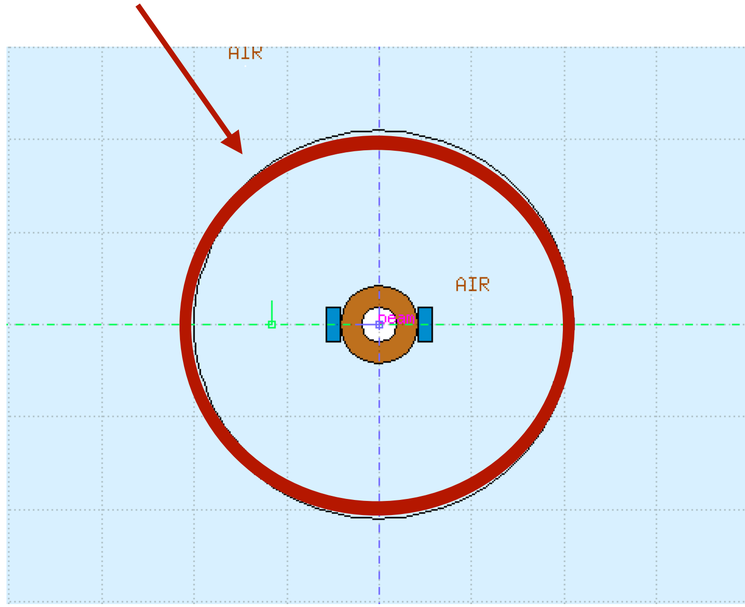
- The number of particles traced forward, crossing the accelerator, from the beam dynamics studies, is 114625. This statistic is too low to be used as input for the FLUKA simulations. Therefore, what has been done is to **increase the multiplicity in the azimuthal angle** ϕ of each outgoing primary particle.

 # particles before = 114625

 # particles after = 1146250

- The evaluation of the dispersed flux was performed in a **cylindrical region surrounding the accelerator**. Here, the scoring of the following quantities was carried out.

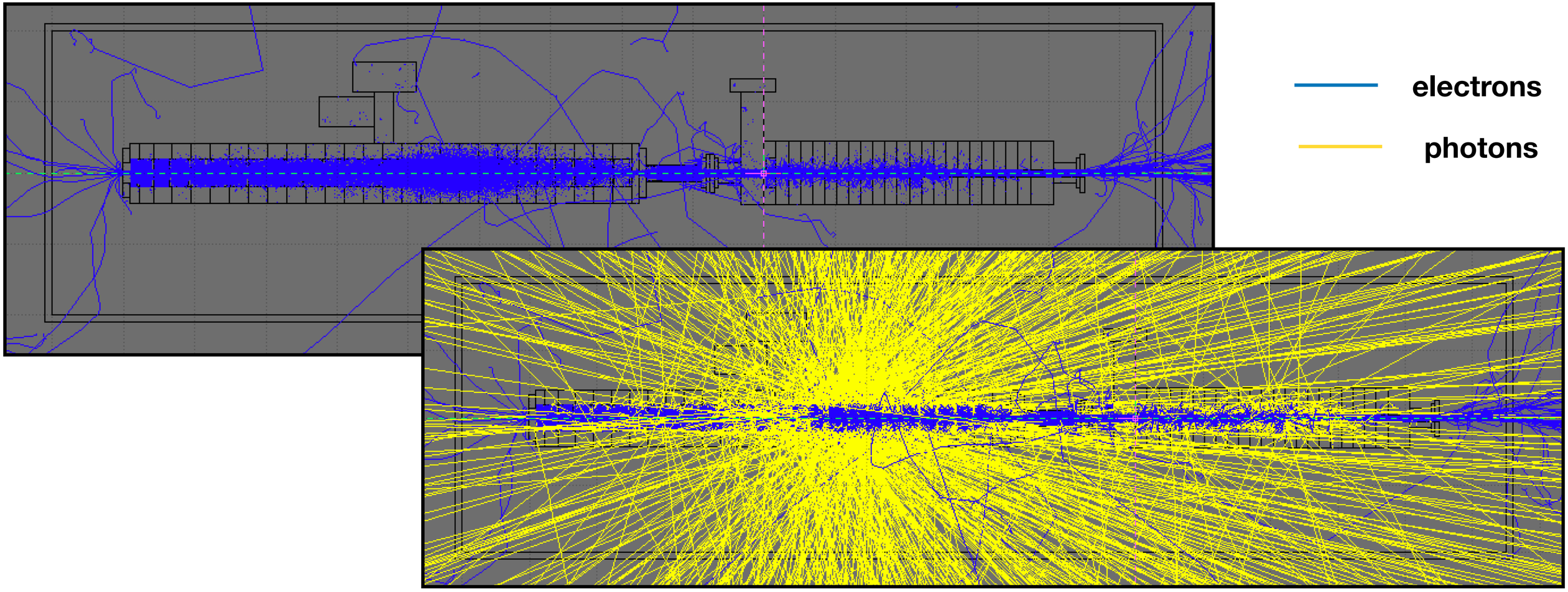




- Scoring cylinder dimensions: $R_{in} = 20cm$ $R_{out} = 21cm$ $\Delta z_{in} = 230cm$ $\Delta z_{out} = 232cm$

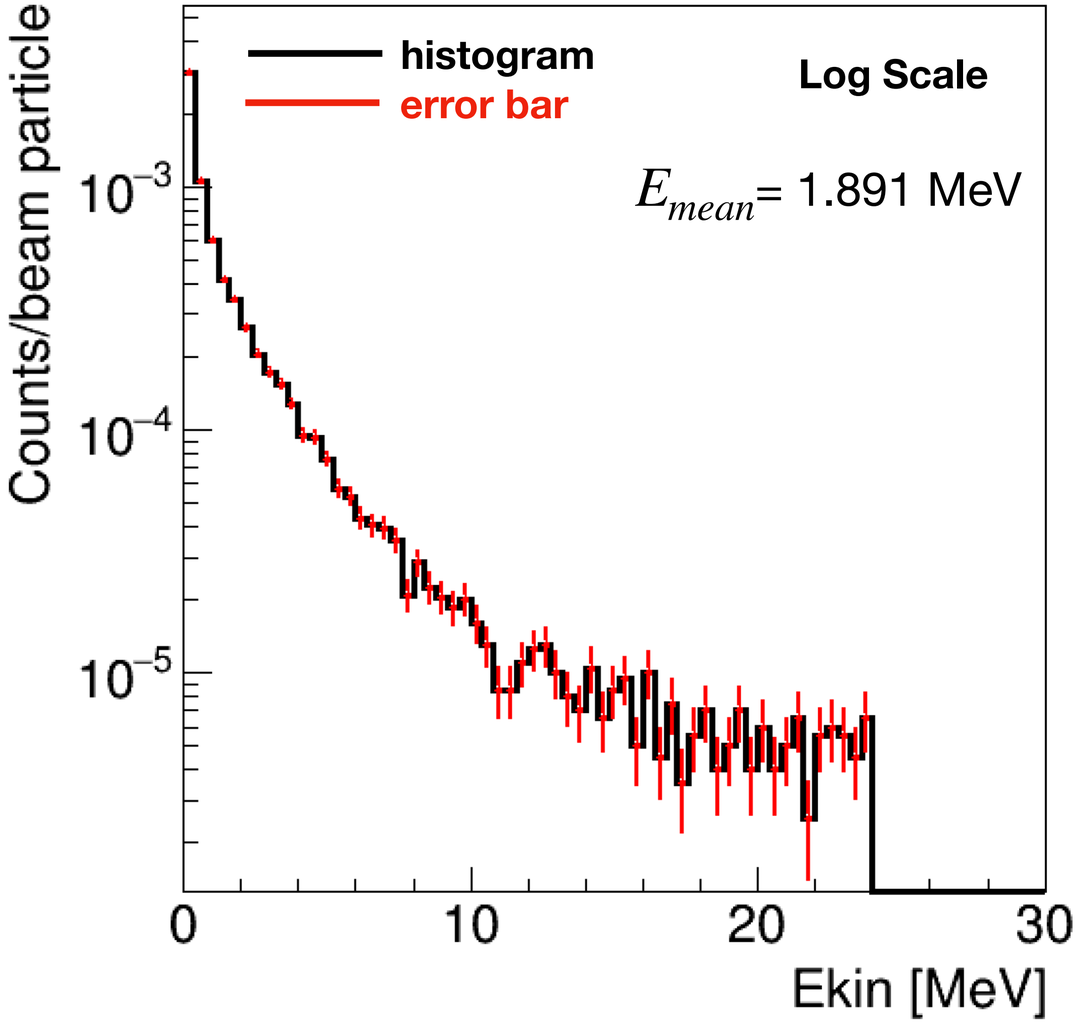
FLUKA tracks

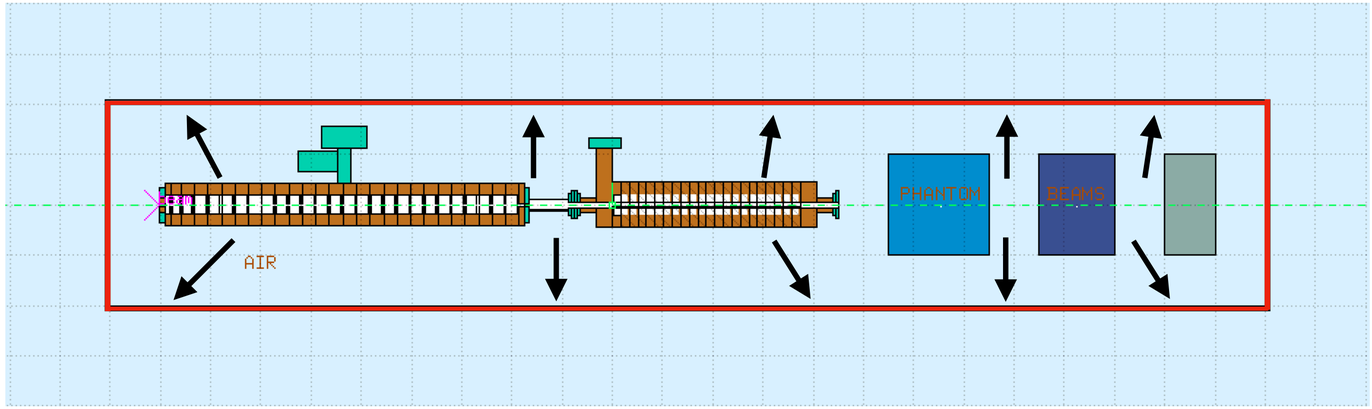
- Graphic representation of the interactions between the primary beam and the accelerating structure simulated by FLUKA.



Electrons distribution

- **Energy distribution** of the **electrons** arriving on the cylindrical scoring surface.

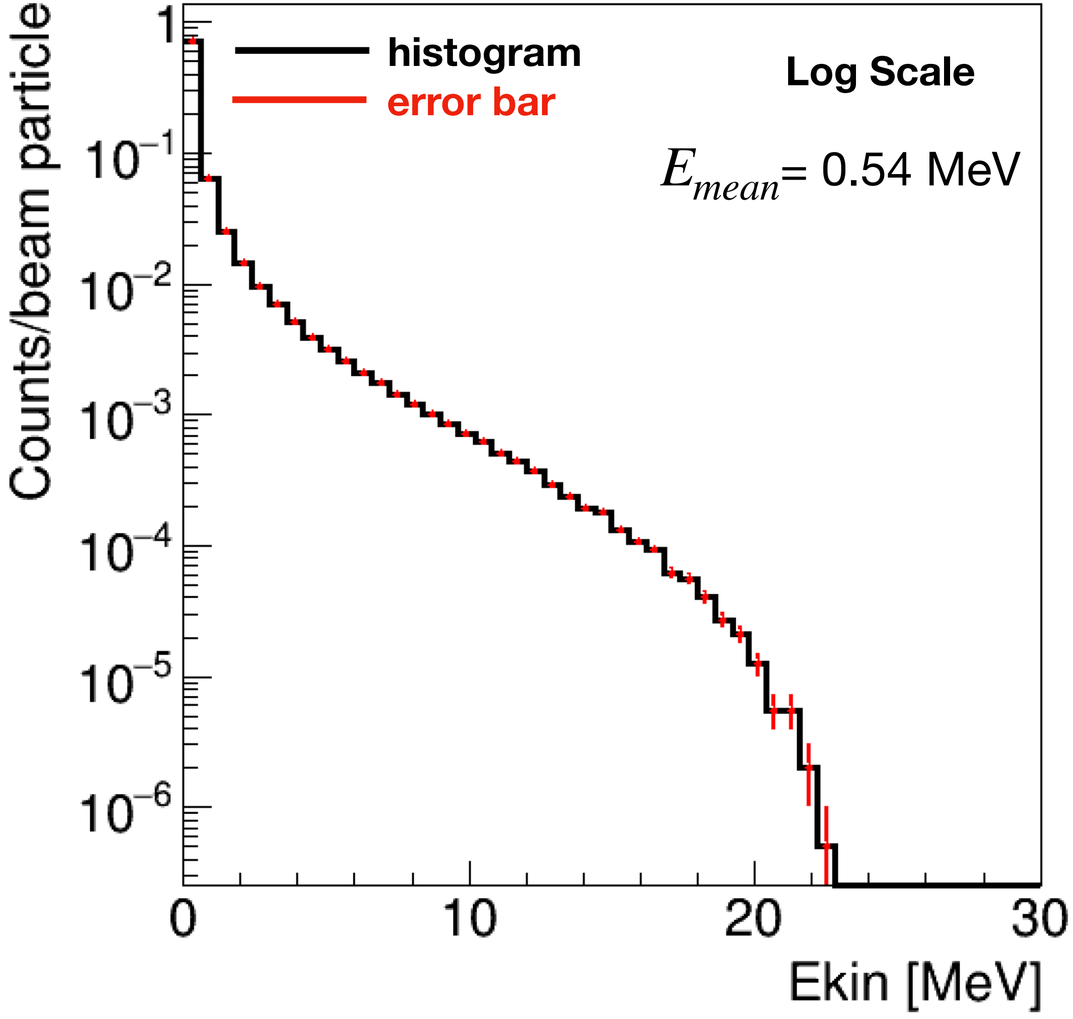


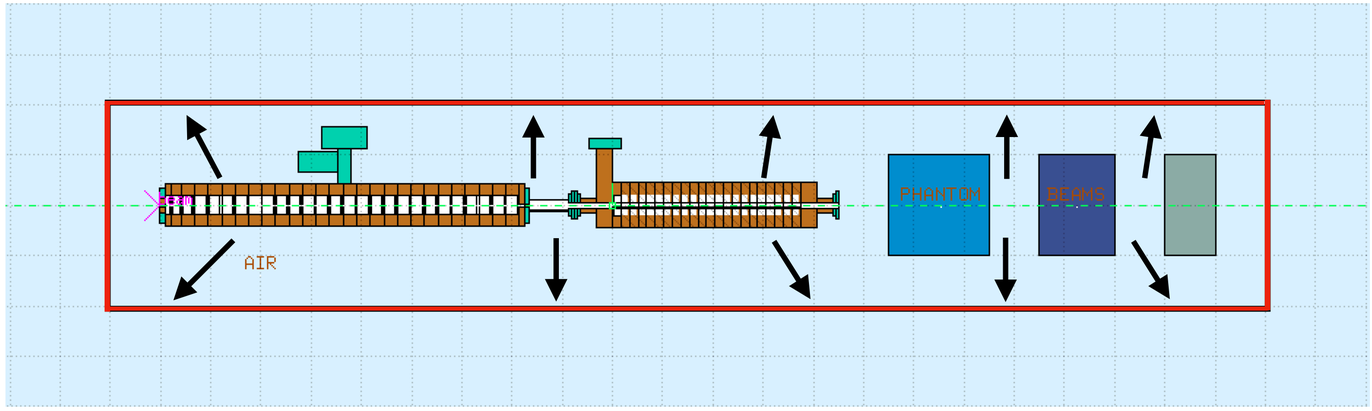


- The histograms are **normalized to the number of particles simulated with PARMELA**. These results indicate the number and energy distribution of particles (electrons, photons, positrons, and neutrons) produced **per beam particle**.

Photons distribution

- **Energy distribution** of the **photons** arriving on the cylindrical scoring surface.

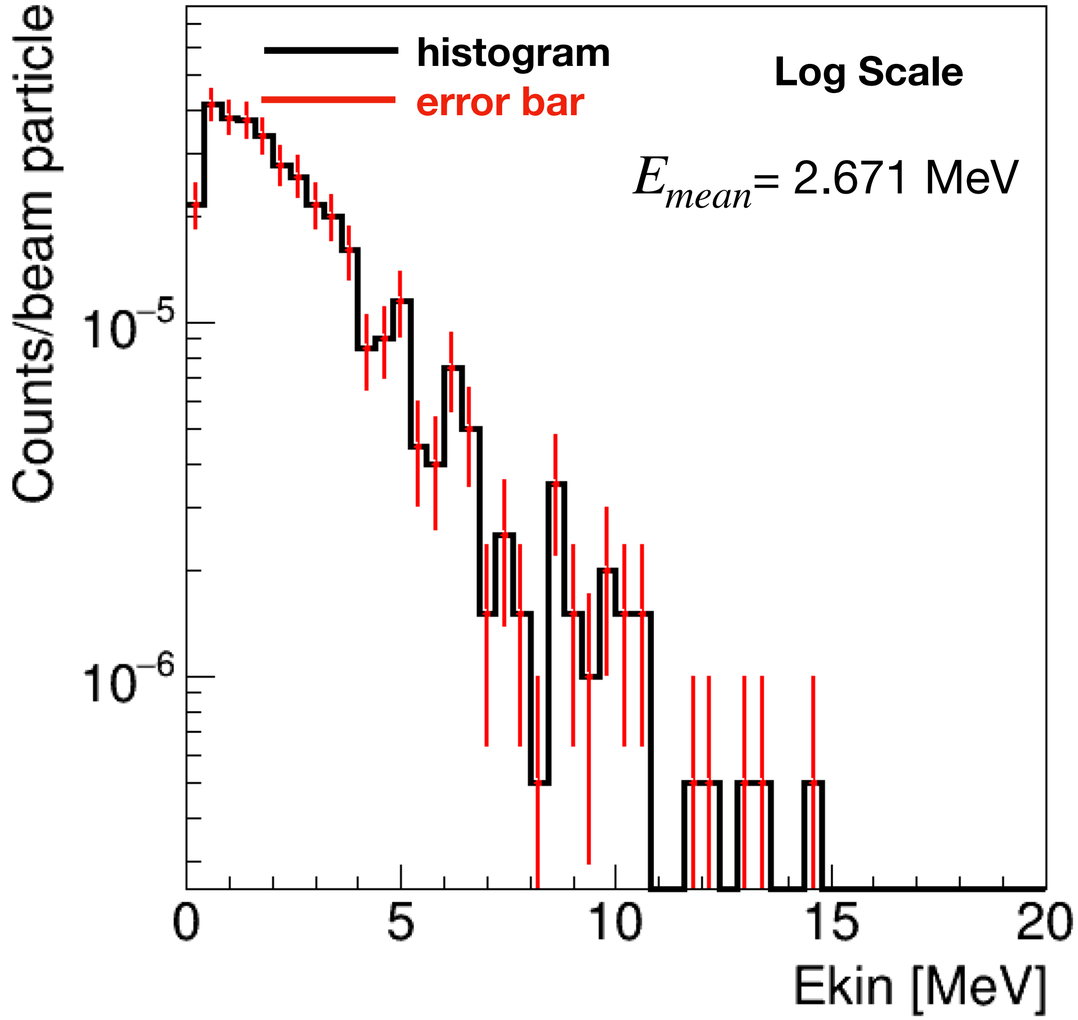


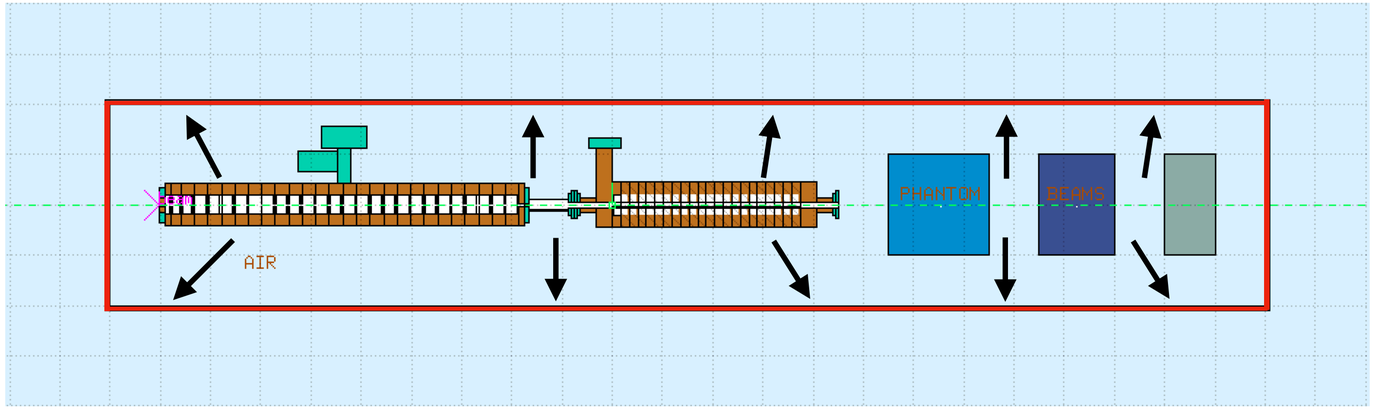


- The histograms are **normalized to the number of particles simulated with PARMELA**. These results indicate the number and energy distribution of particles (electrons, photons, positrons, and neutrons) produced **per beam particle**.

Positron distribution

- **Energy distribution** of the **positrons** arriving on the cylindrical scoring surface.

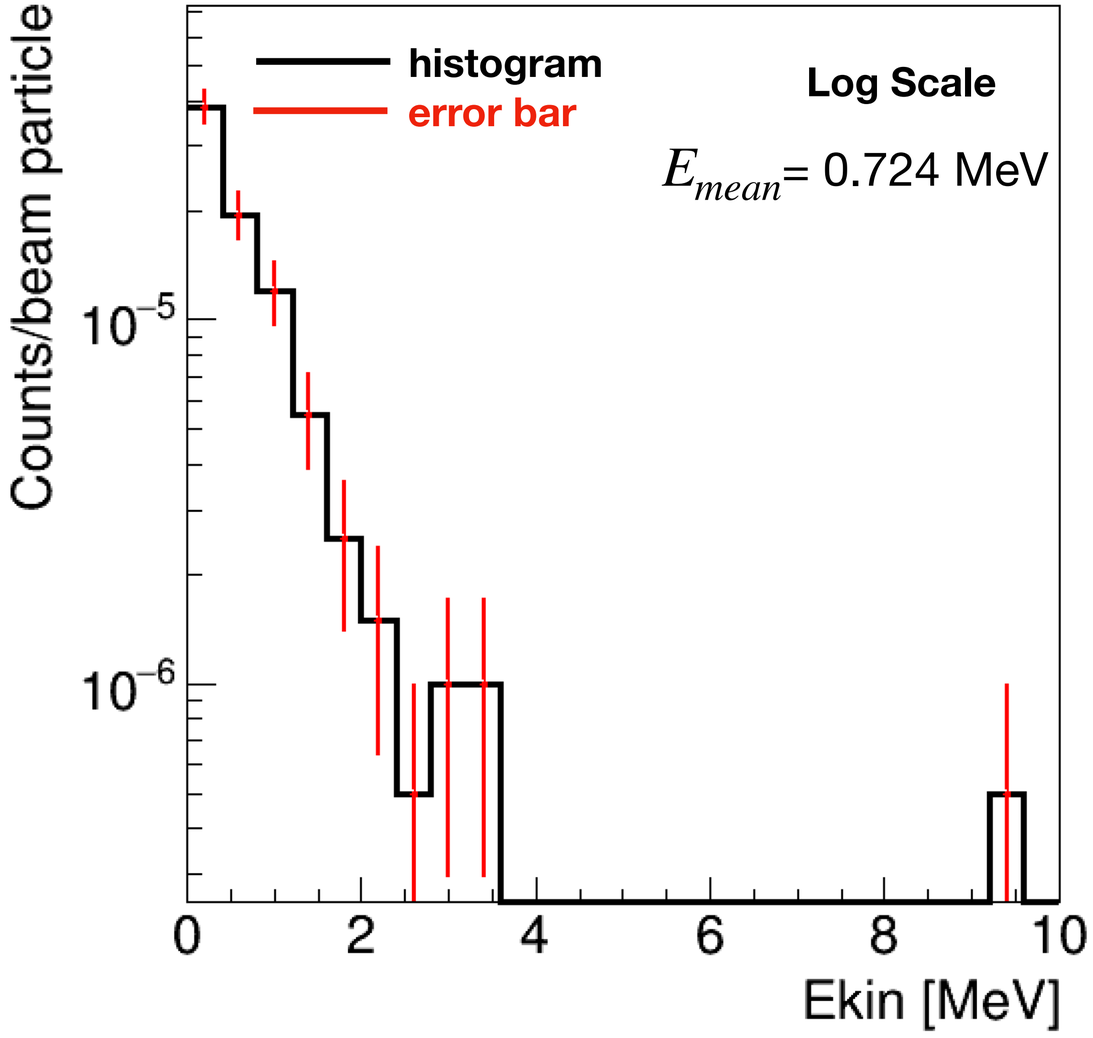


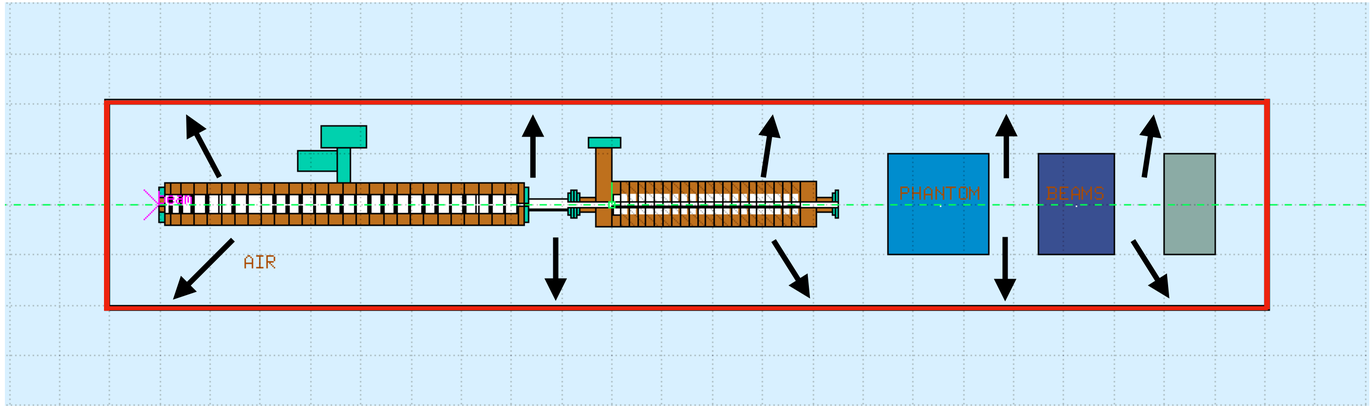


- The histograms are **normalized to the number of particles simulated with PARMELA**. These results indicate the number and energy distribution of particles (electrons, photons, positrons, and neutrons) produced **per beam particle**.

Neutrons distribution

- **Energy distribution** of the **neutrons** arriving on the cylindrical scoring surface.





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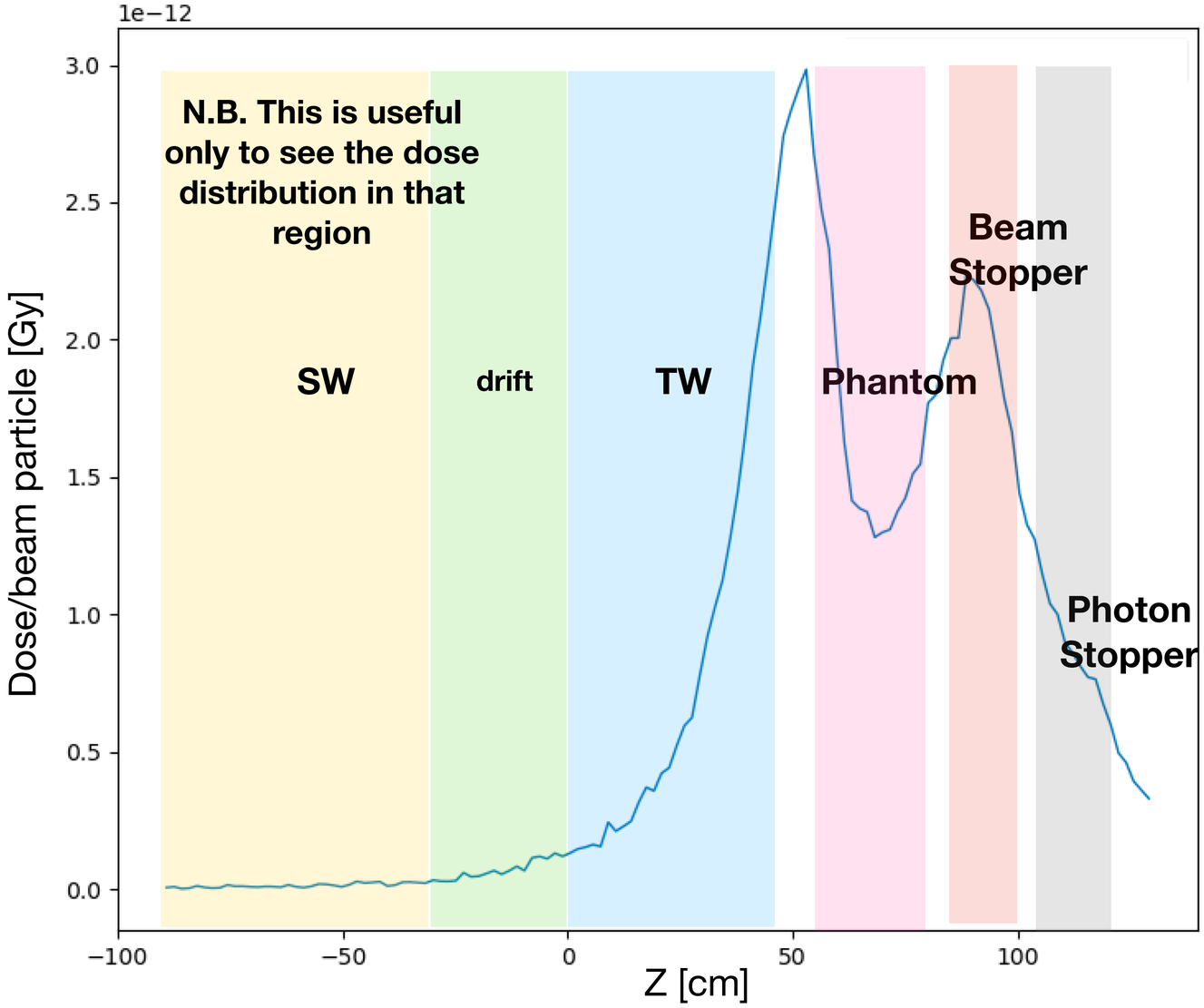
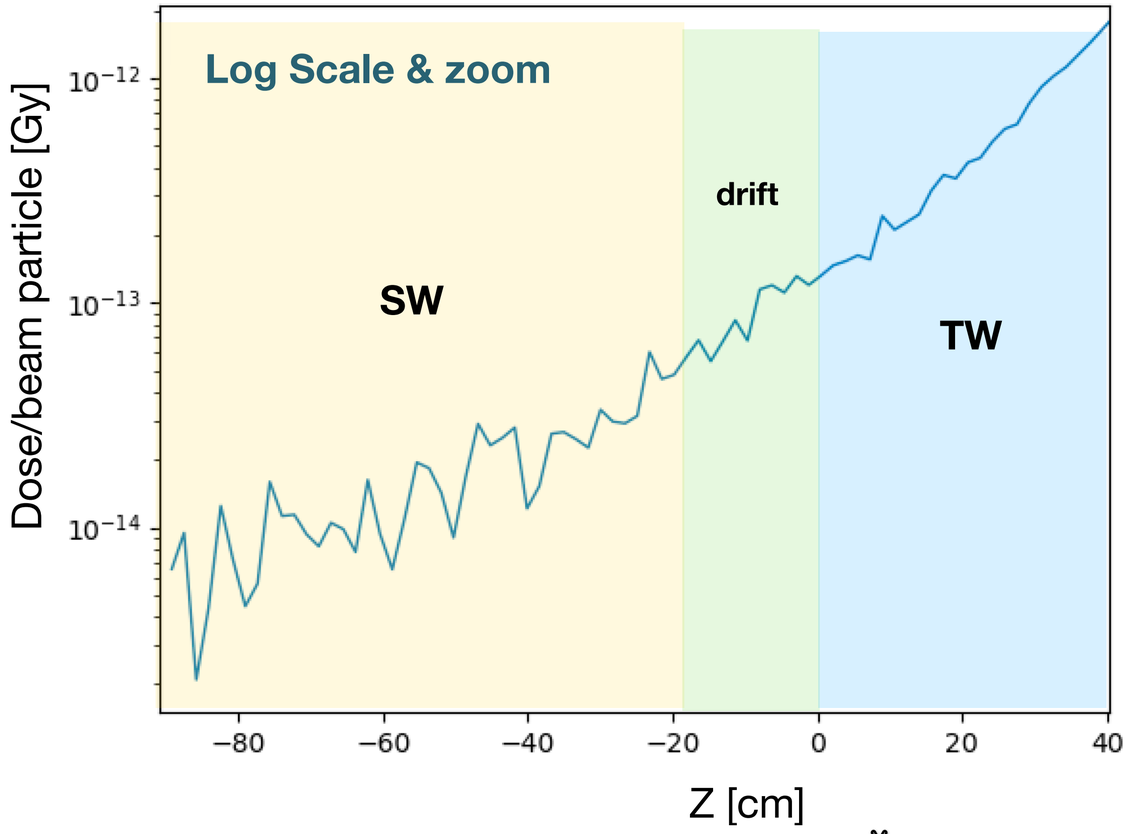
Dose calculated around the structure

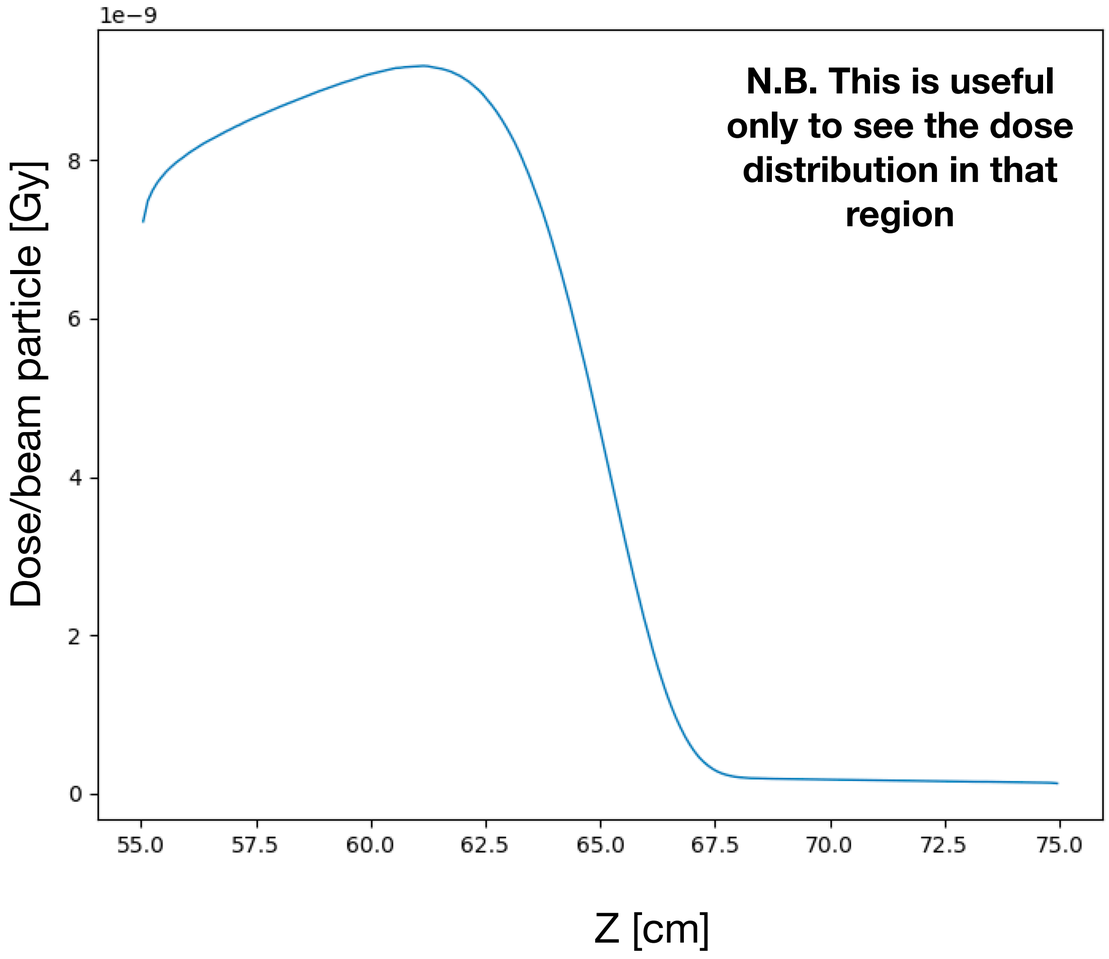


- **Integrated dose along the beam axes** (z) per particle beam.

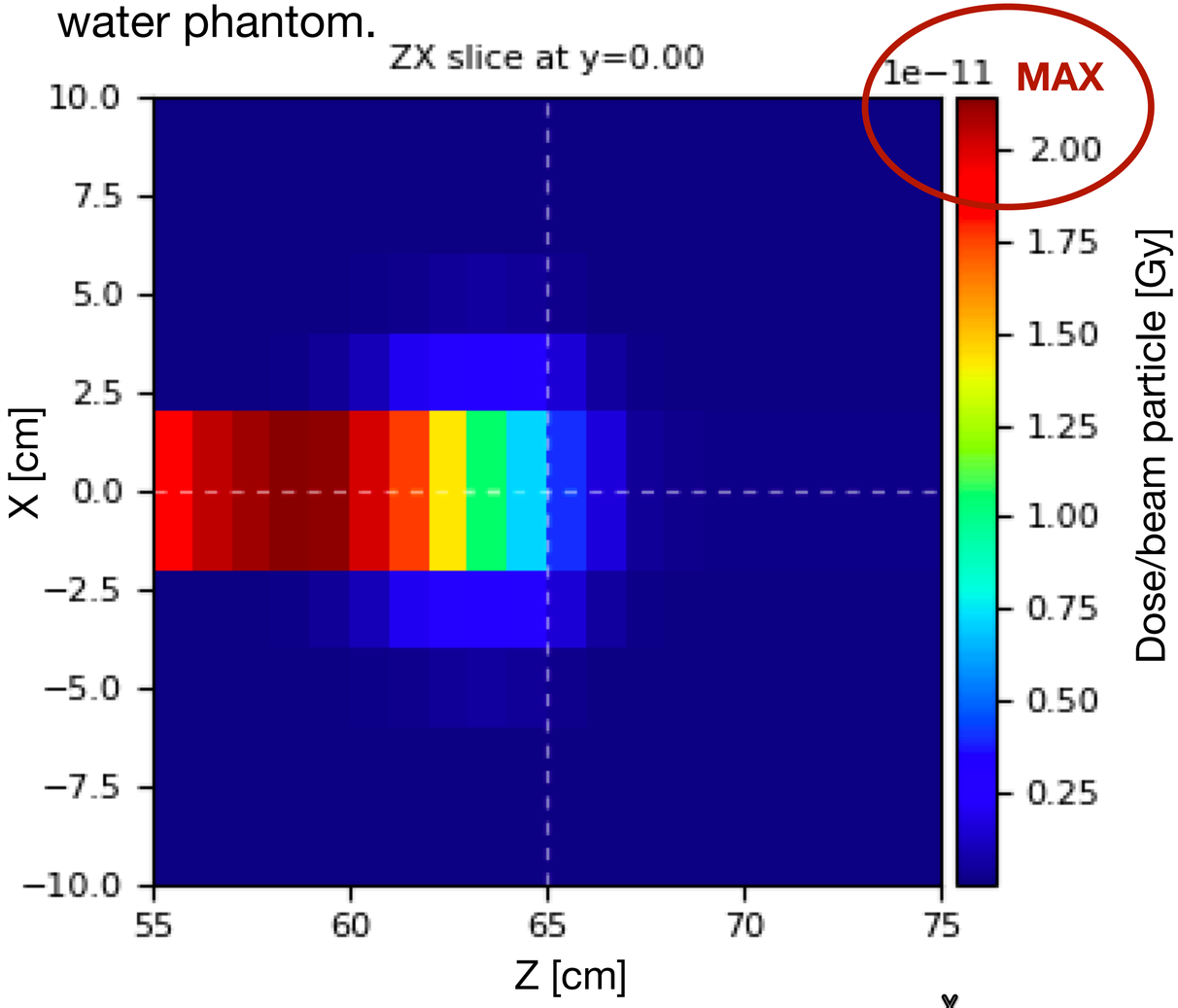


Dose calculated inside the Phantom

- This is the **INTEGRATED dose profile along the beam axes**, per particle beam inside the water phantom.

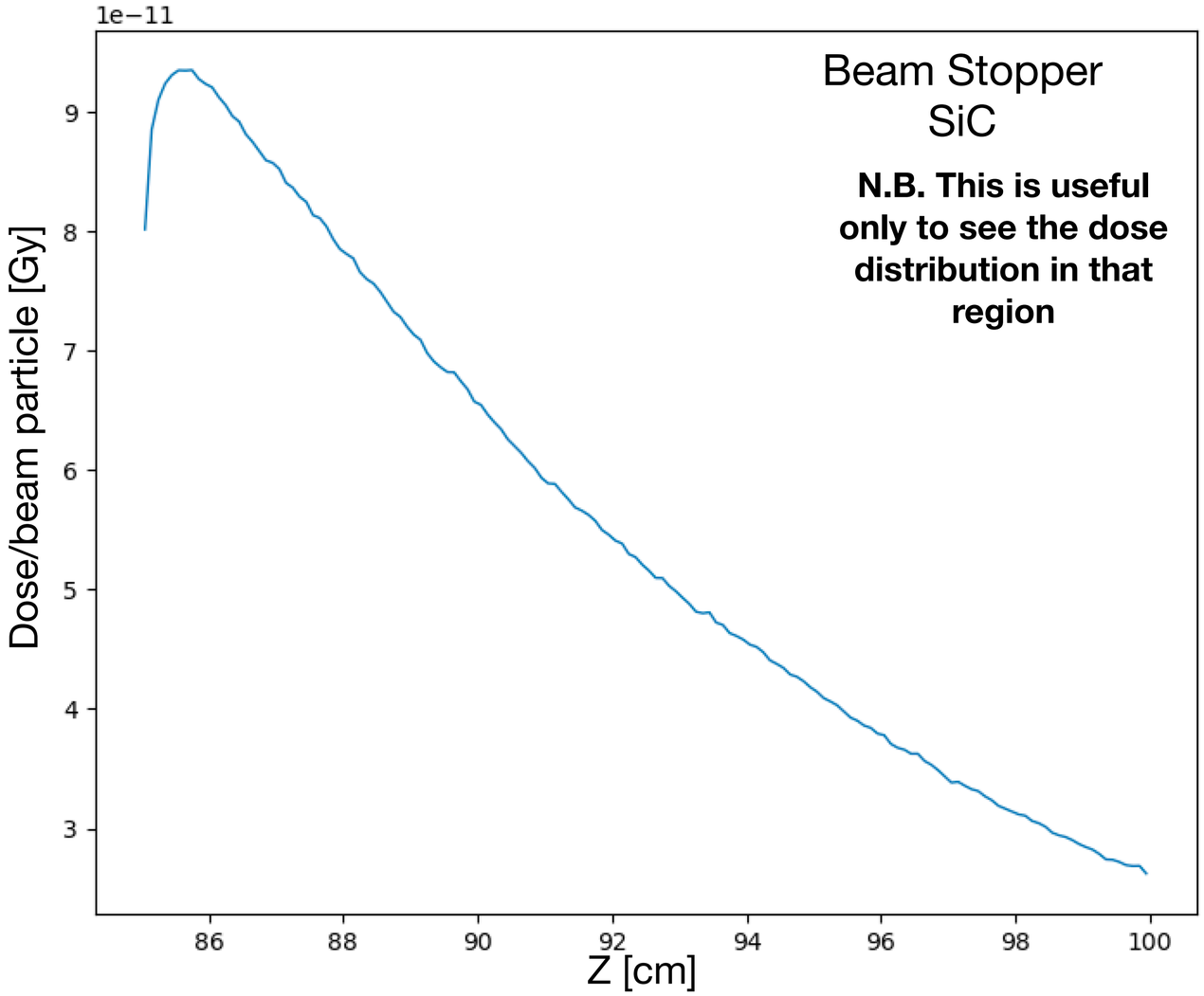


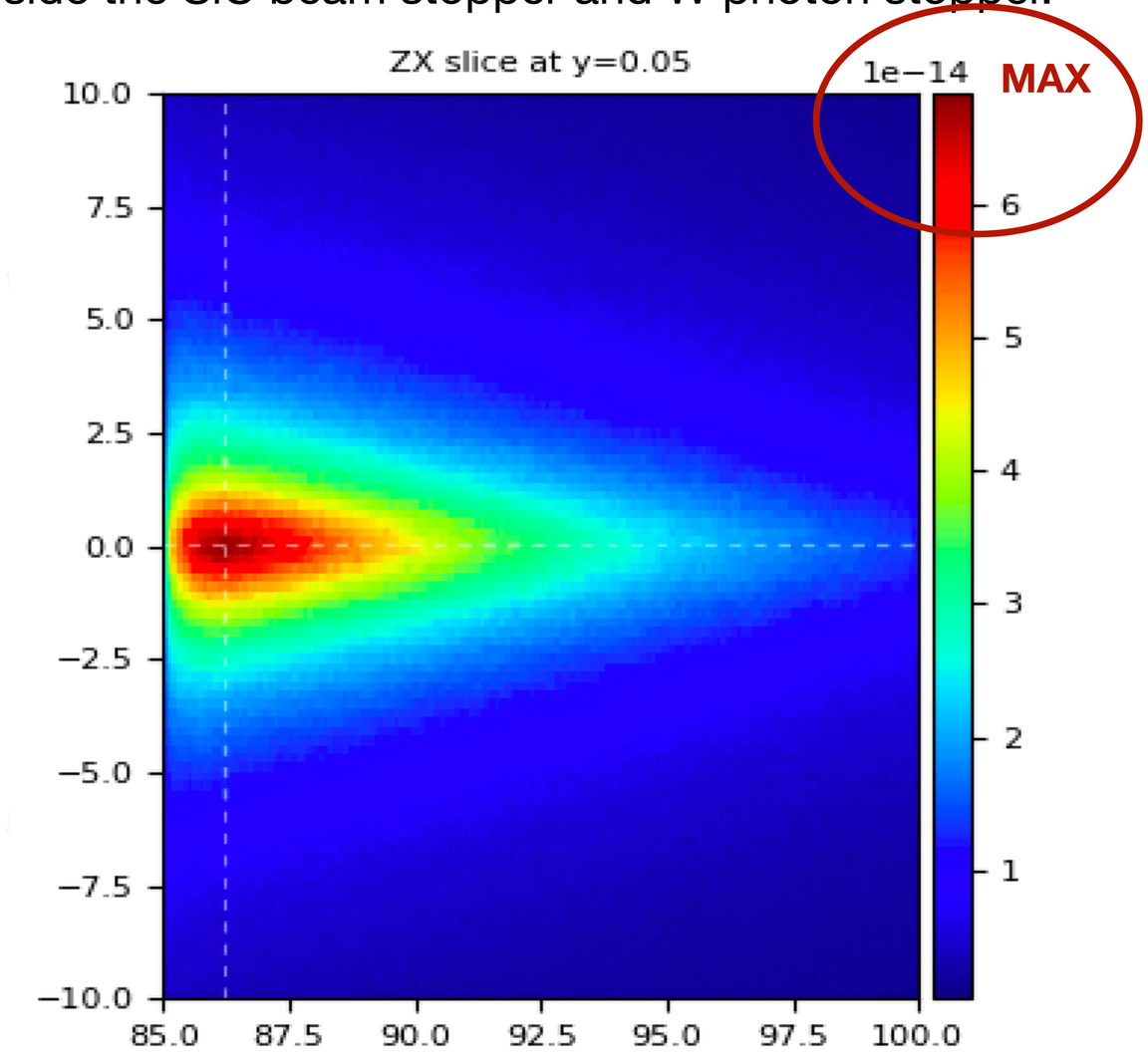
- This is the **DOSE MAP** per particle beam inside the water phantom.



Dose in Beam Stopper

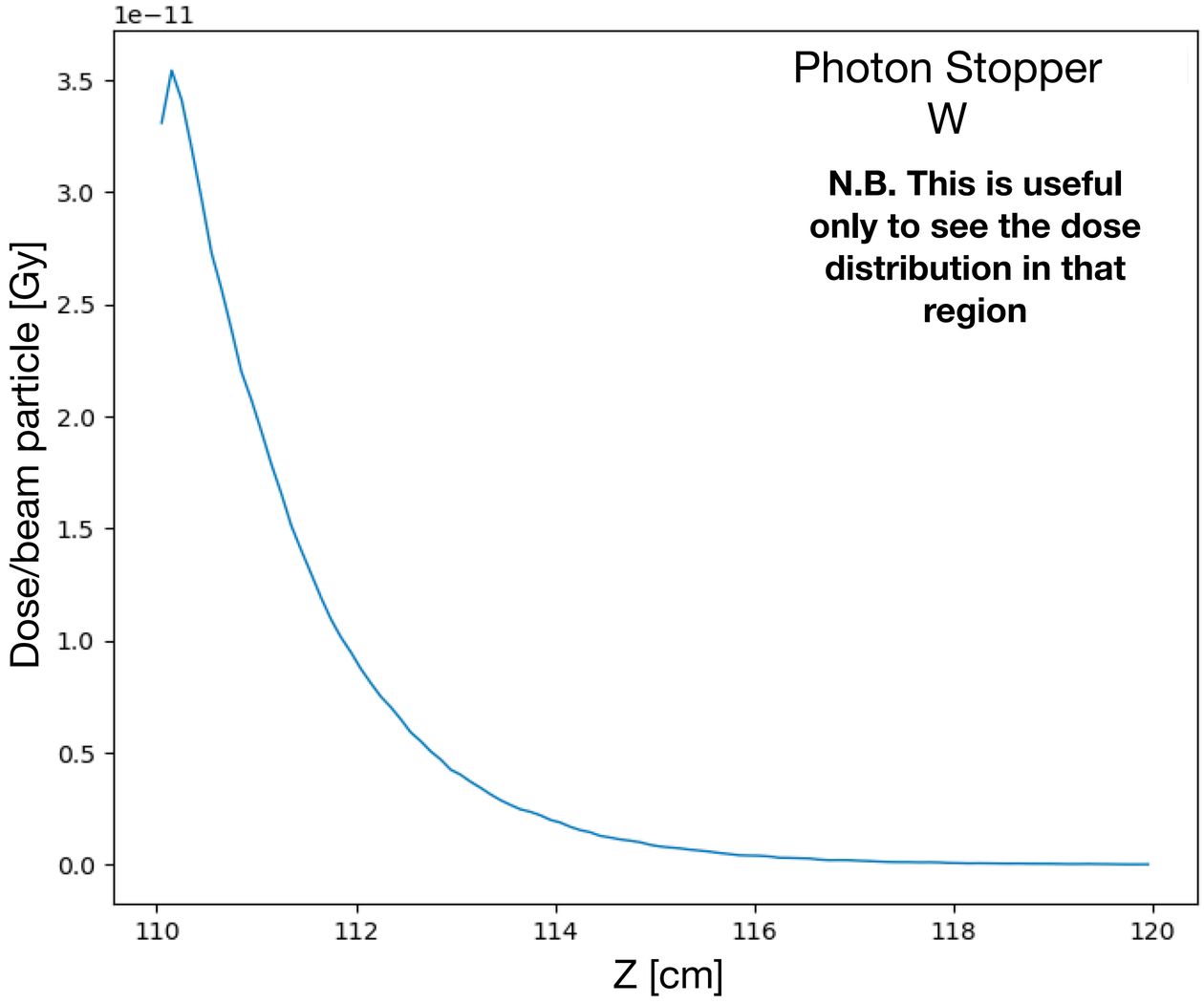
- **Integrated dose along the beam axes** (z) per particle beam inside the SiC beam stopper and W photon stopper.

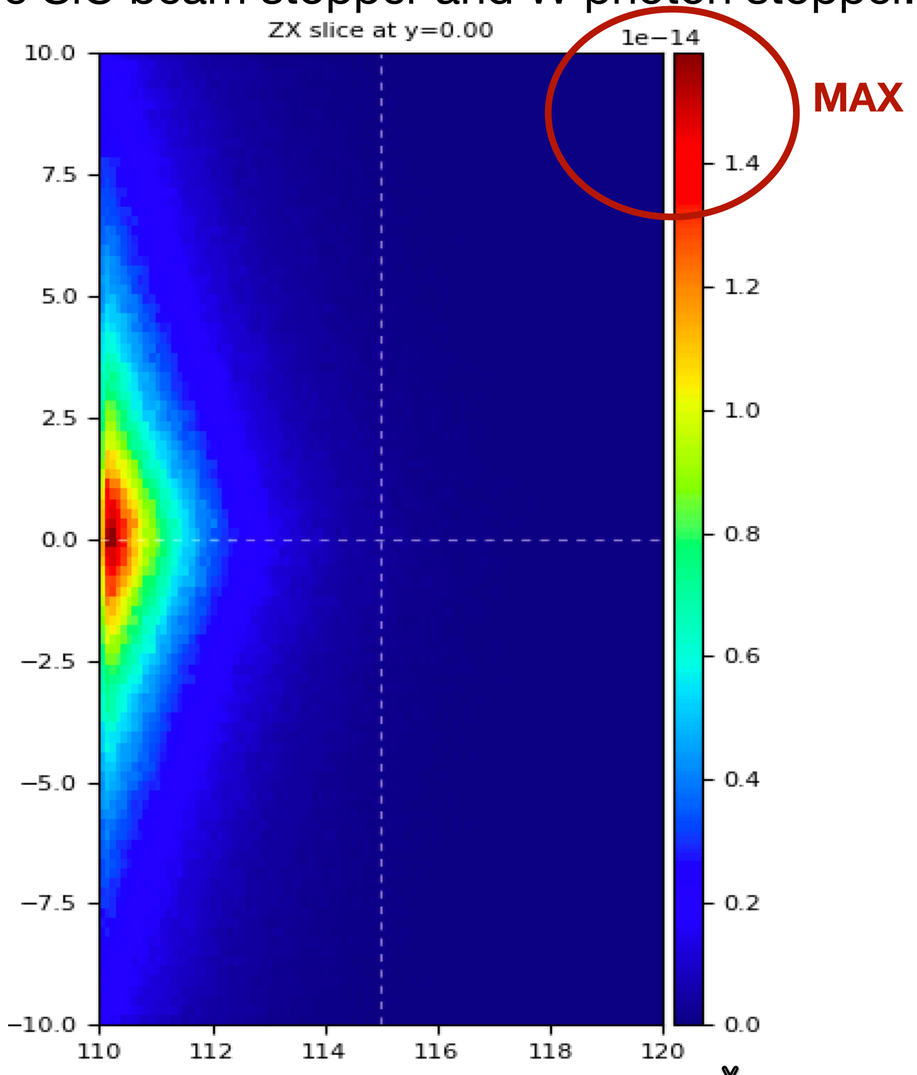




Dose in Photon Stopper

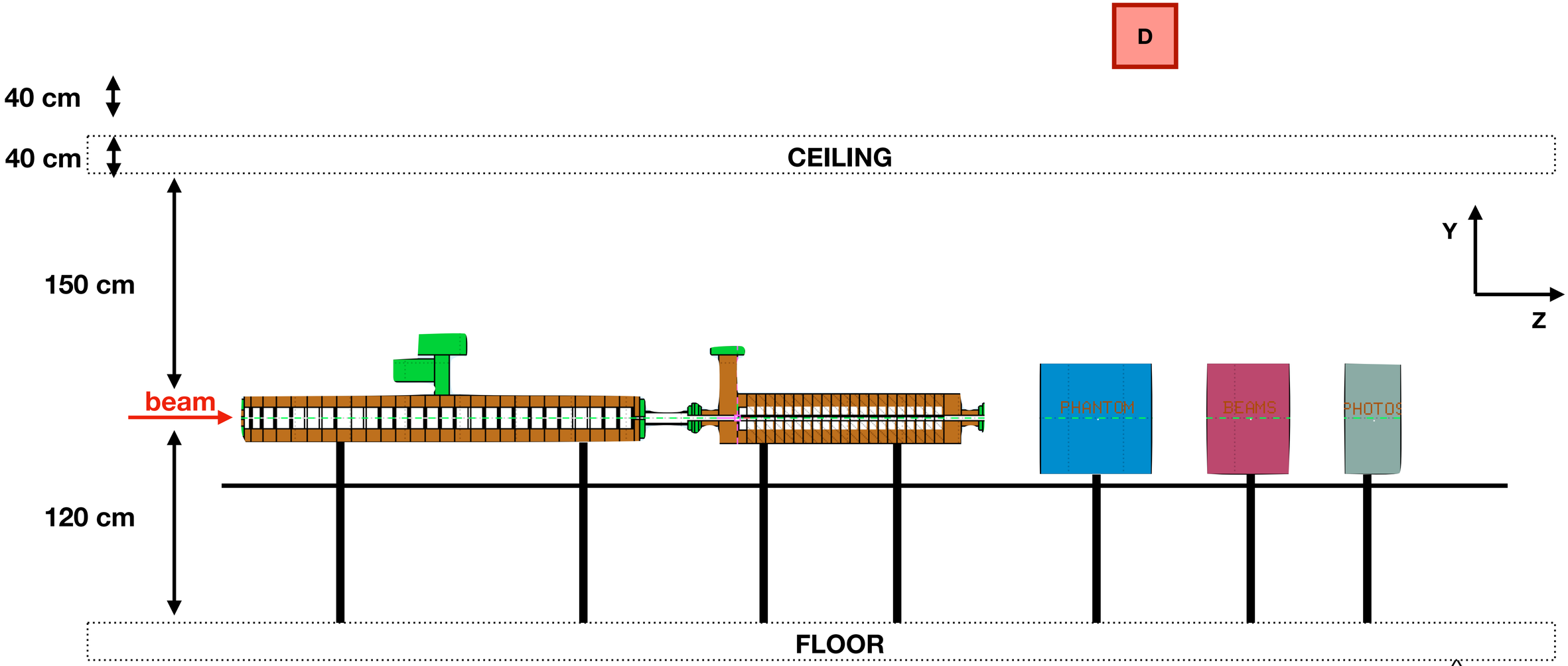
- **Integrated dose along the beam axes** (z) per particle beam inside the SiC beam stopper and W photon stopper.





Dose evaluation for Radioprotection protocols

- For radioprotection protocols, the dose must be evaluated at **specific points** in the space surrounding the accelerator.



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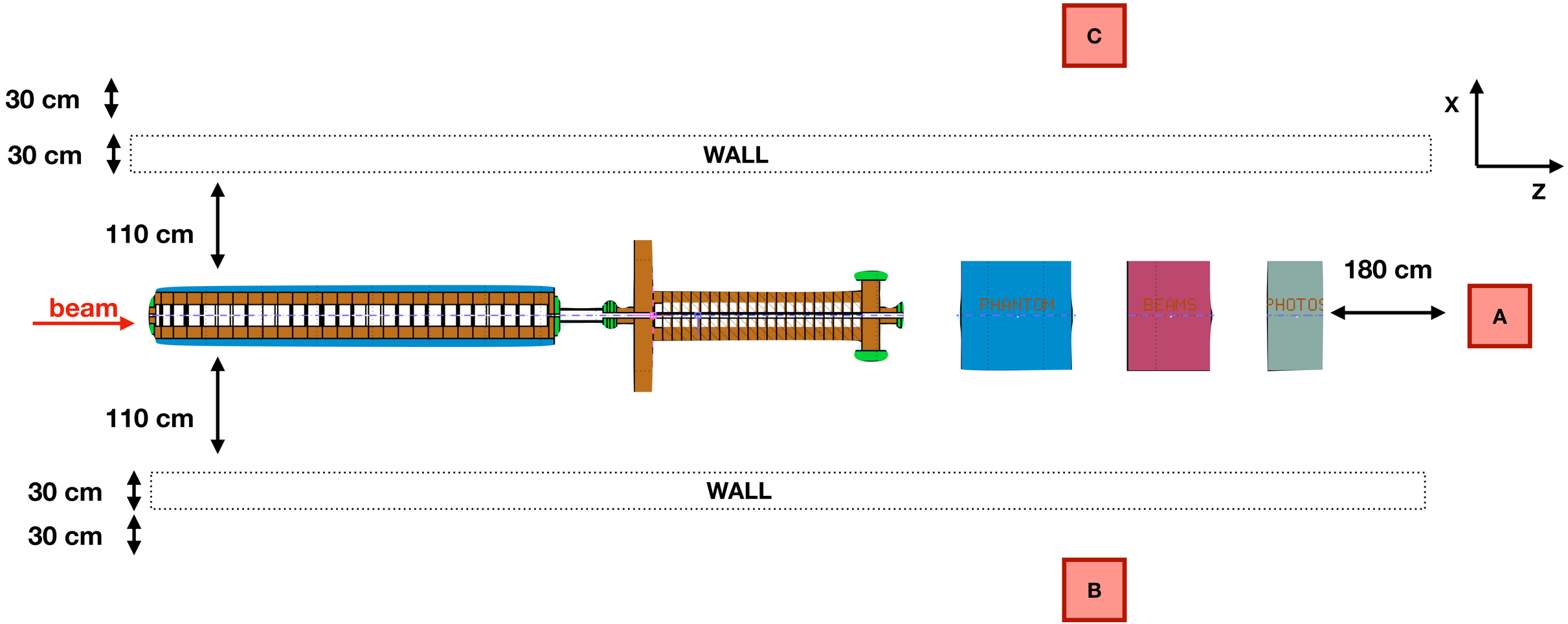
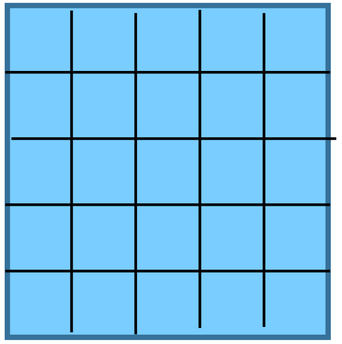


Dose evaluation for Radioprotection protocols

- The cubic **air volumes** in which the dose is evaluated have dimensions of $5 \cdot 5 \cdot 5 cm^3$ and are voxelized into $5 \cdot 5 \cdot 5$bins.



- The dose of each volume was taken as the **average of the doses of individual bins**, with an error given by the uncertainty on the mean. For each voxel, the standard deviation is also reported.

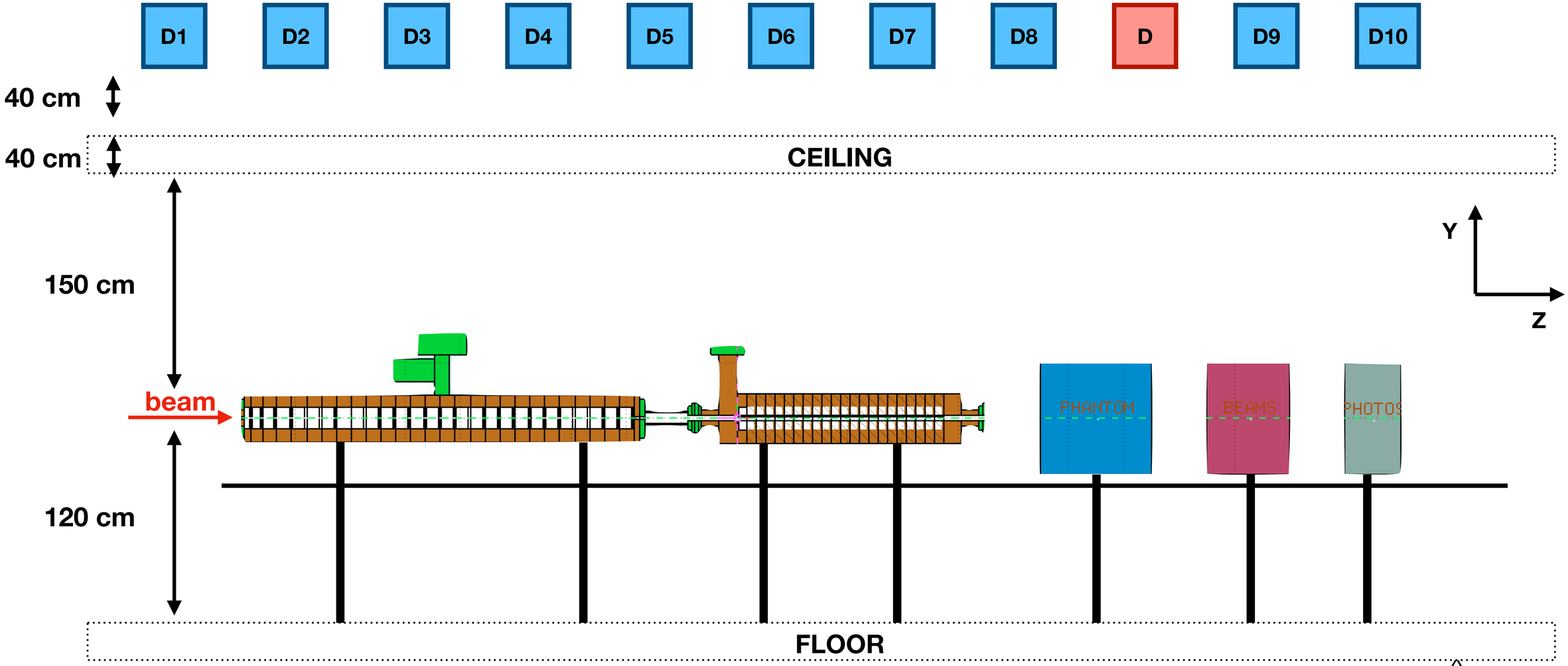
TOTAL DOSE RELEASE

	Mean Dose [Gy/primary]	Stdev [Gy/primary]
A	$9.73 \cdot 10^{-18} \pm 3.06 \cdot 10^{-19}$	$3.42 \cdot 10^{-18}$
B	$7.28 \cdot 10^{-18} \pm 3.28 \cdot 10^{-19}$	$3.67 \cdot 10^{-18}$
C	$7.82 \cdot 10^{-18} \pm 3.48 \cdot 10^{-19}$	$3.89 \cdot 10^{-18}$
D	$3.86 \cdot 10^{-18} \pm 2.27 \cdot 10^{-19}$	$2.54 \cdot 10^{-18}$

With a statistics of $5 \cdot 10^8$ primary electrons

Dose evaluation for Radioprotection protocols

- To evaluate the variation of dose with respect to spatial coordinates along the accelerator, the same air volumes were replicated in the same directions as before, spaced 15 cm apart.



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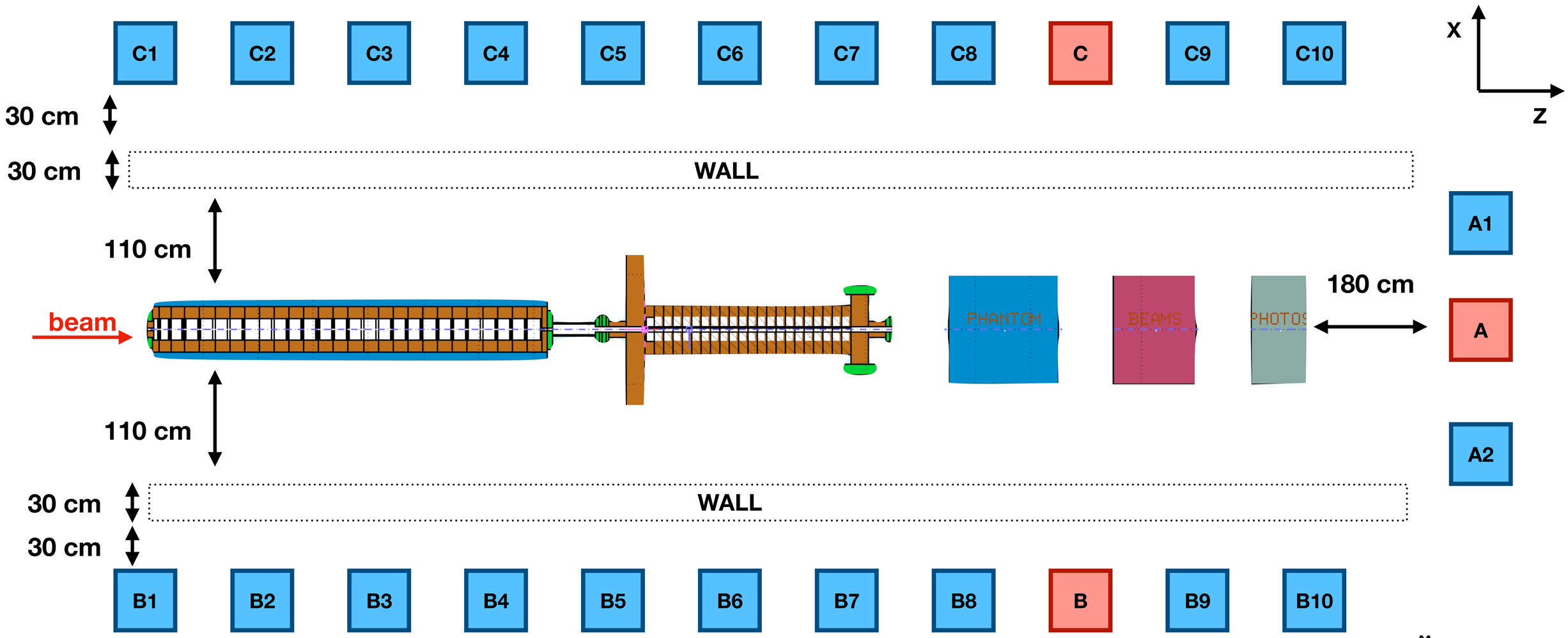
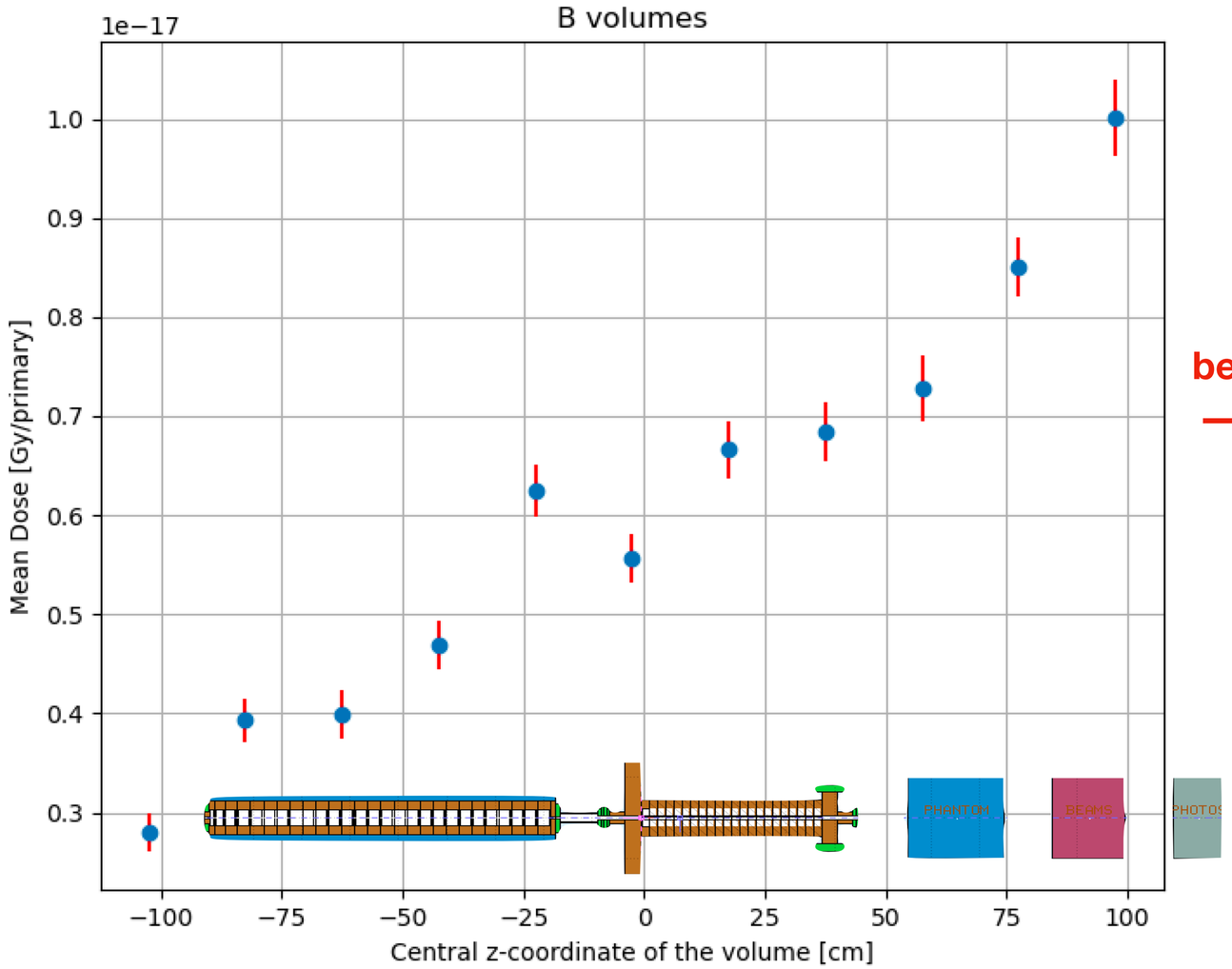
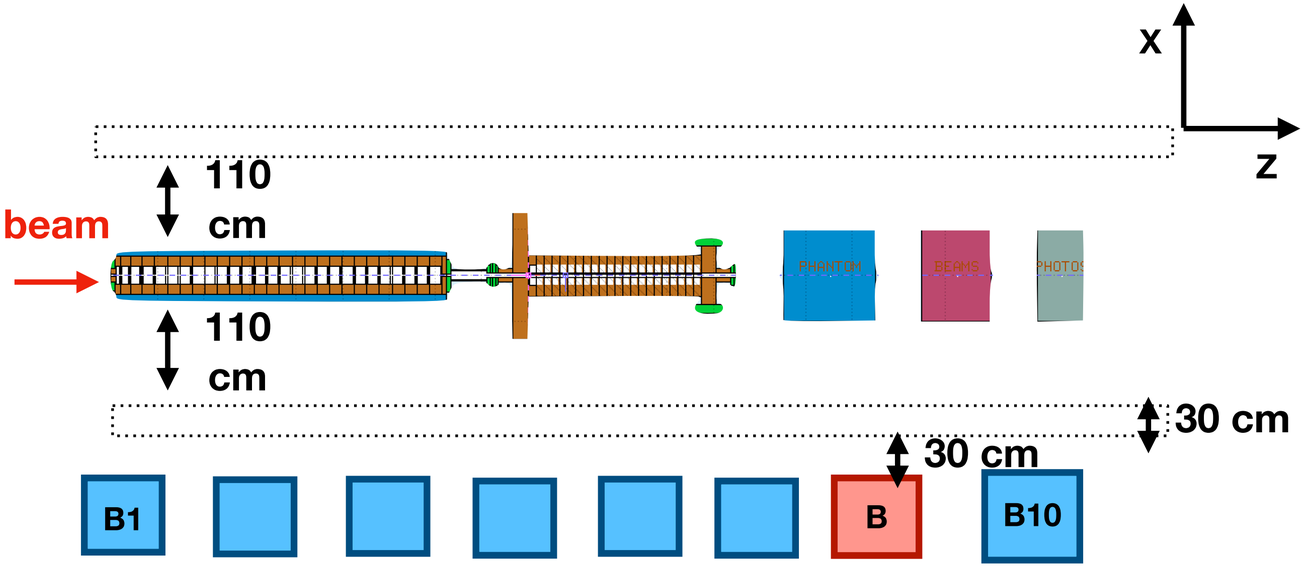


Dose evaluation for Radioprotection protocols

- The average dose values per primary electron (with associated error) are reported as a function of spatial coordinates, for each direction.





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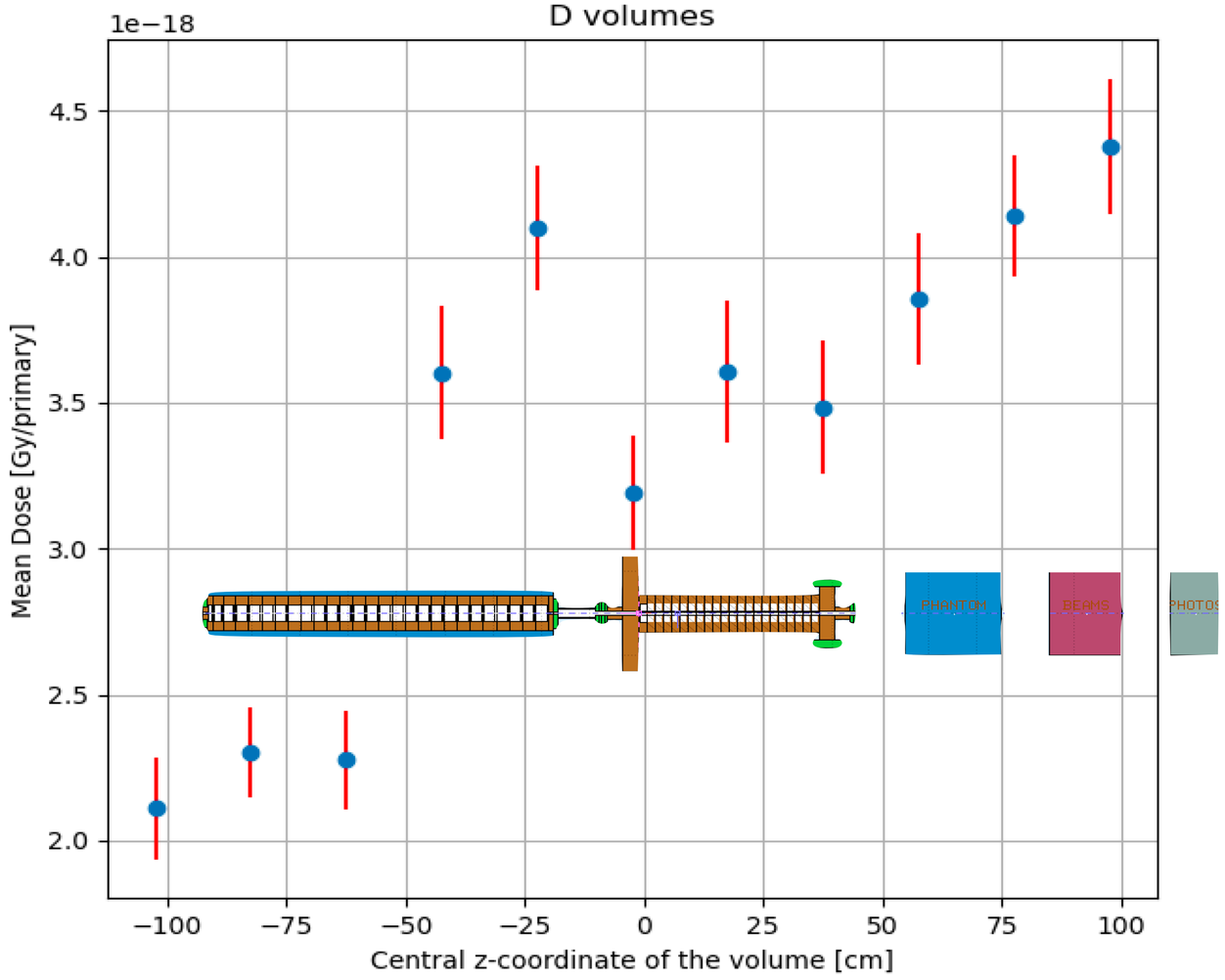

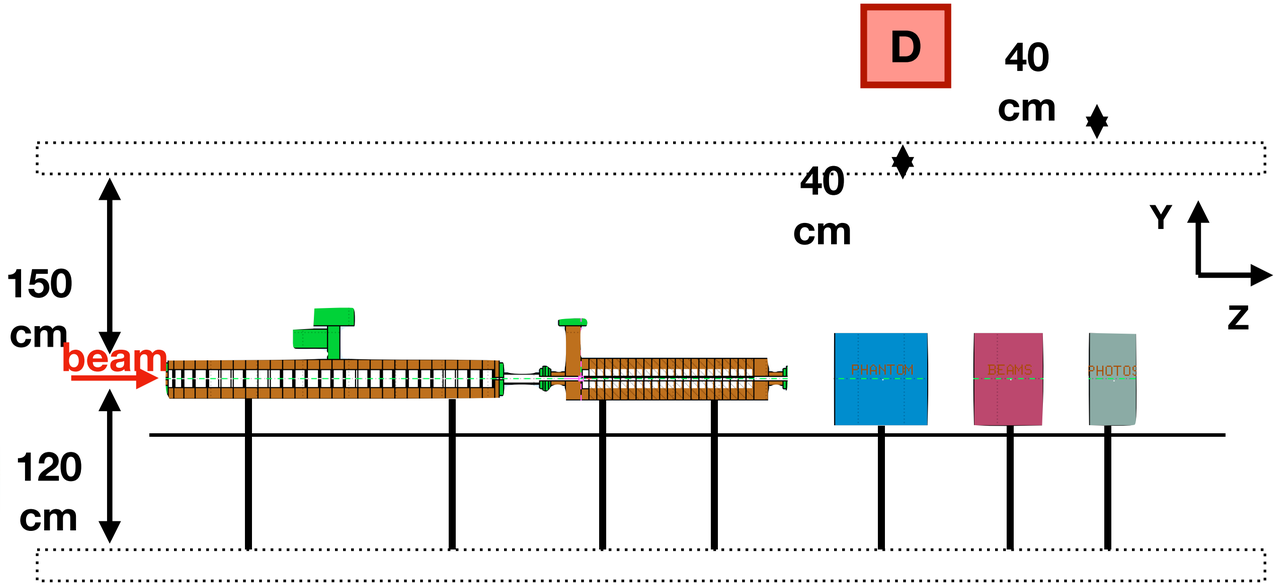

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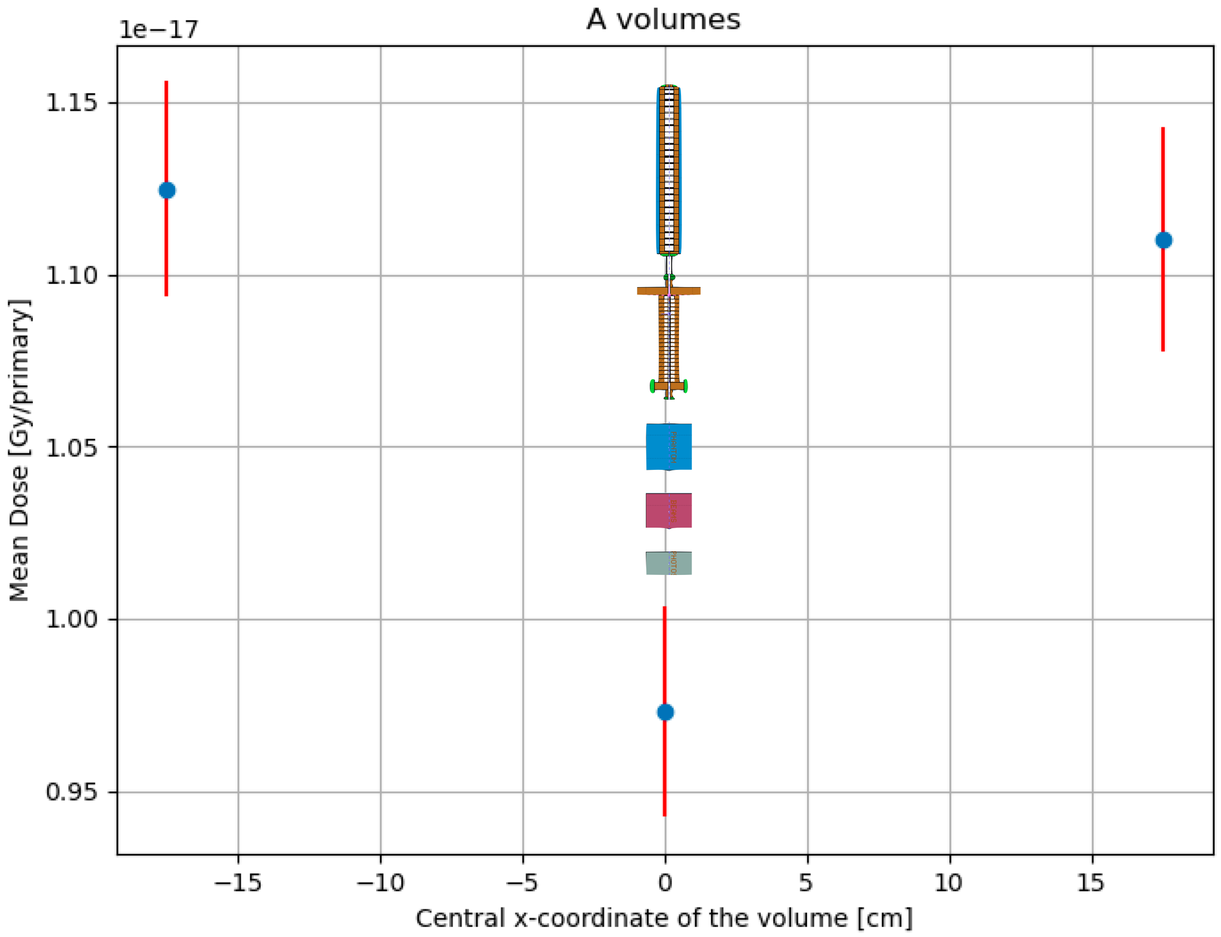
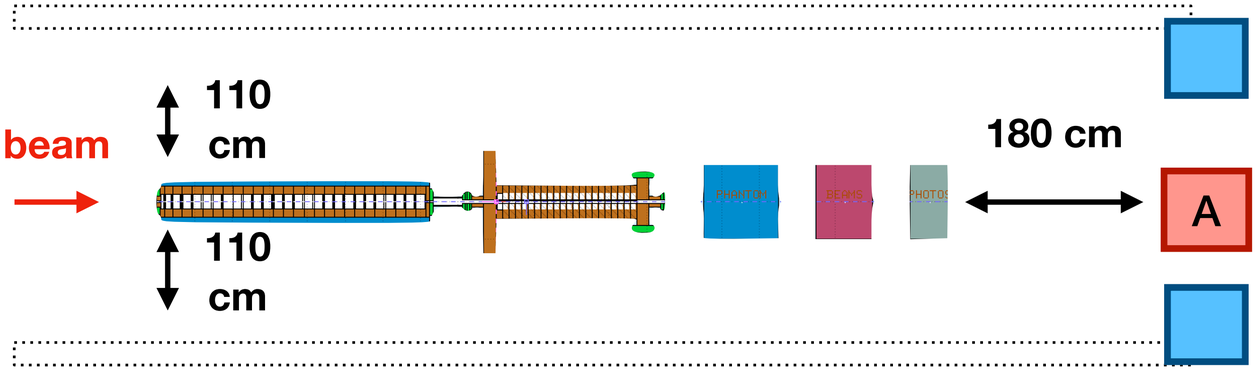
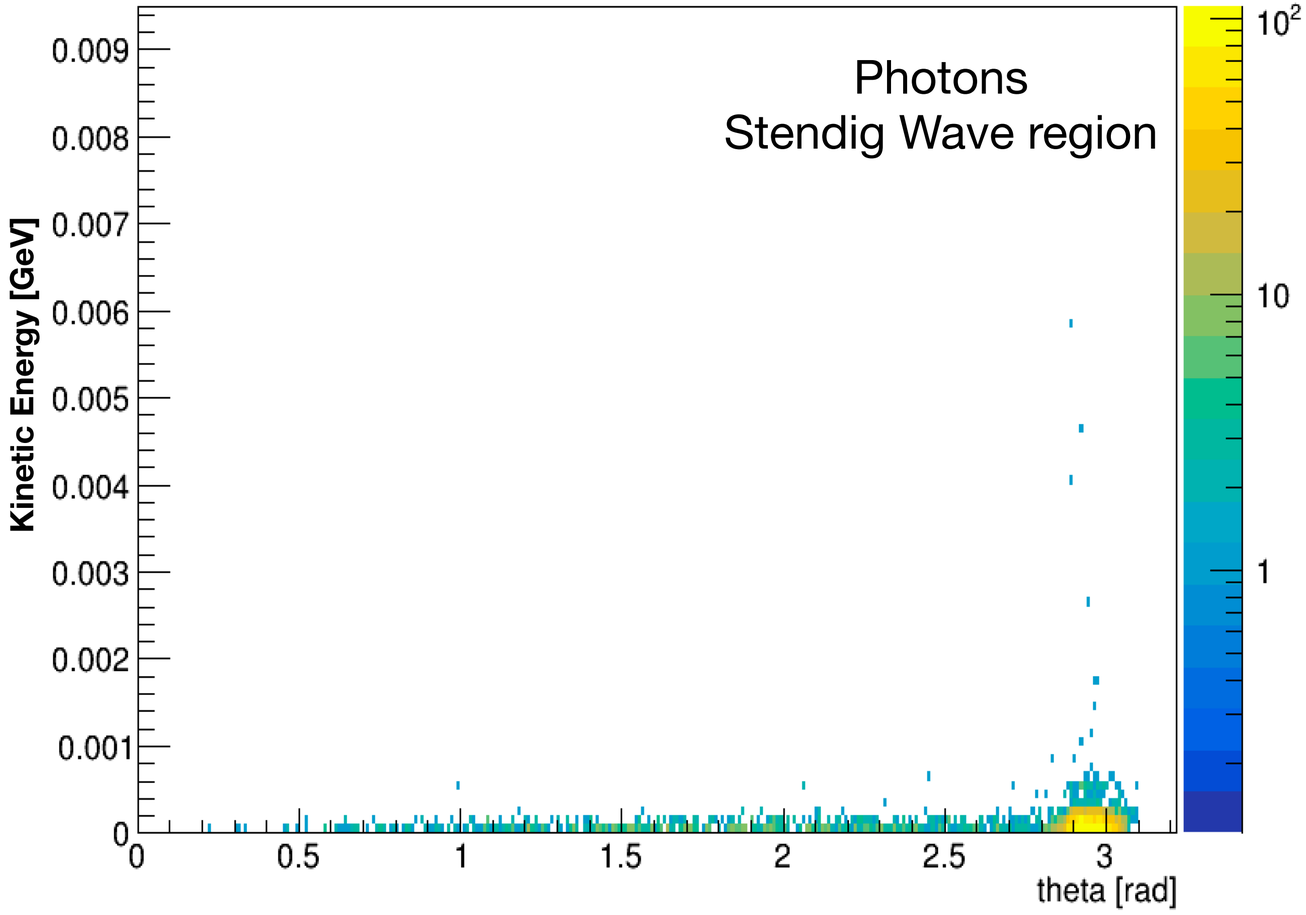
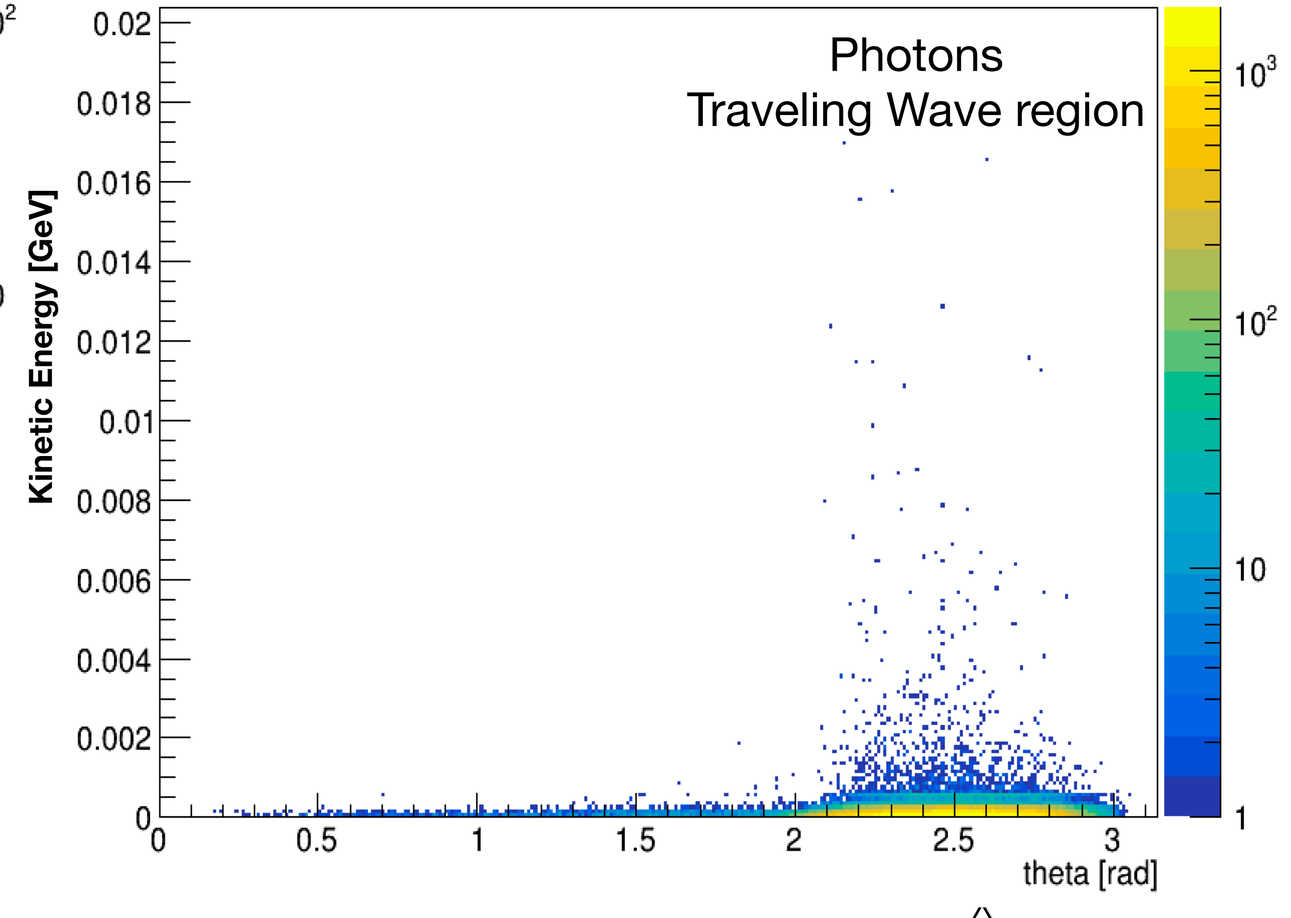




Dose evaluation for Radioprotection protocols

- To understand which region of space is affected by scattered radiation flux, the crossing angles relative to the axis of the photon and electron beam were evaluated along the entire accelerator.





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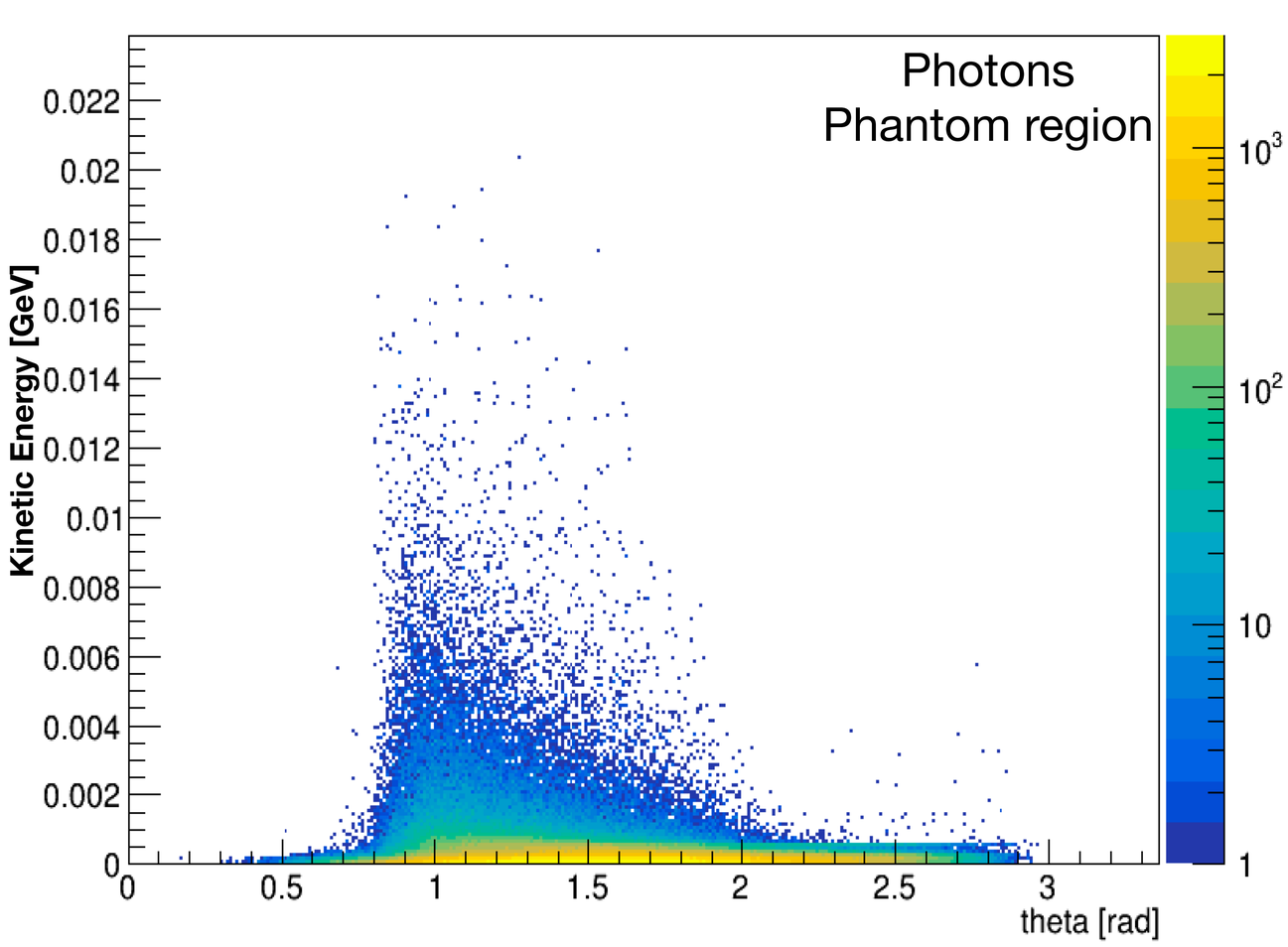

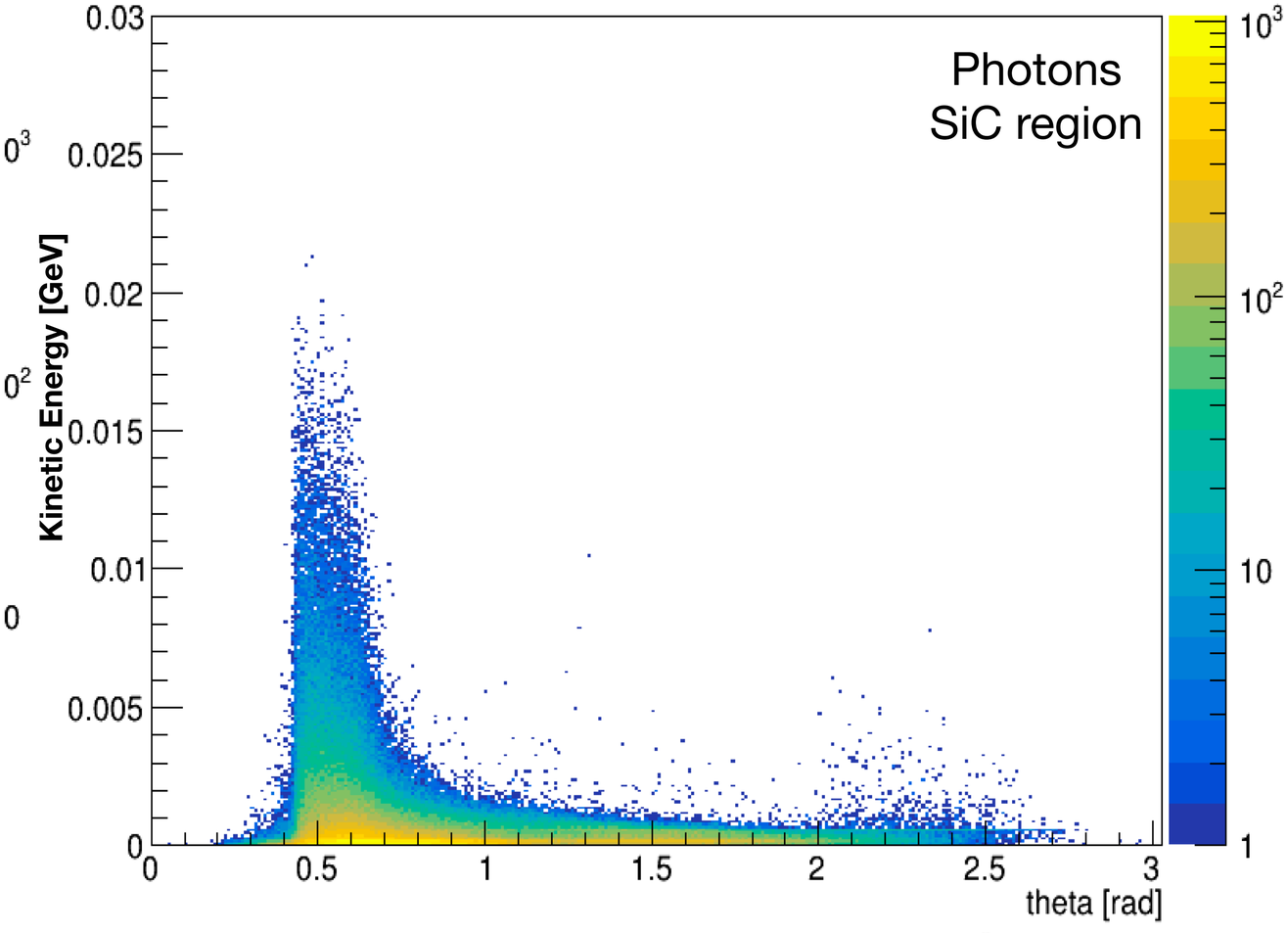

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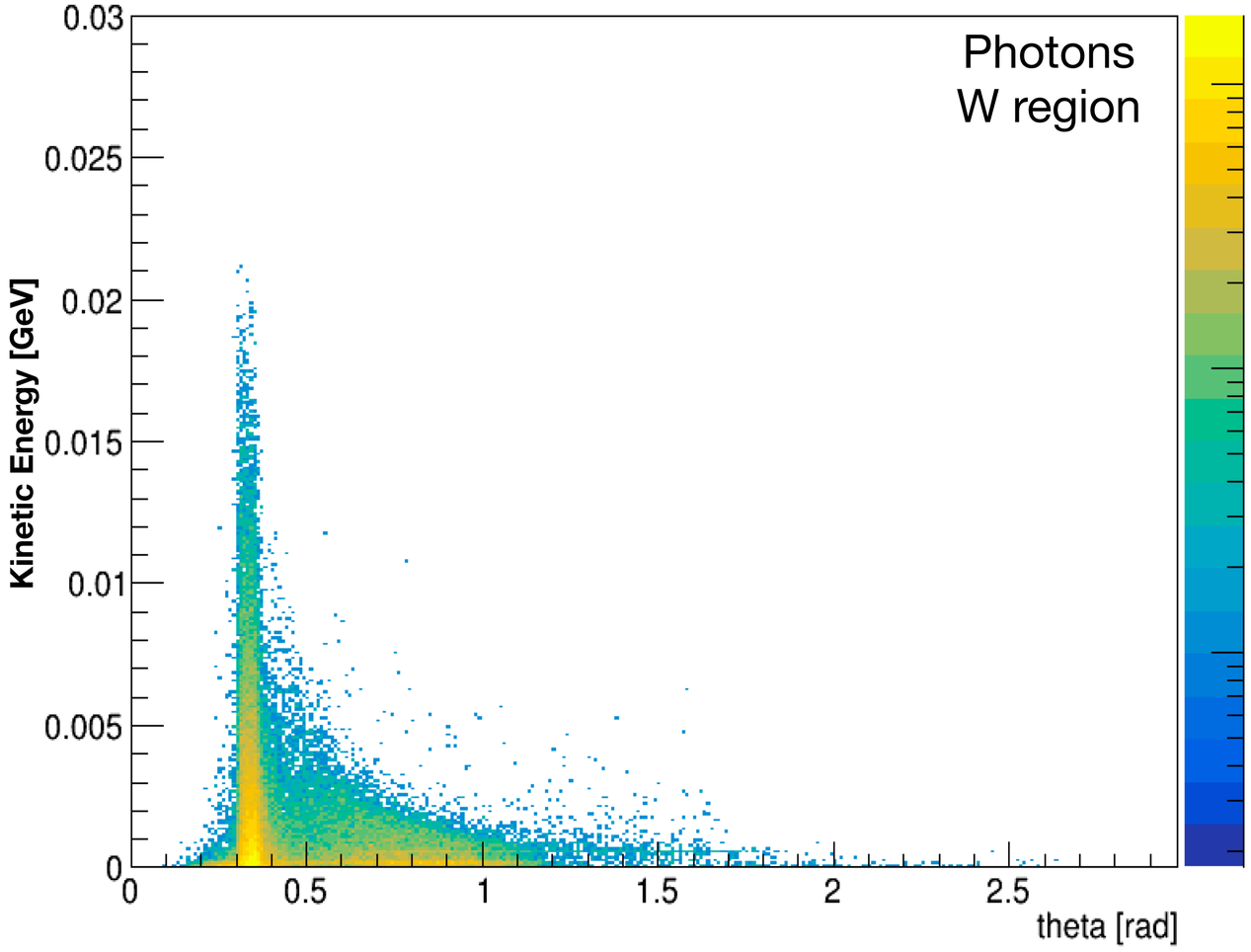

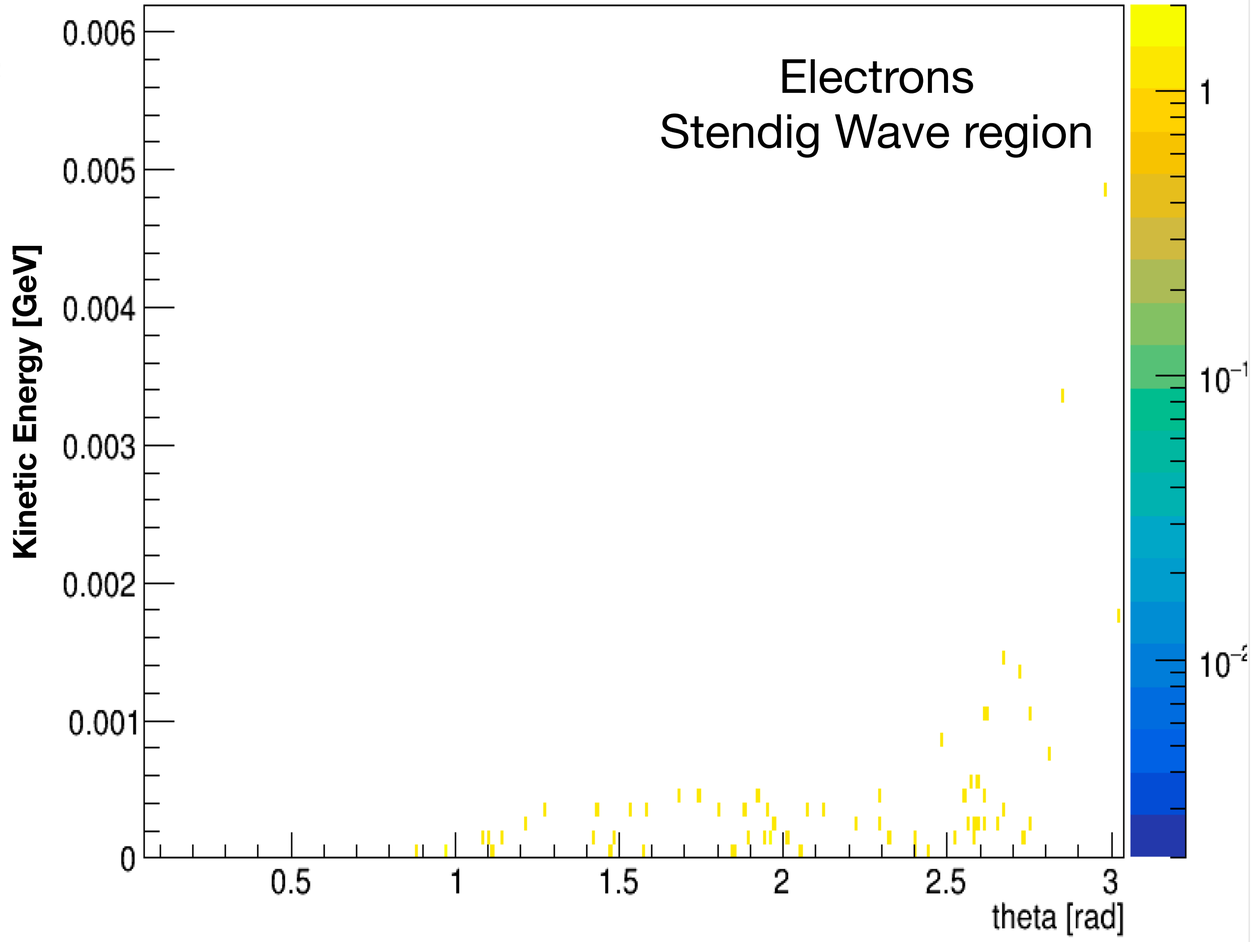

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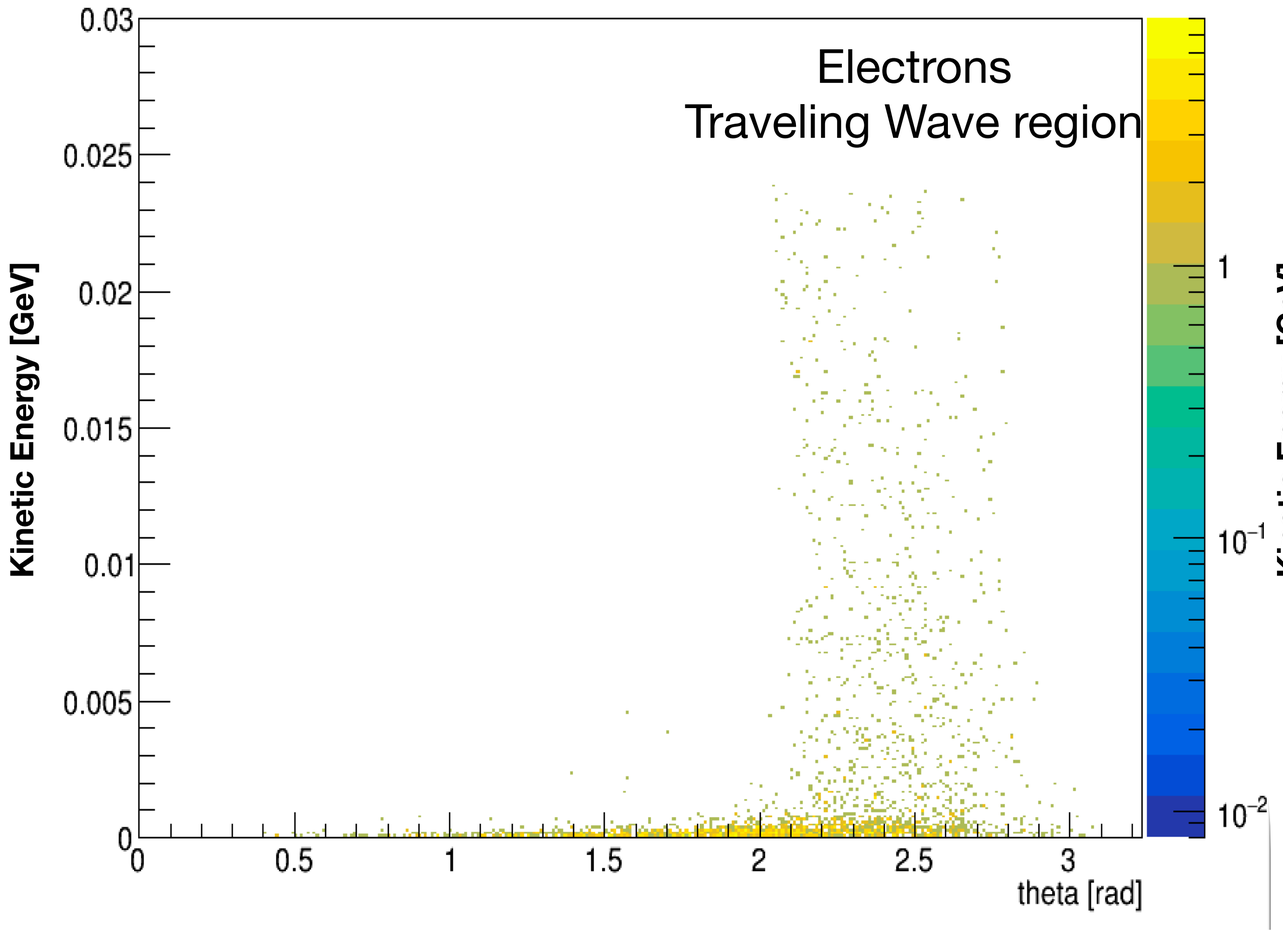

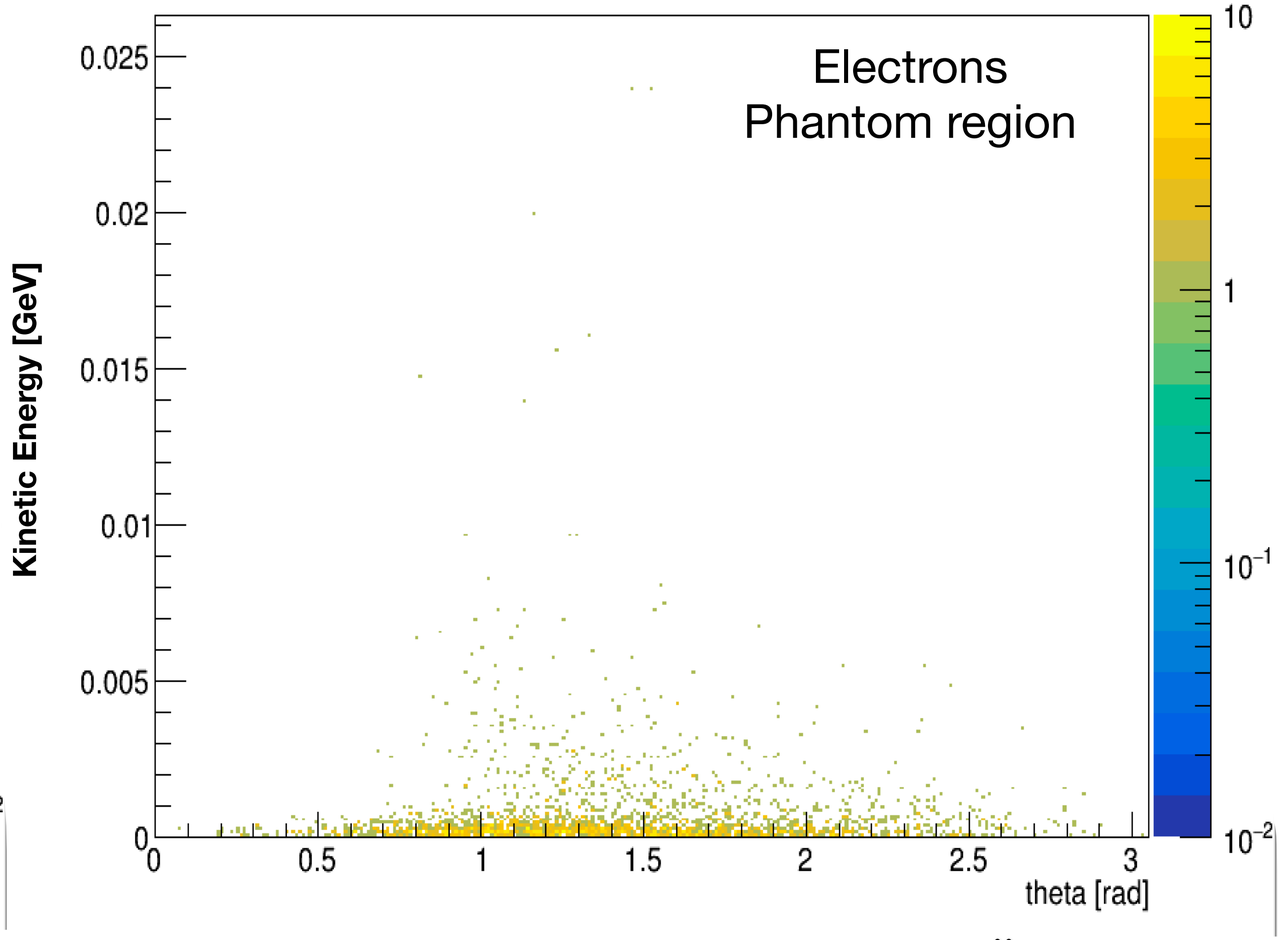

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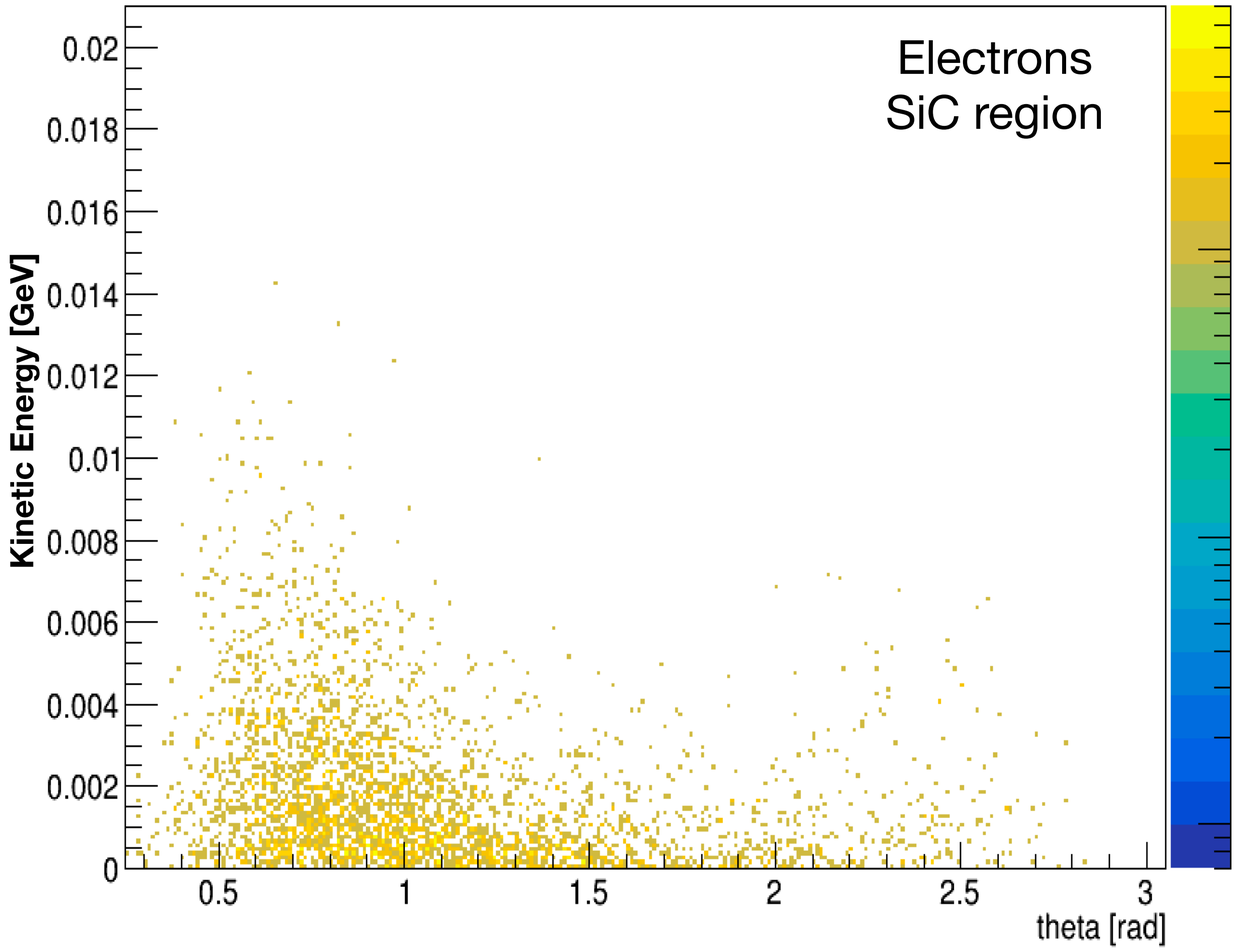

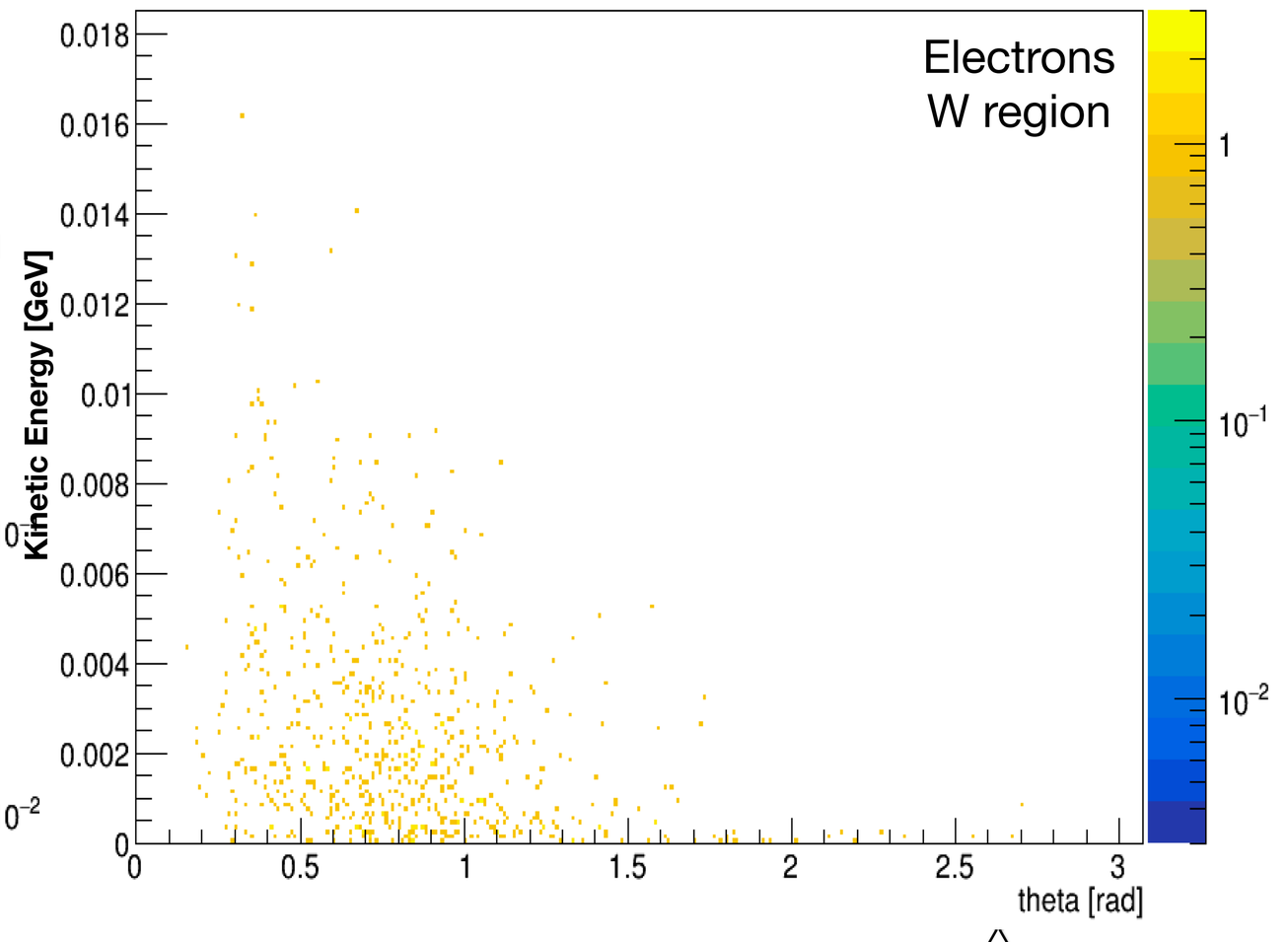

Dose evaluation for Radioprotection protocols

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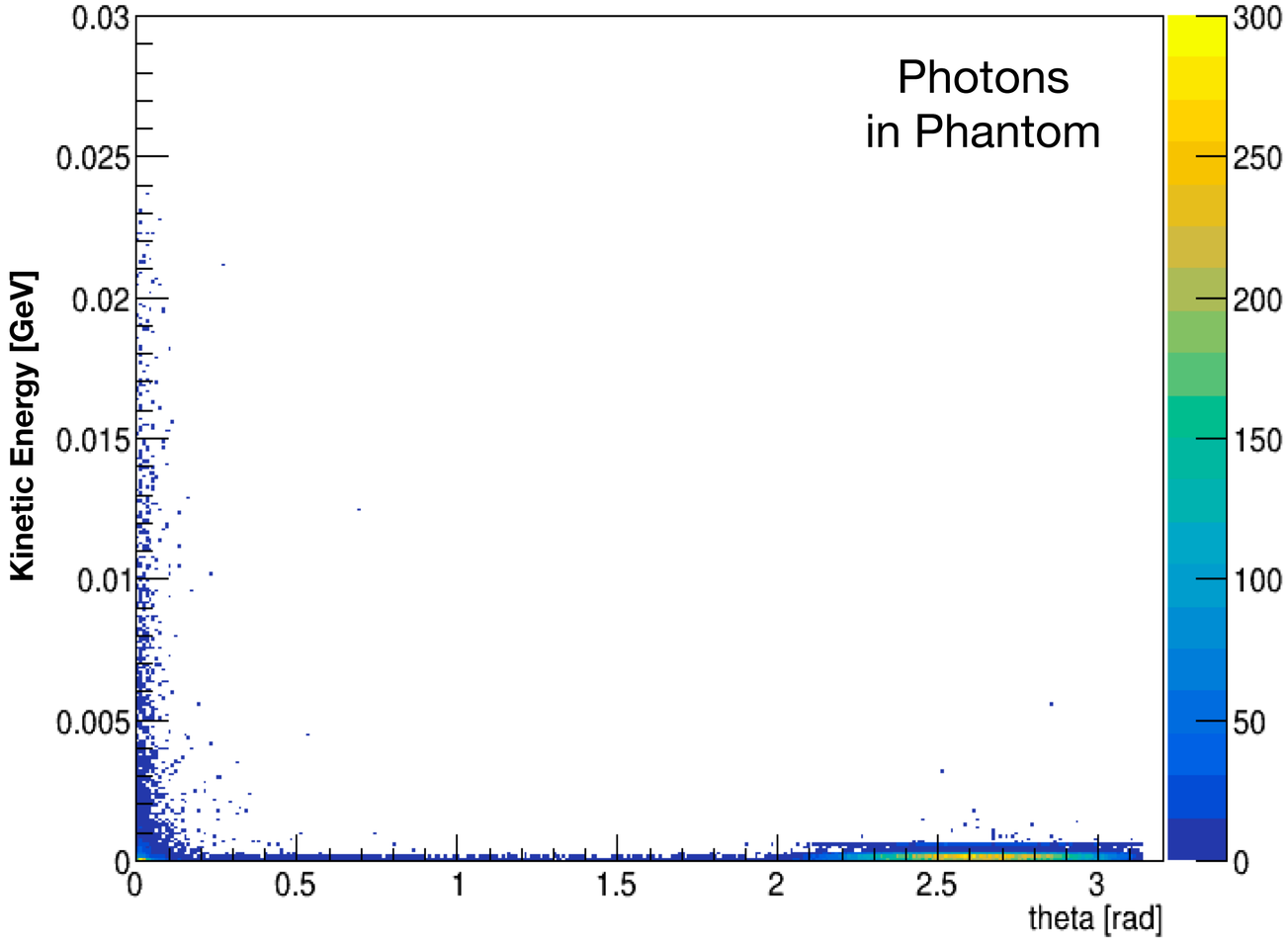

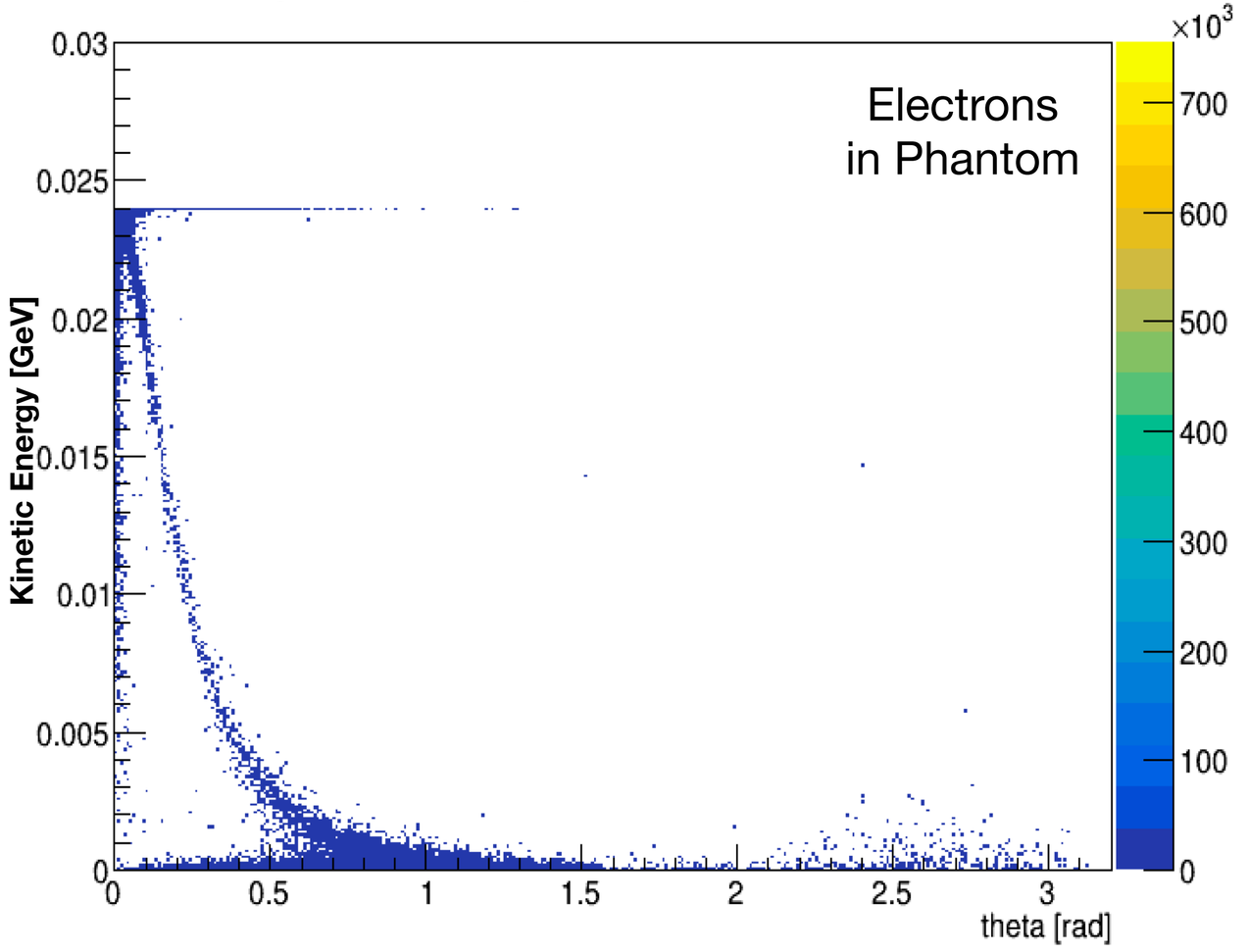

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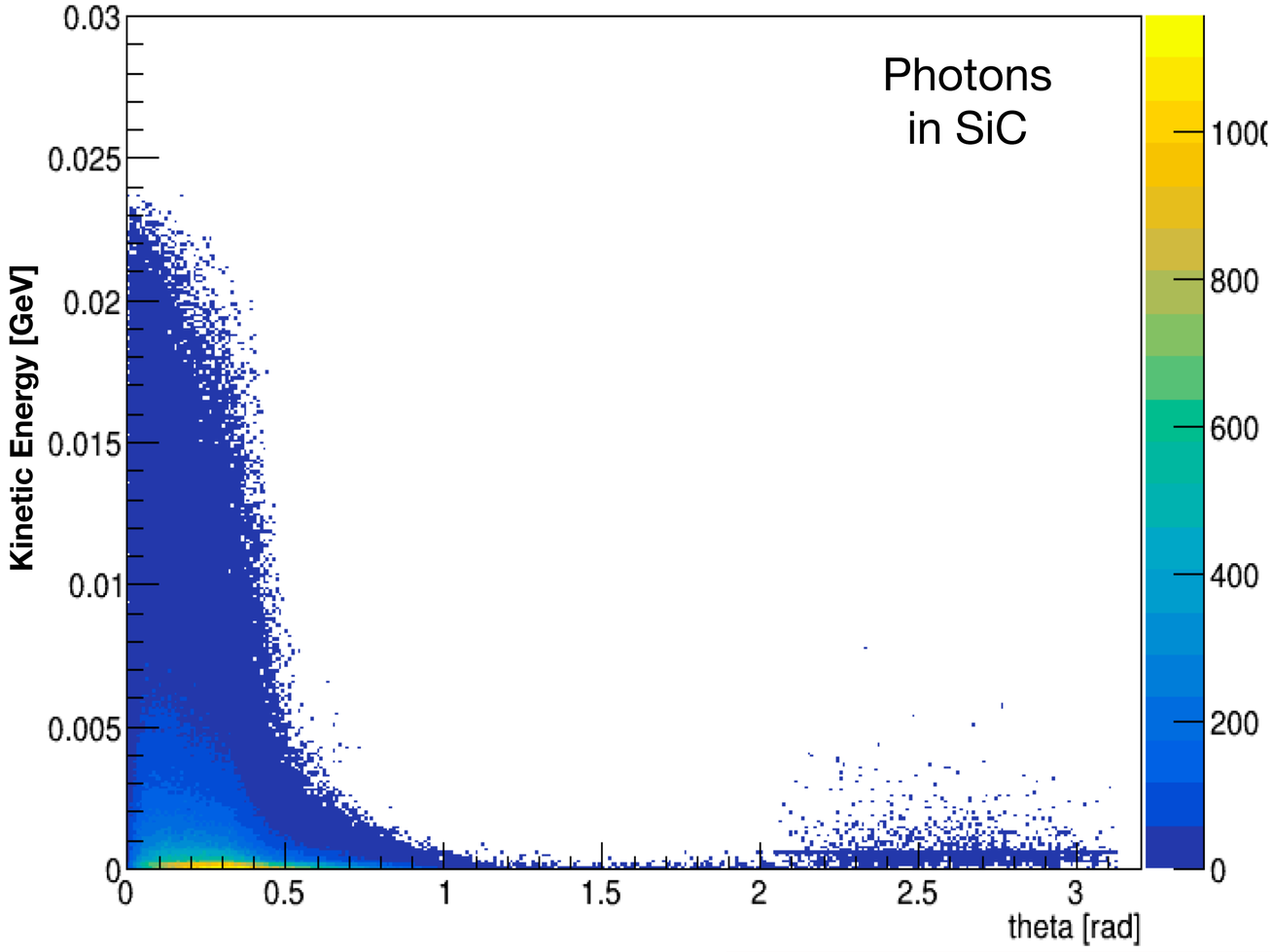
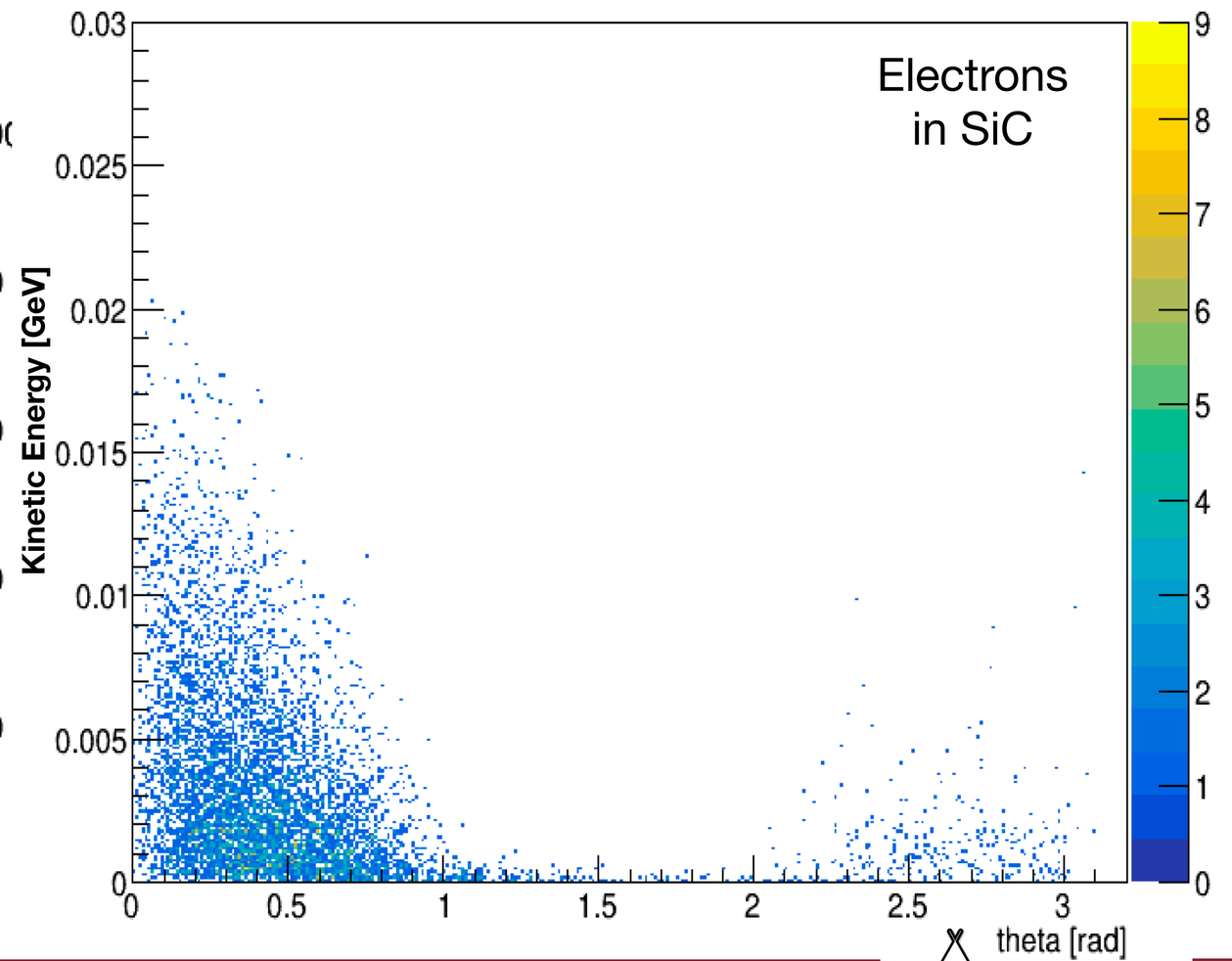
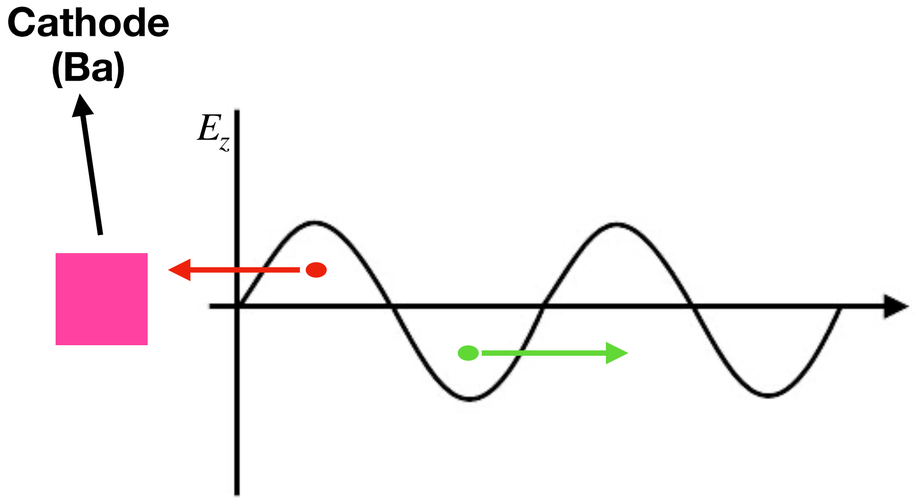




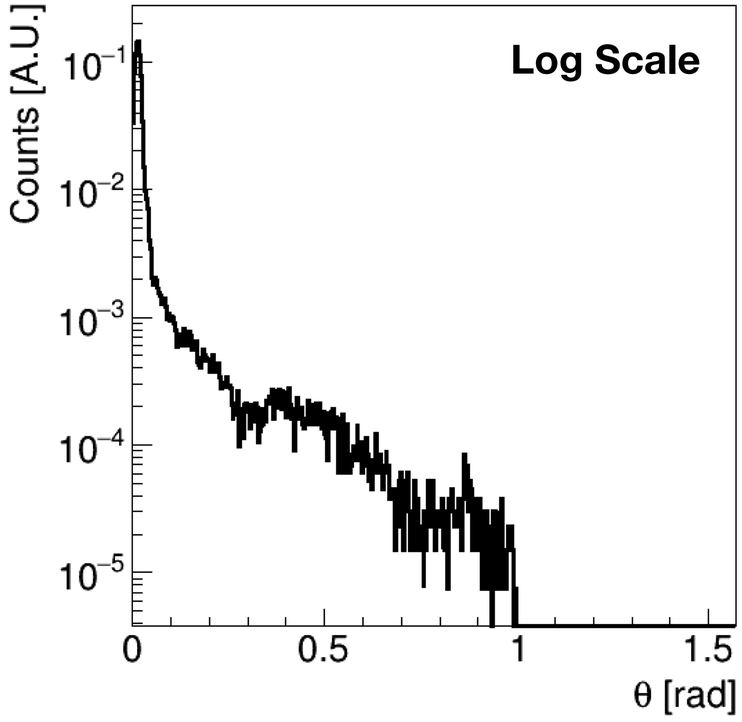
Analysis of the FLUKA simulation: DISPERSED FLUX back-scattered

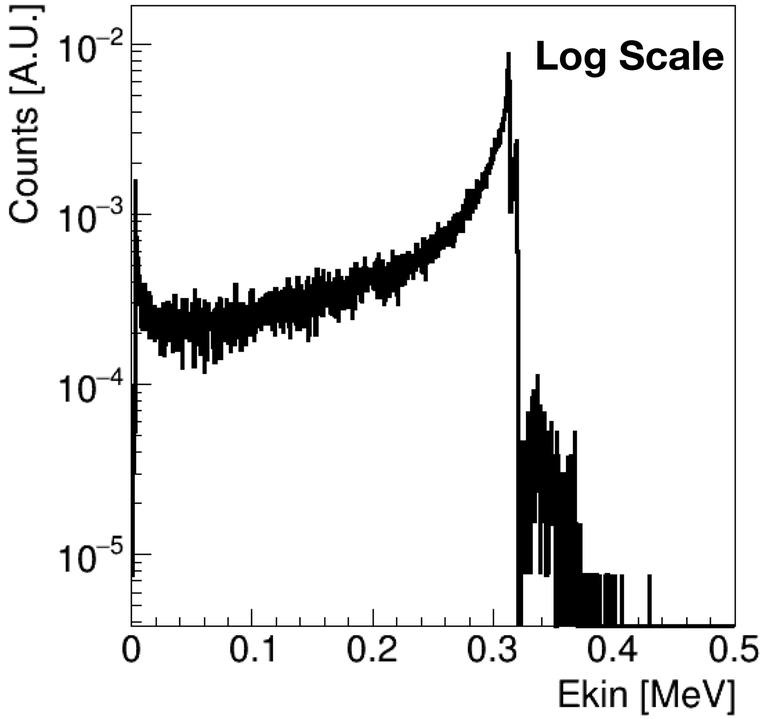
Backscattered primaries

Inside a standing wave structure, approximately half of the particles within the first cell will experience a decelerating electric field, causing these particles to be **transported backward towards the cathode**. It is not possible to access the geometric and energetic information of these particles, but we know that they travel in the opposite direction to the accelerated beam and that their energy distribution is, at most, that of the particles accelerated forward from the second cavity onwards.



N tot e^-	$2 \cdot 10^5$
N forward e^-	114625
N backscattered e^-	**85375**



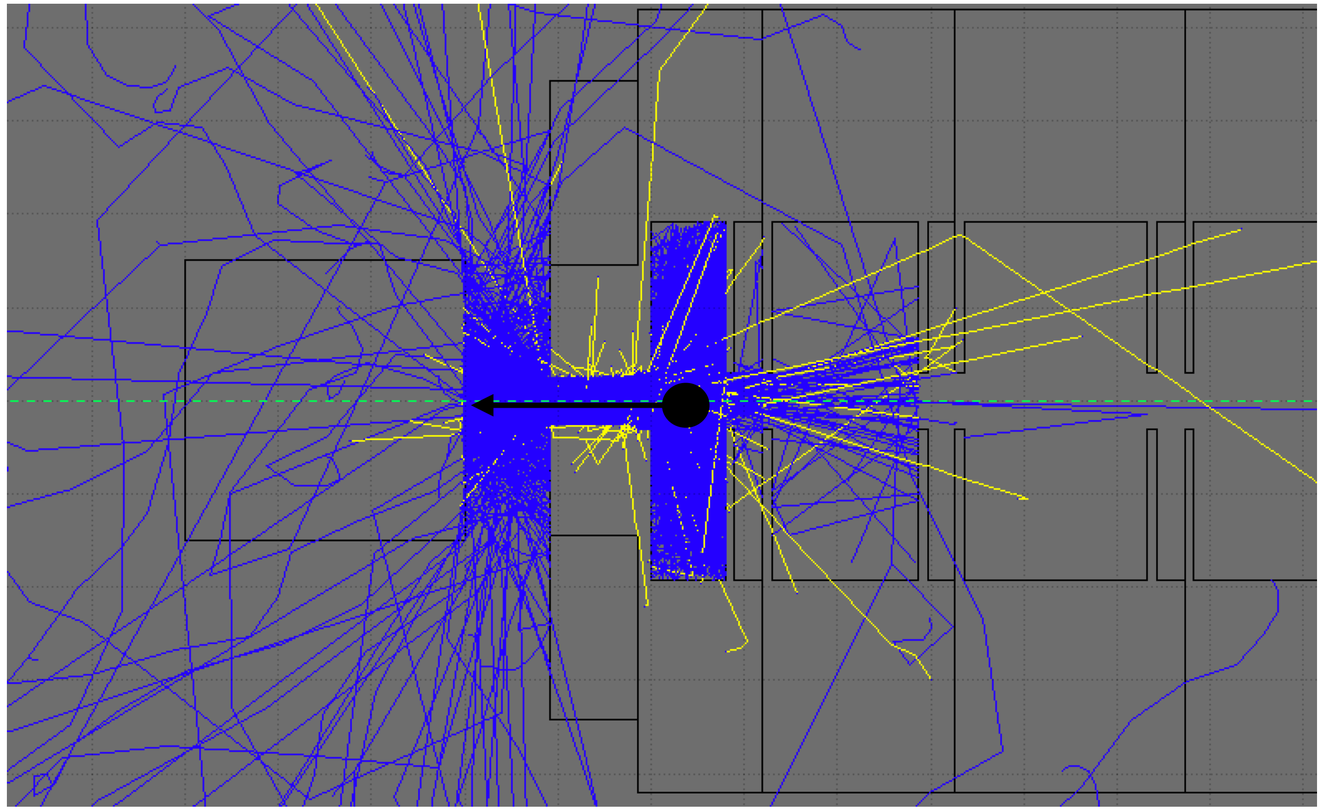


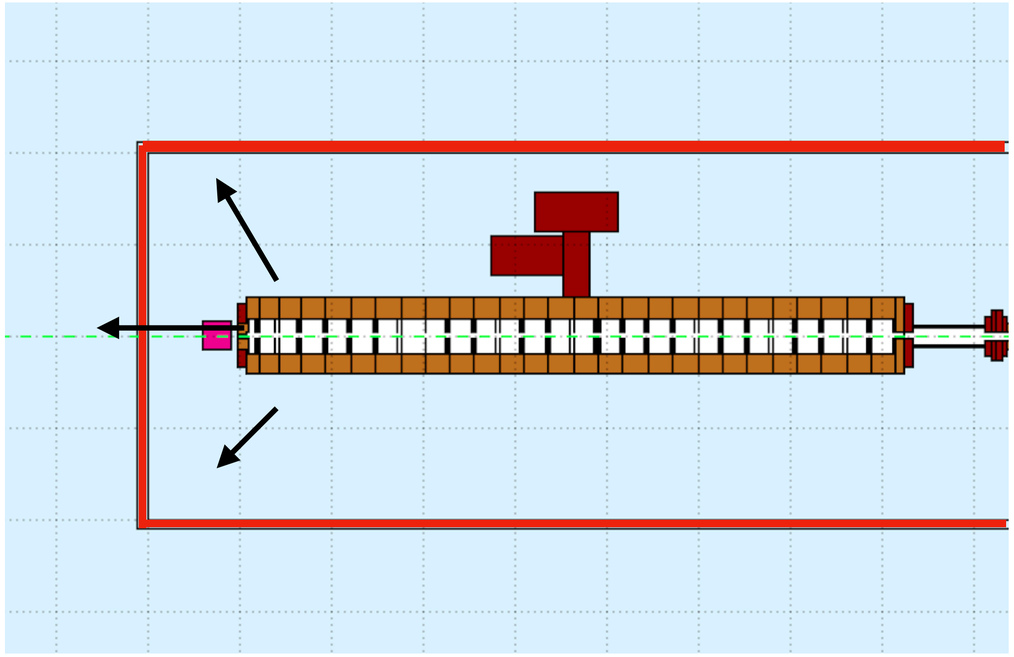
Angle and energy distributions of the particles accelerated forward at the second cavity.

FLUKA tracks

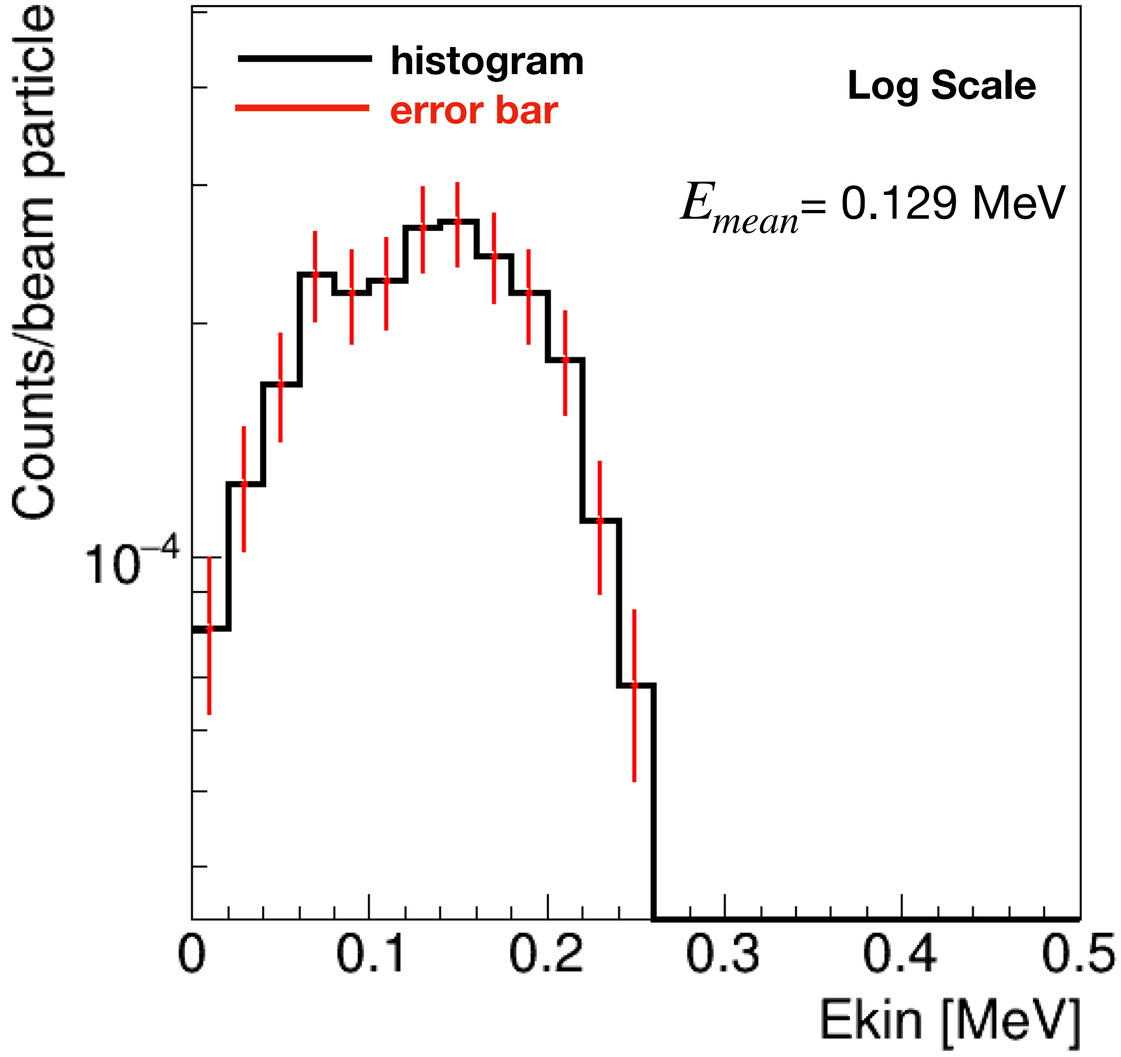
The majority of these electrons are absorbed by the materials composing the accelerator (copper and steel) and by the cathode (barium). Some of them contribute to the scattered flux, which is evaluated around the accelerator, as previously shown.

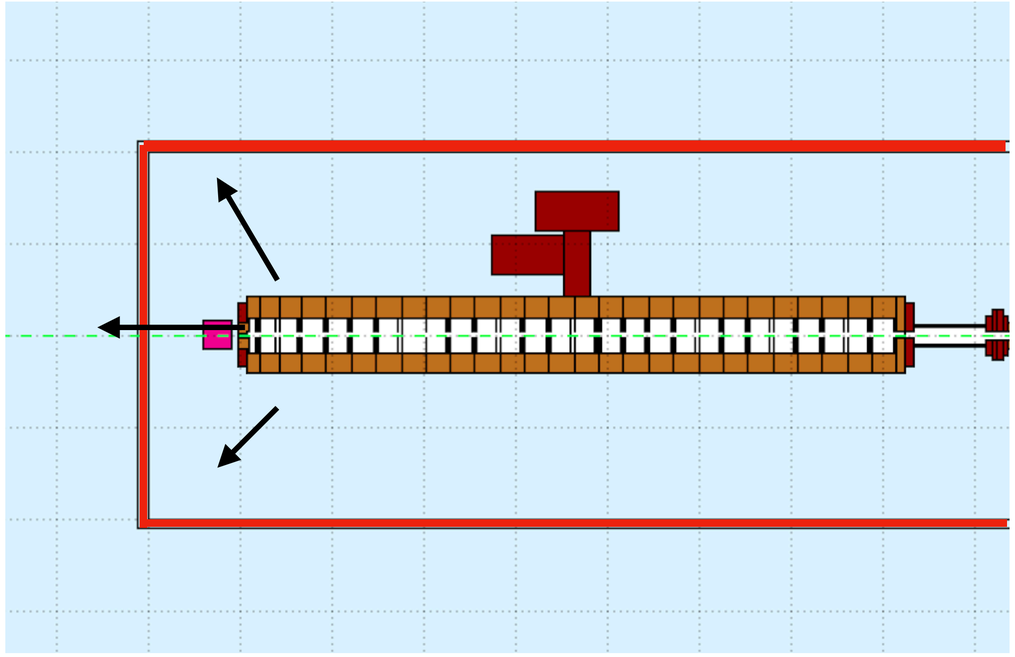
electrons **photons**





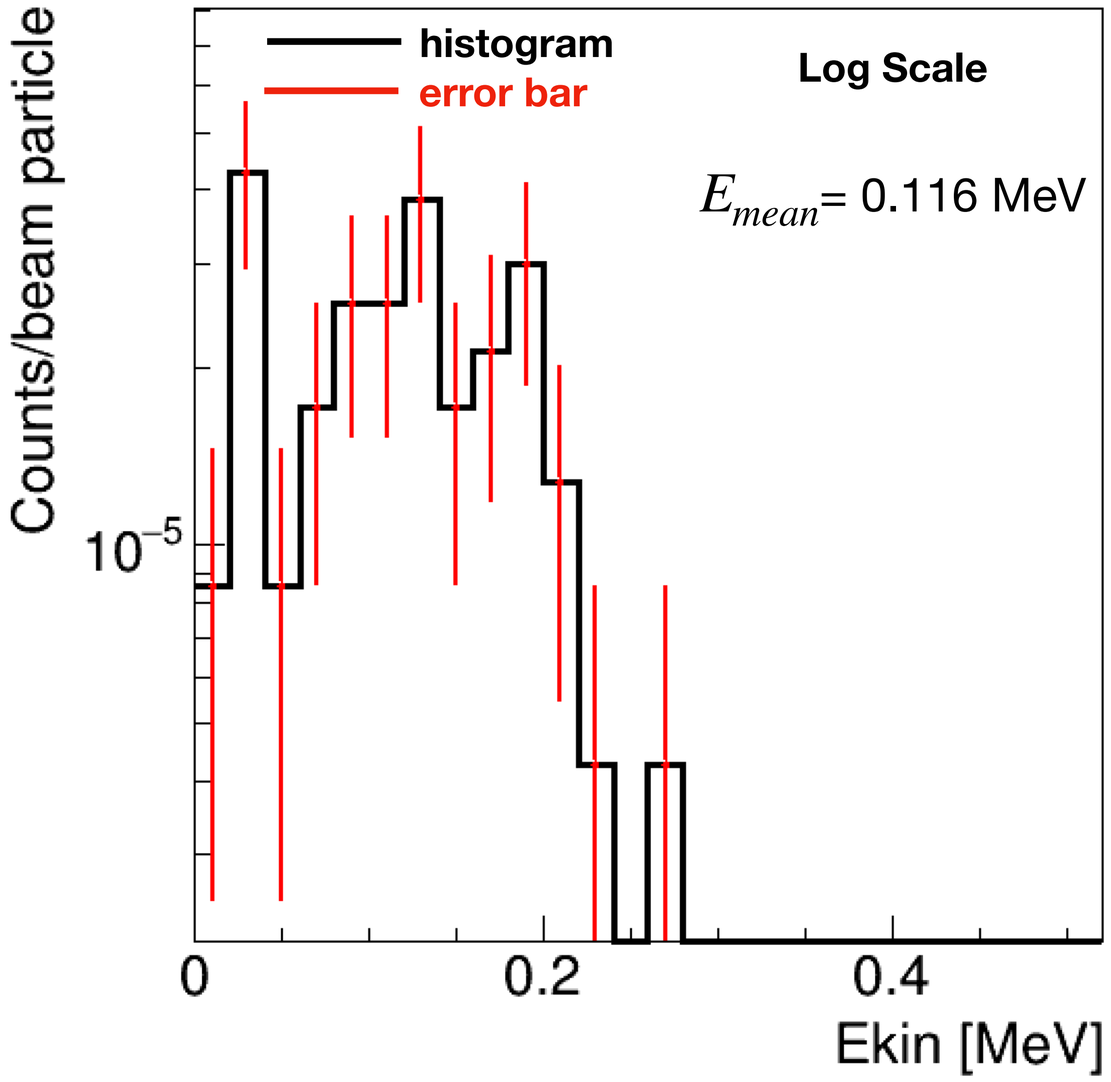
Electrons propagated by FLUKA

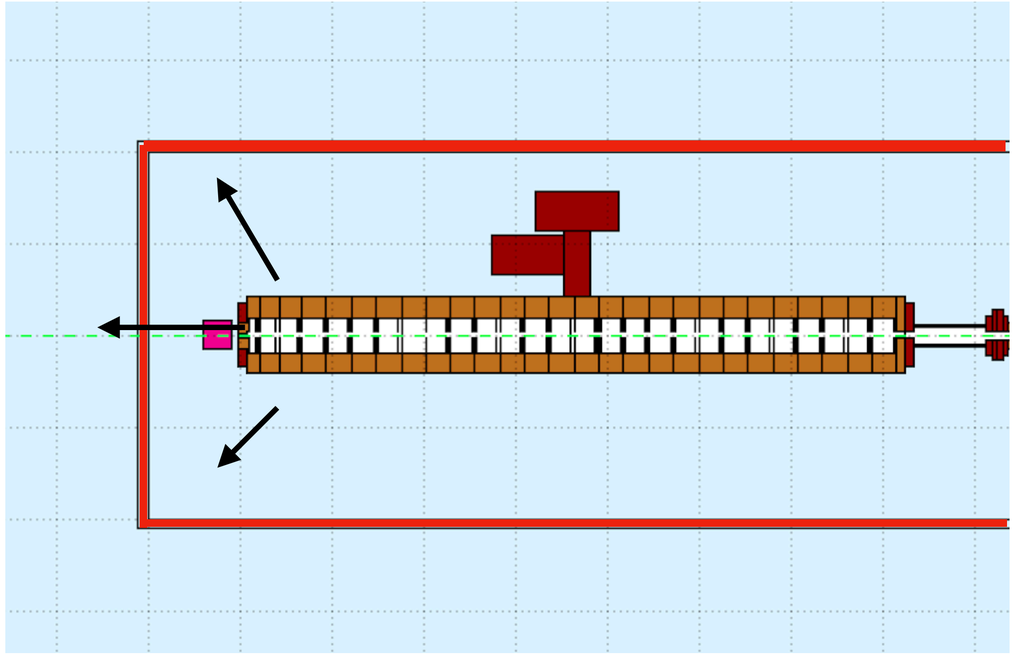




The histograms are **normalized to the number of particles simulated with FLUKA**. These results indicate the number and energy distribution of particles (electrons and photons) produced **per beam particle**.

Photons propagated by FLUKA





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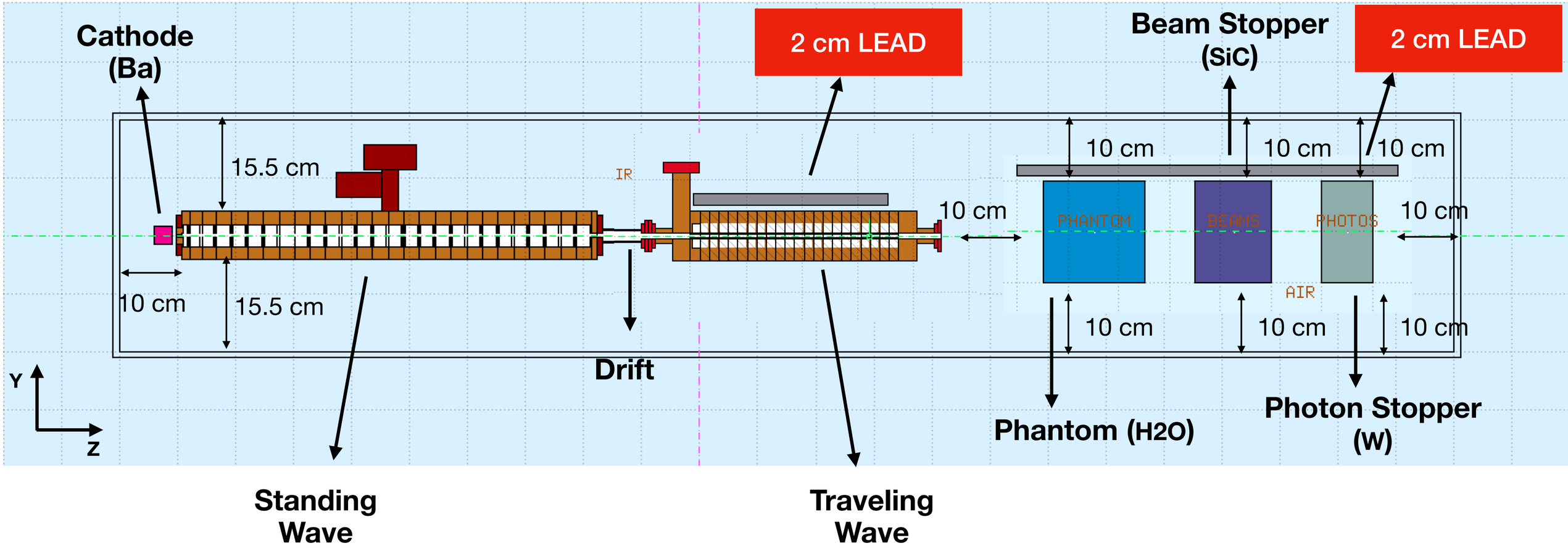
1st SHIELDING ATTEMPT

FLUKA geometry

- The full **geometry** (including **materials**) of the accelerator has been implemented **in FLUKA**.



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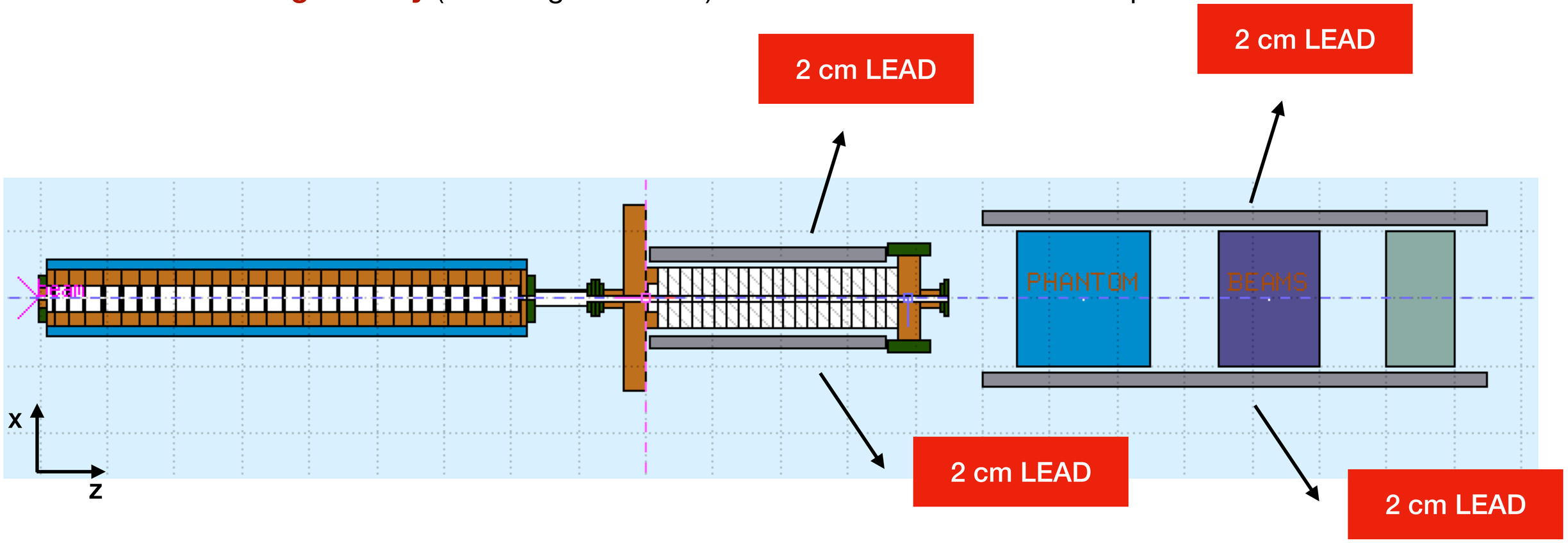
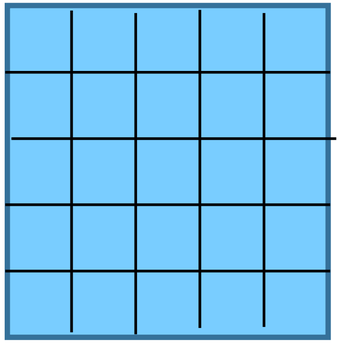


Dose evaluation for Radioprotection protocols

- The cubic **air volumes** in which the dose is evaluated have dimensions of $5 \cdot 5 \cdot 5 cm^3$ and are voxelized into $5 \cdot 5 \cdot 5$bins.



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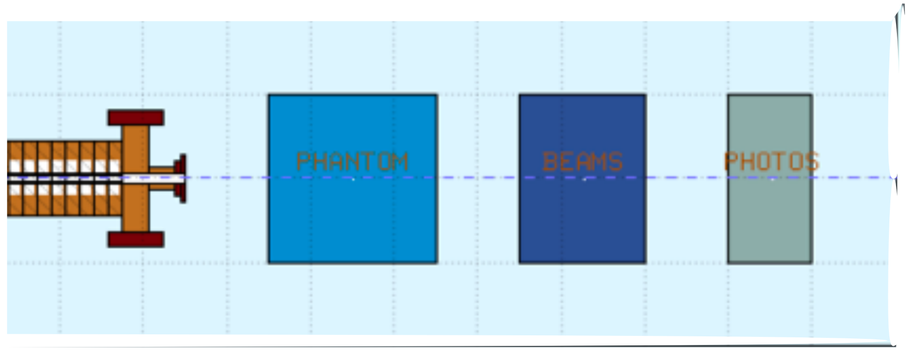
TOTAL DOSE RELEASE

	Mean Dose [Gy/primary]	Stdev [Gy/primary]
A	$3.73 \cdot 10^{-18} \pm 1.56 \cdot 10^{-19}$	$1.74 \cdot 10^{-18}$
B	$1.66 \cdot 10^{-18} \pm 1.49 \cdot 10^{-19}$	$1.67 \cdot 10^{-18}$
C	$1.53 \cdot 10^{-18} \pm 1.19 \cdot 10^{-19}$	$1.33 \cdot 10^{-18}$
D	$5.65 \cdot 10^{-19} \pm 5.02 \cdot 10^{-20}$	$5.62 \cdot 10^{-19}$

With a statistics of $1 \cdot 10^{7}$ primary electrons

Dose evaluation for Radioprotection protocols

TOTAL DOSE RELEASE WITHOUT SHIELDING



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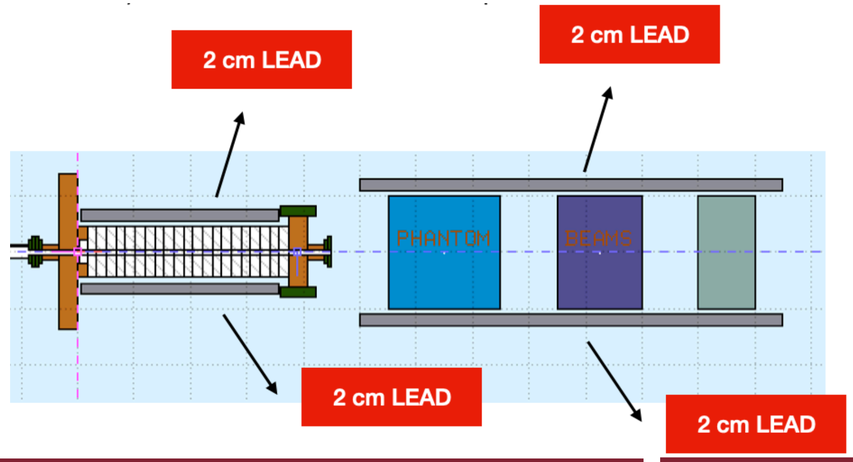

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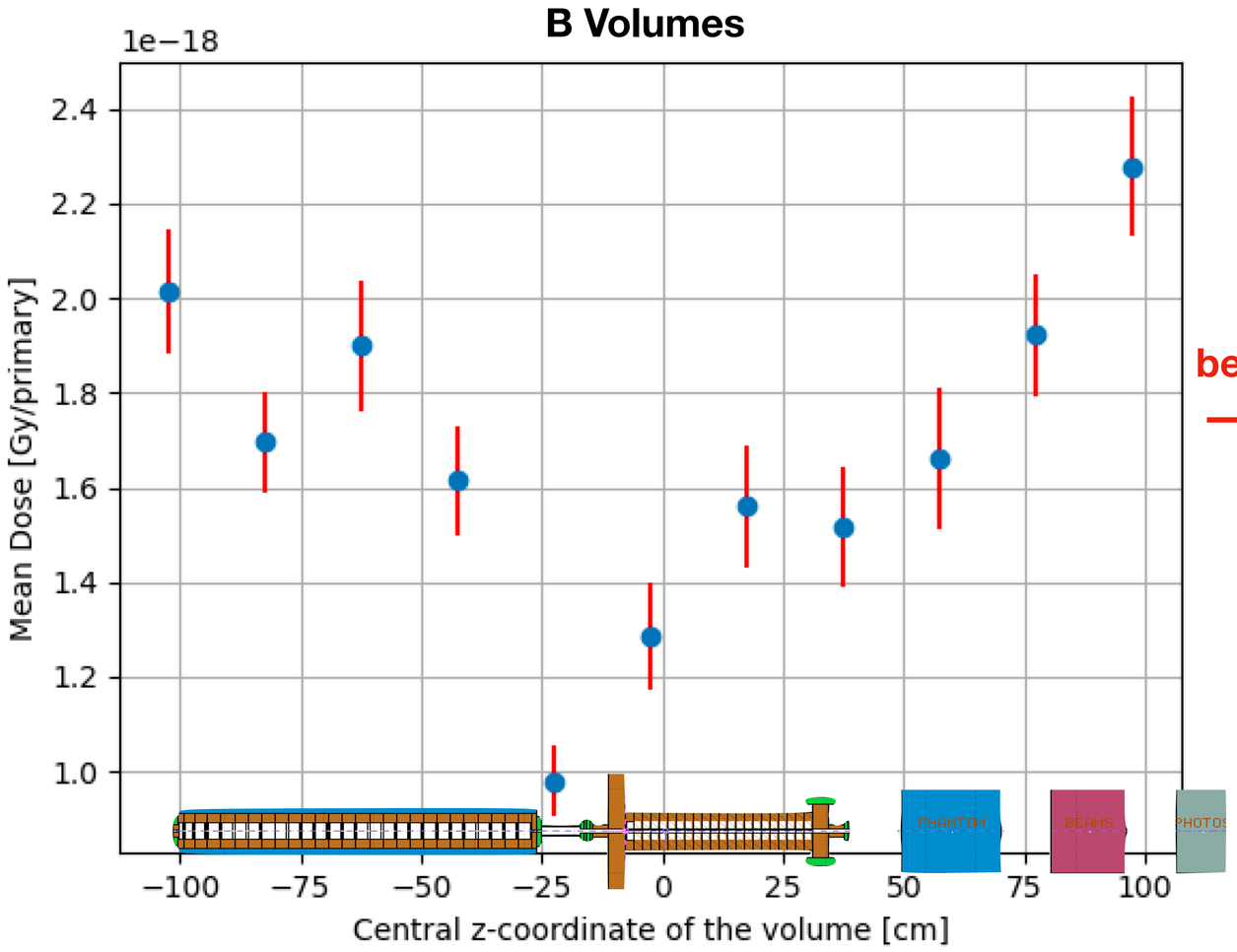

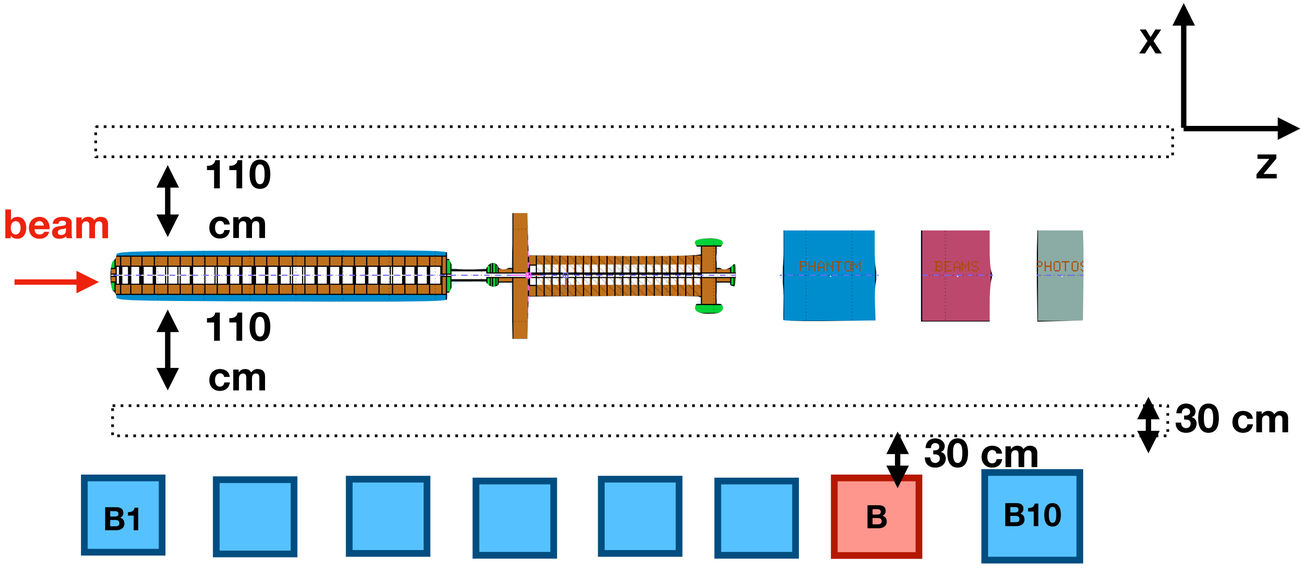

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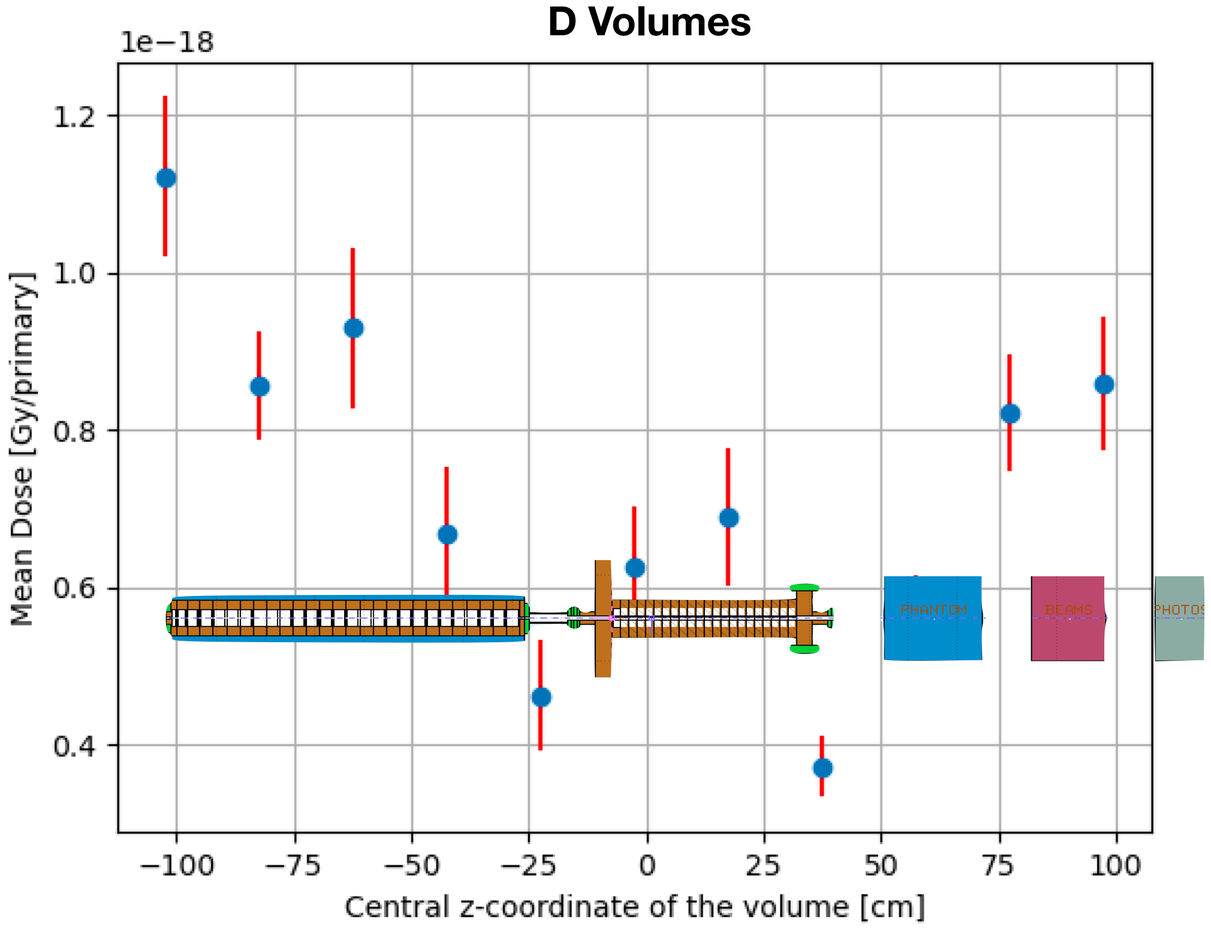

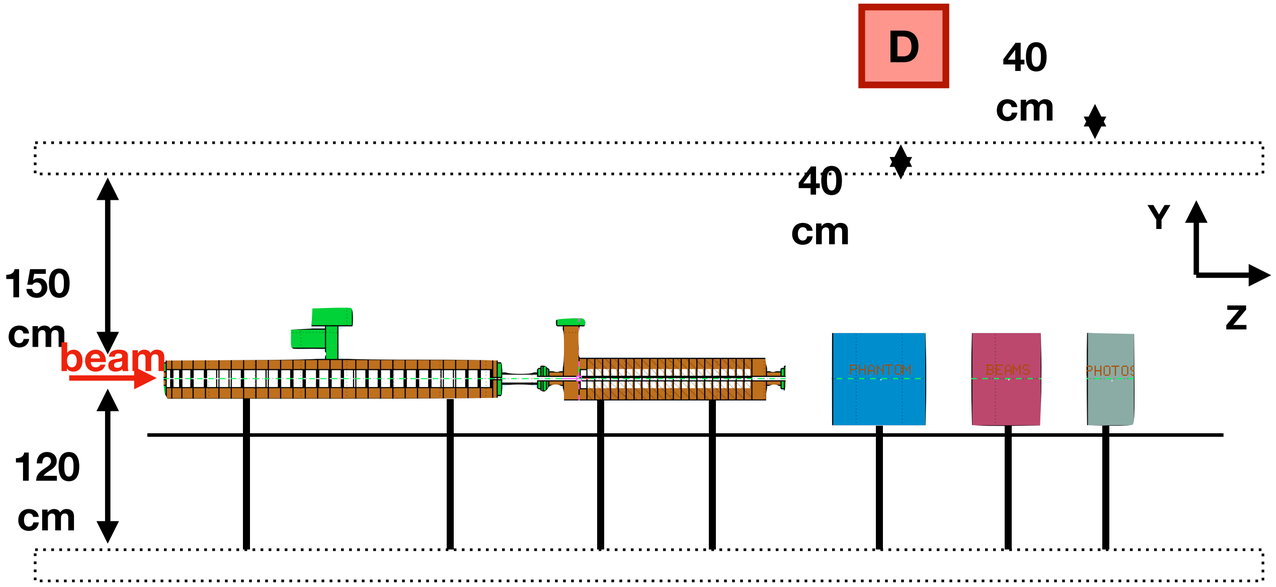

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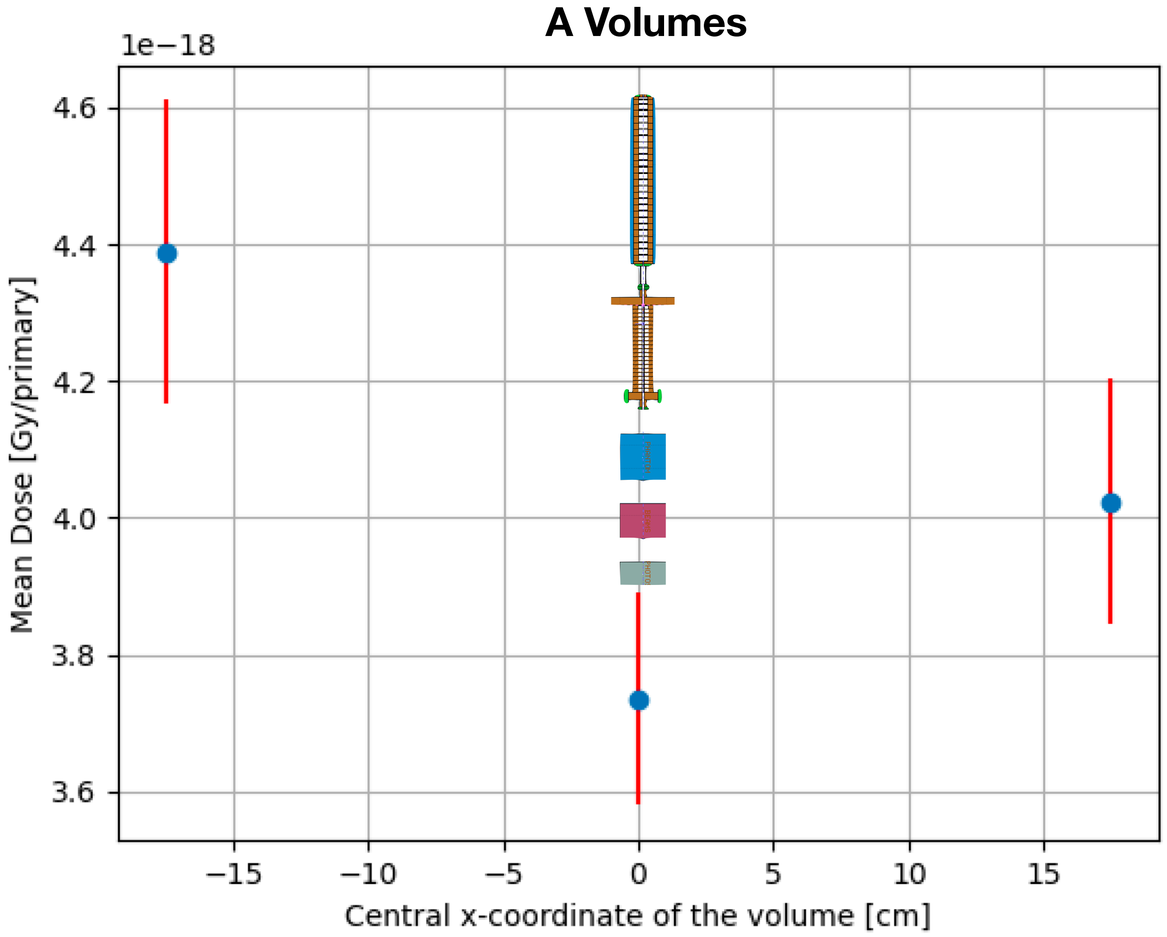

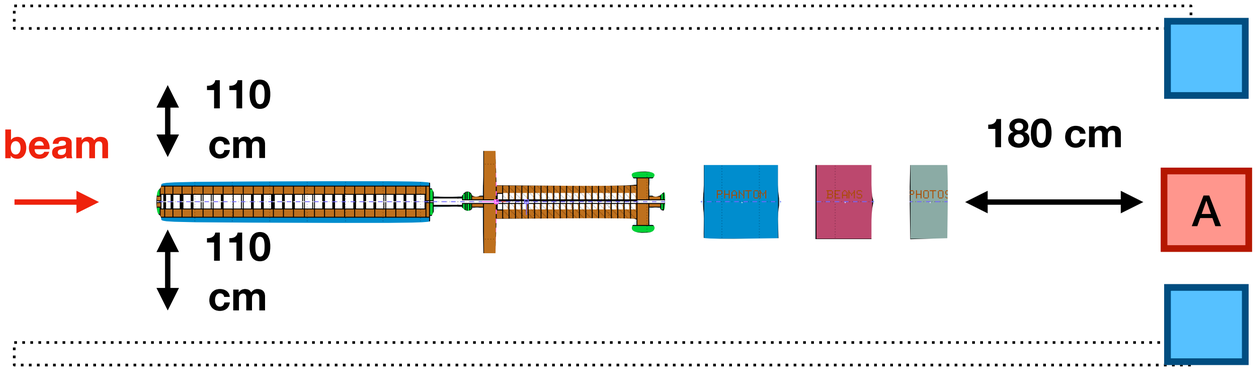

2nd SHIELDING ATTEMPT

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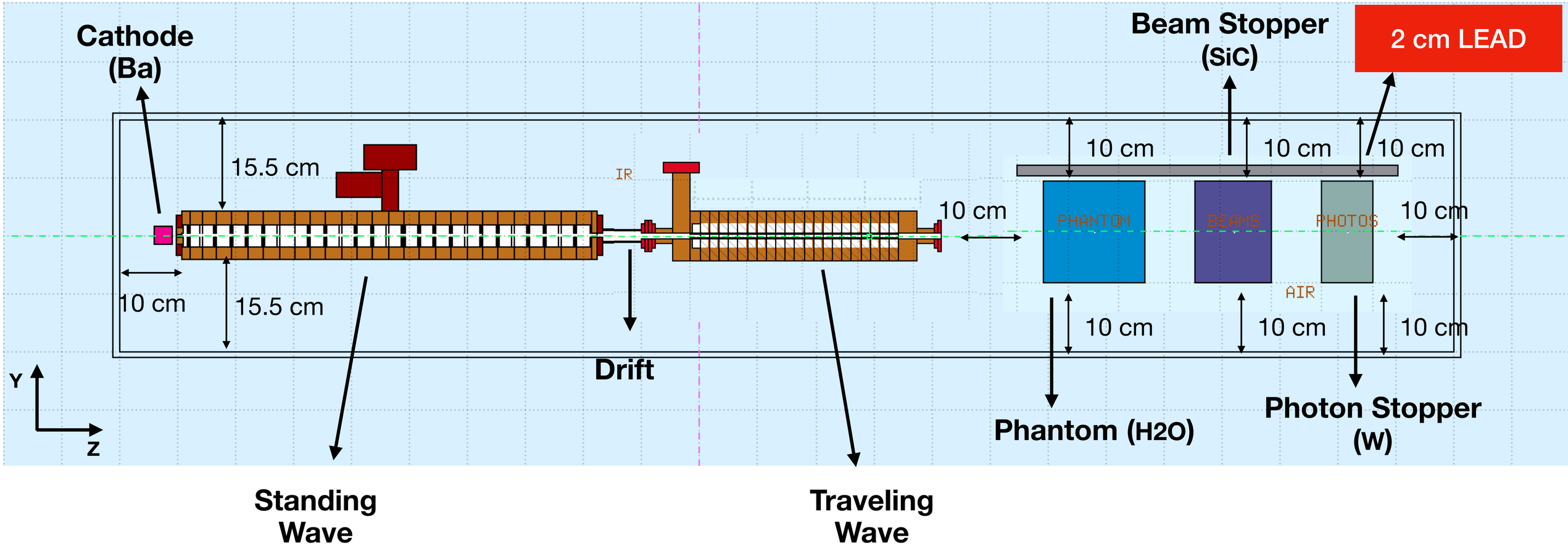

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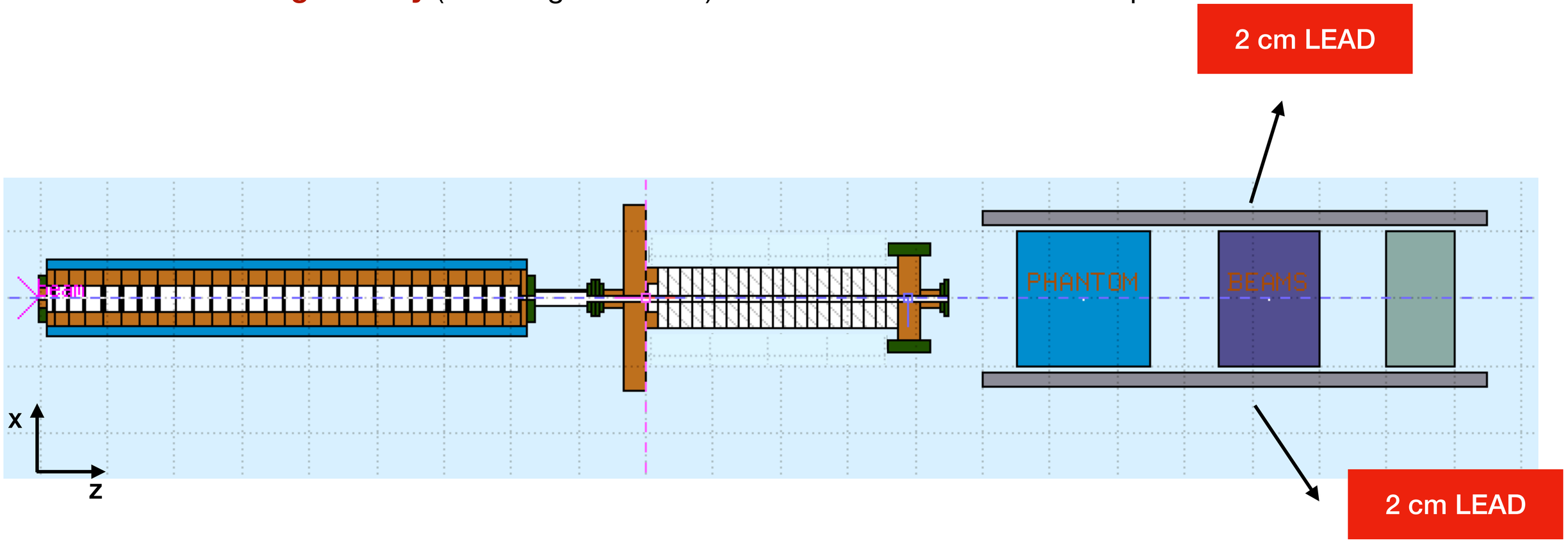

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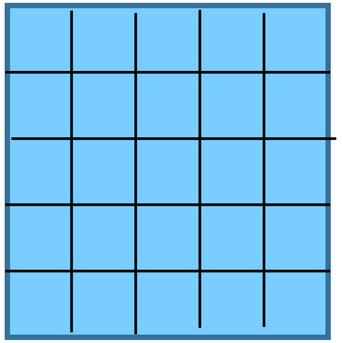

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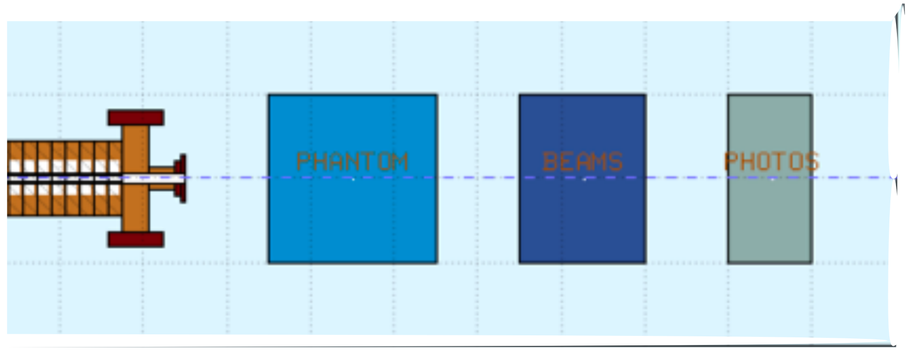

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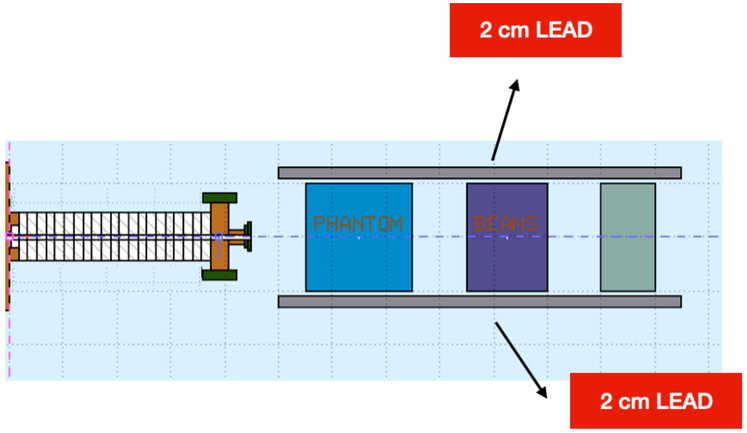

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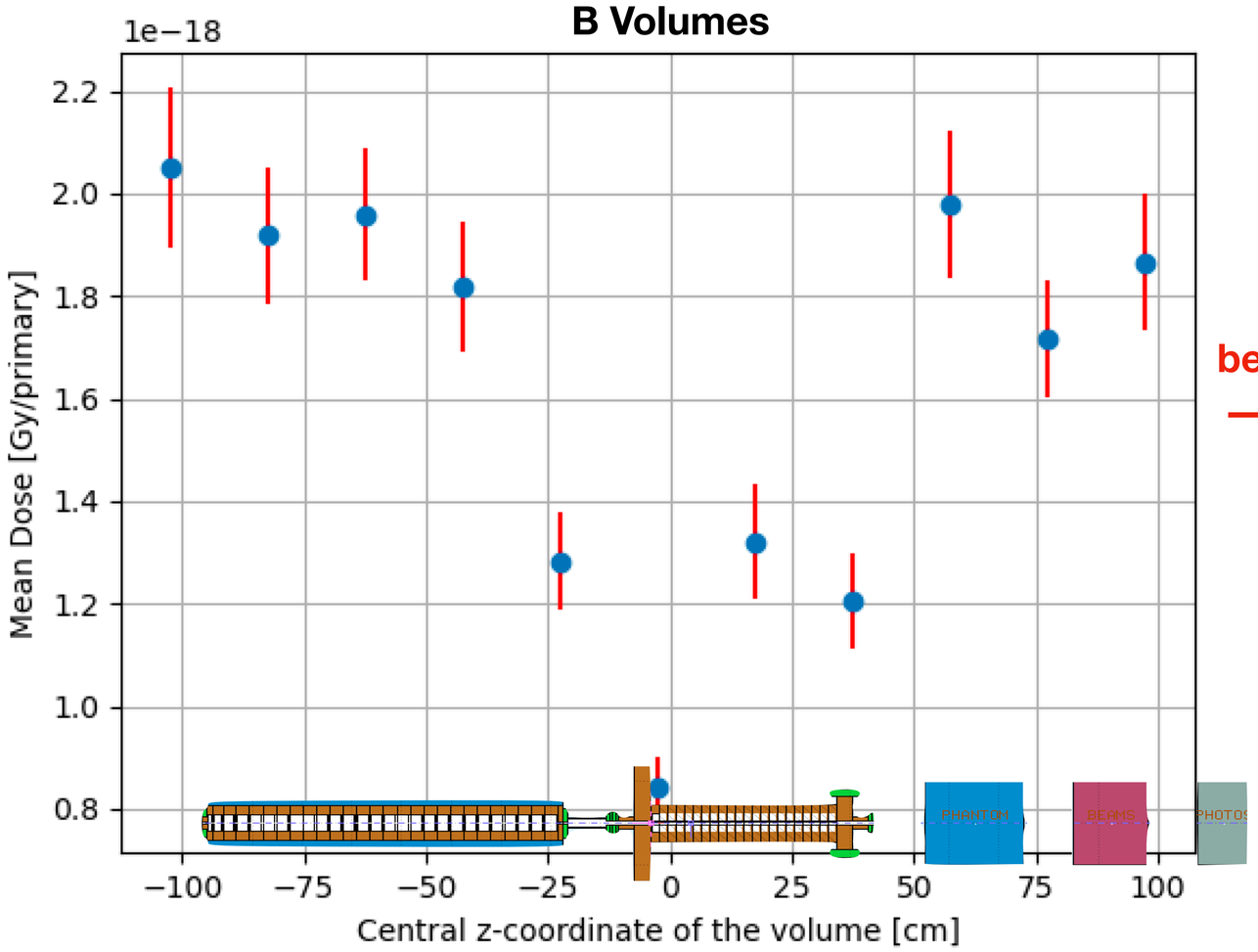

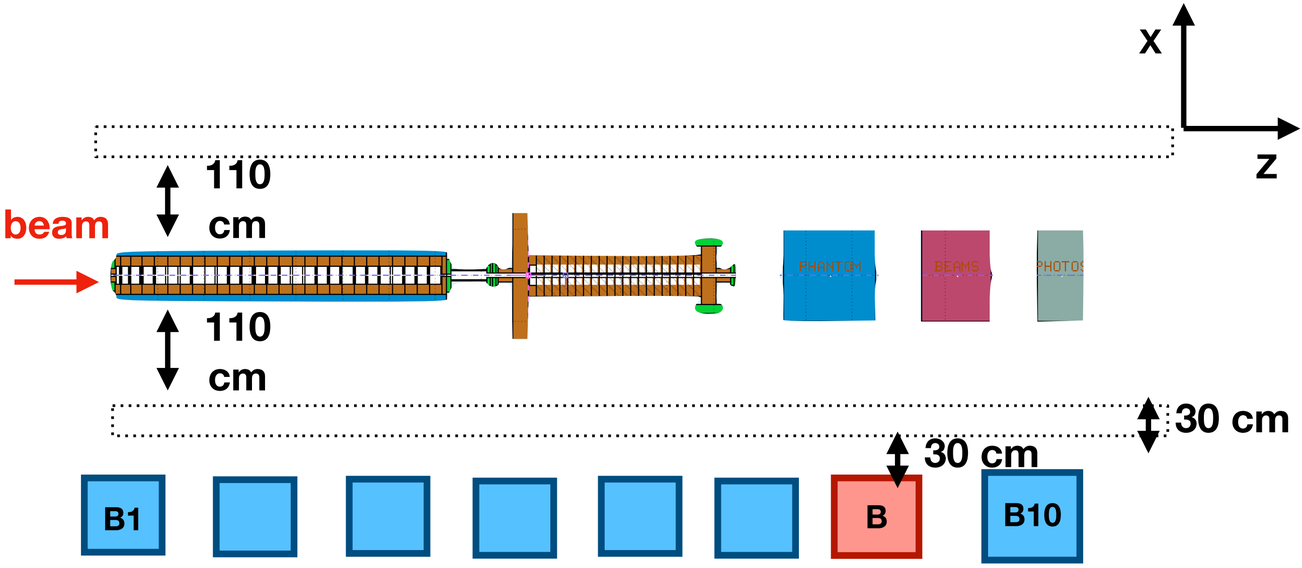

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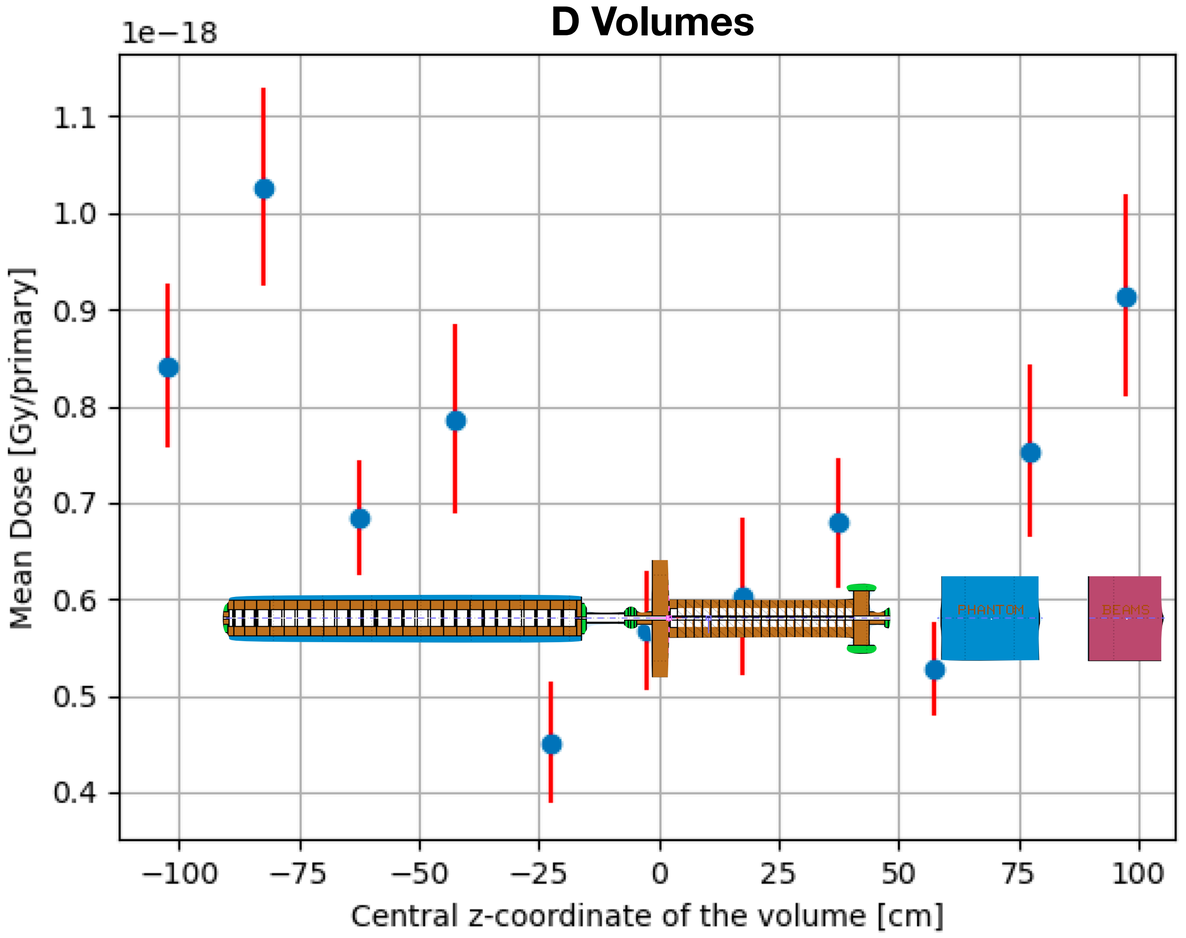

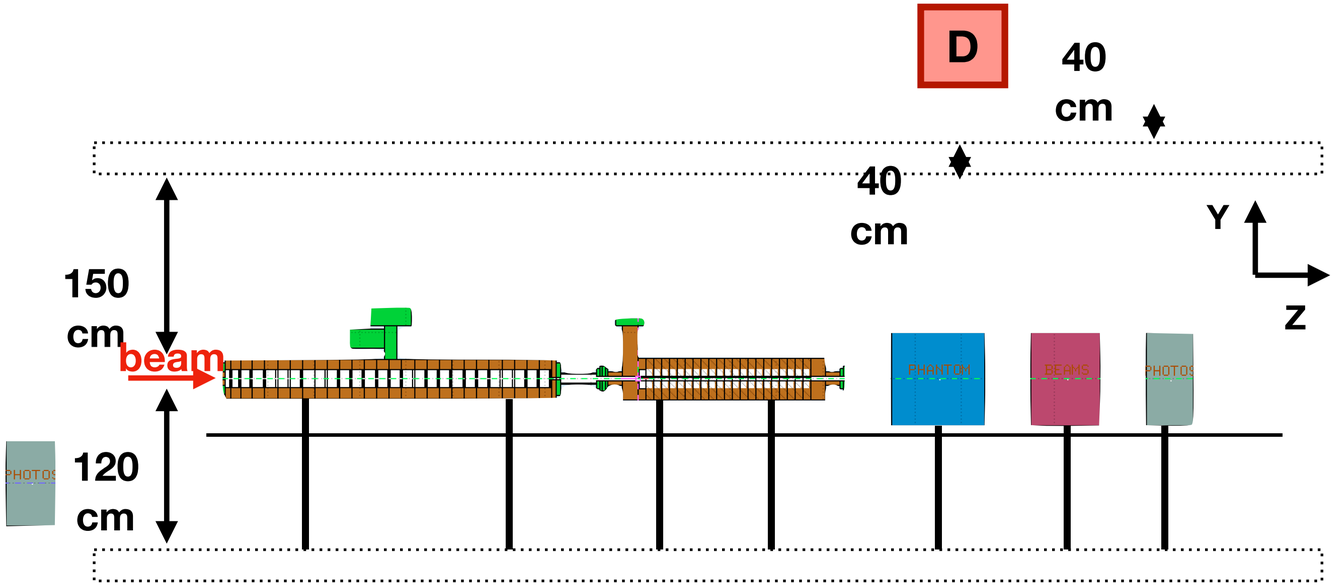

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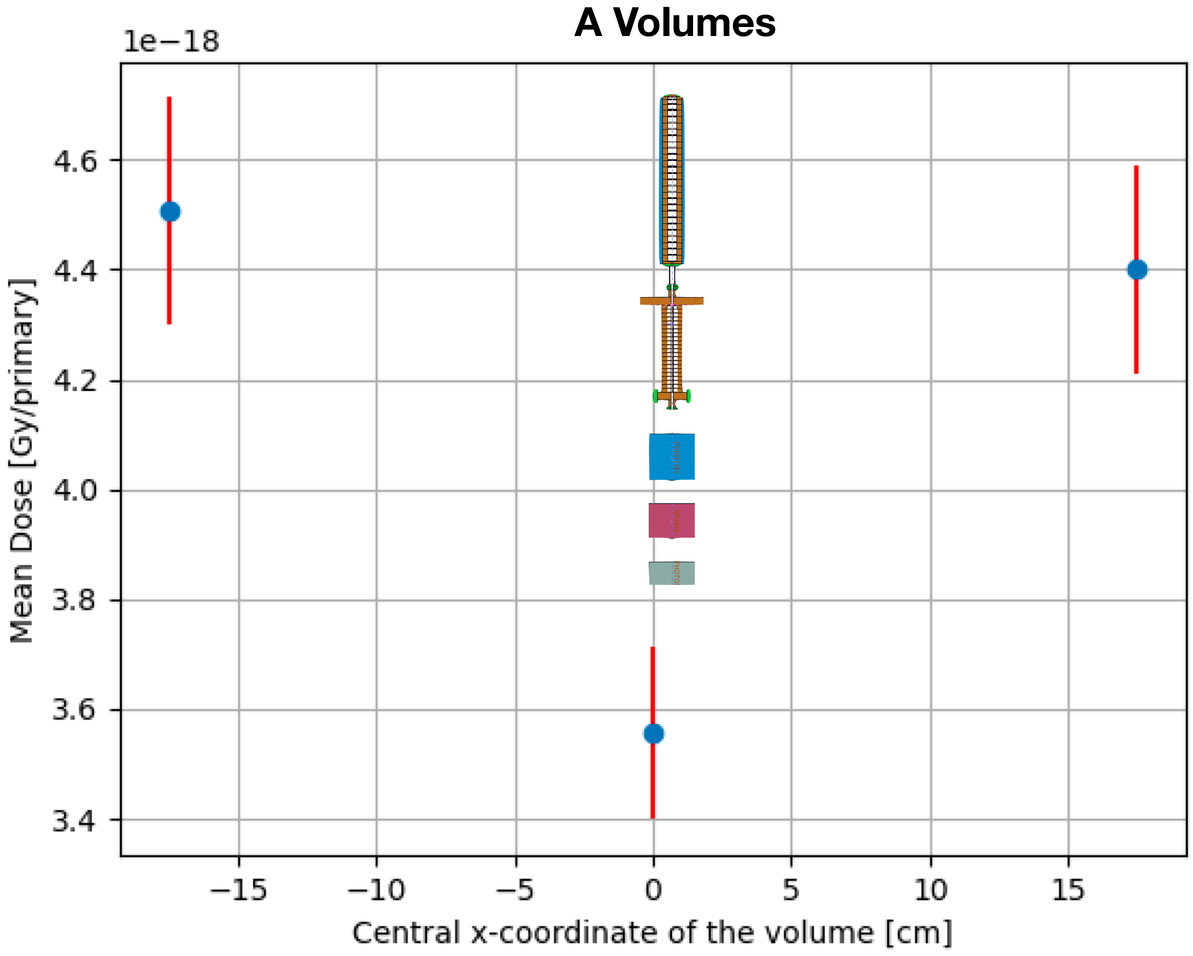
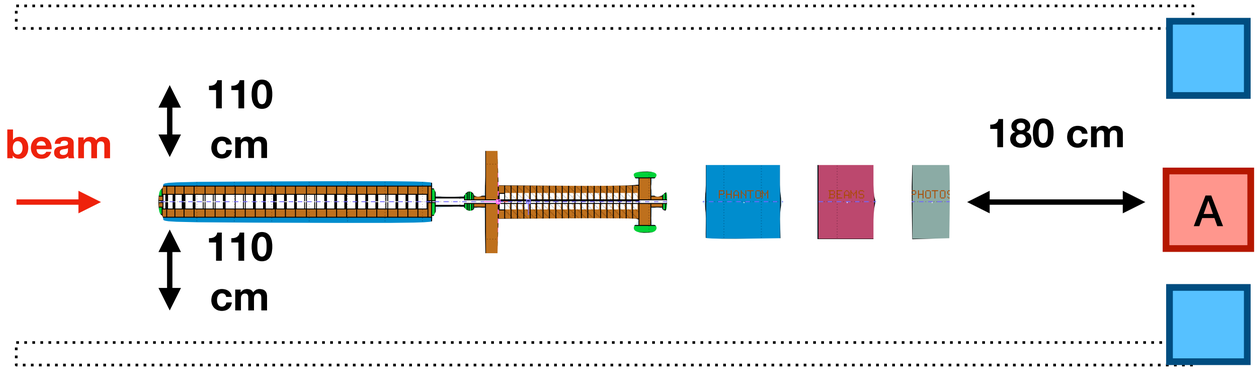
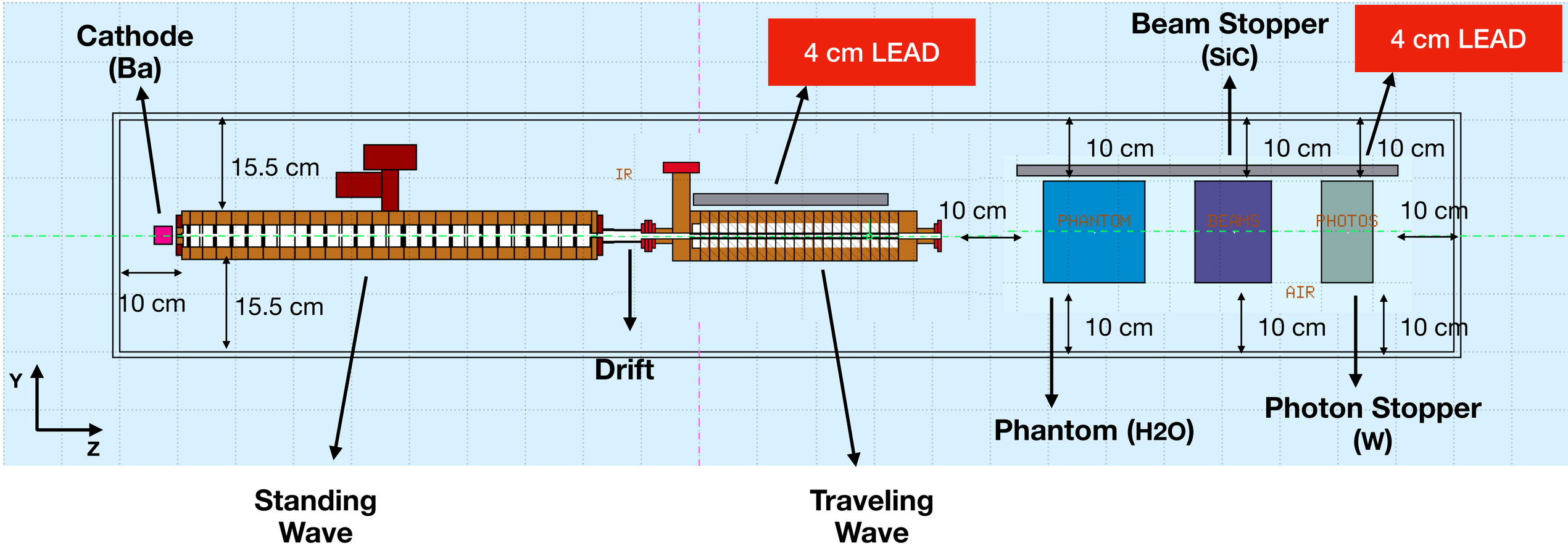




3rd SHIELDING ATTEMPT

FLUKA geometry

- The full **geometry** (including **materials**) of the accelerator has been implemented **in FLUKA**.



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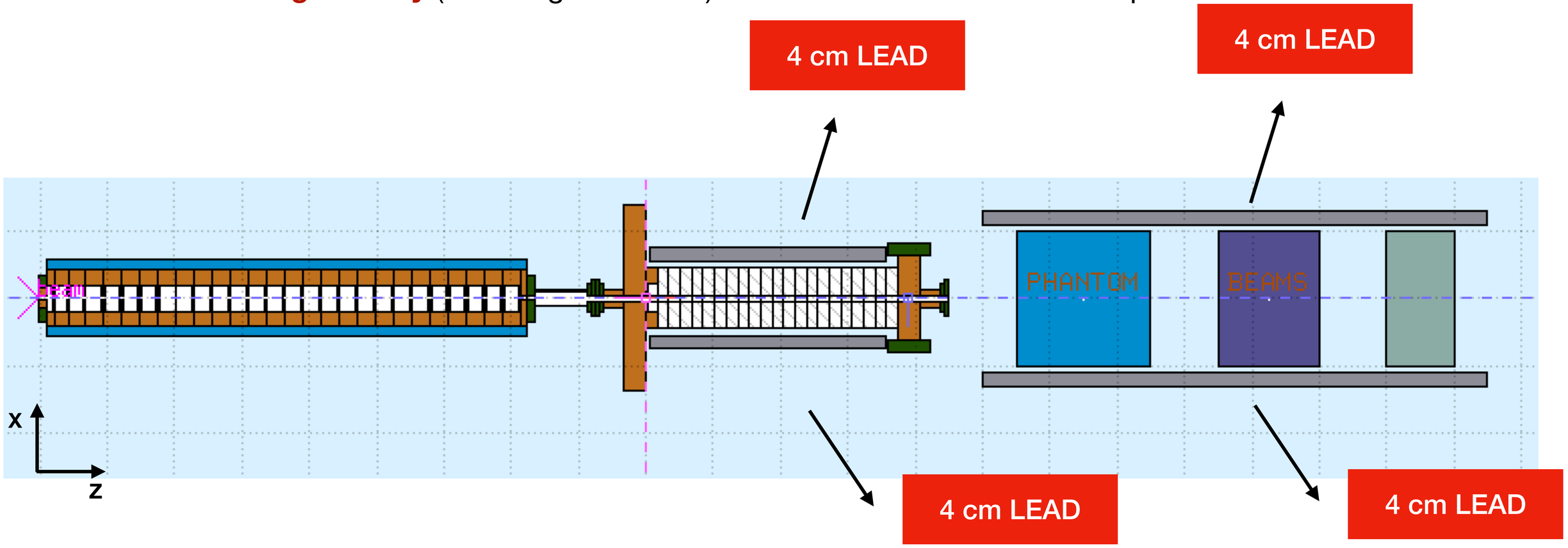
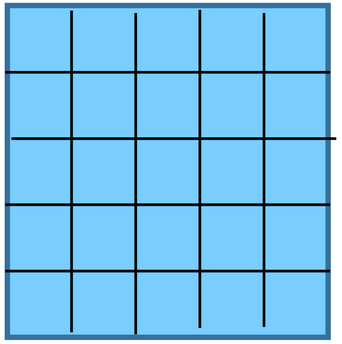


Dose evaluation for Radioprotection protocols

- The cubic **air volumes** in which the dose is evaluated have dimensions of $5 \cdot 5 \cdot 5 cm^3$ and are voxelized into $5 \cdot 5 \cdot 5$bins.



- The dose of each volume was taken as the **average of the doses of individual bins**, with an error given by the uncertainty on the mean. For each voxel, the standard deviation is also reported.

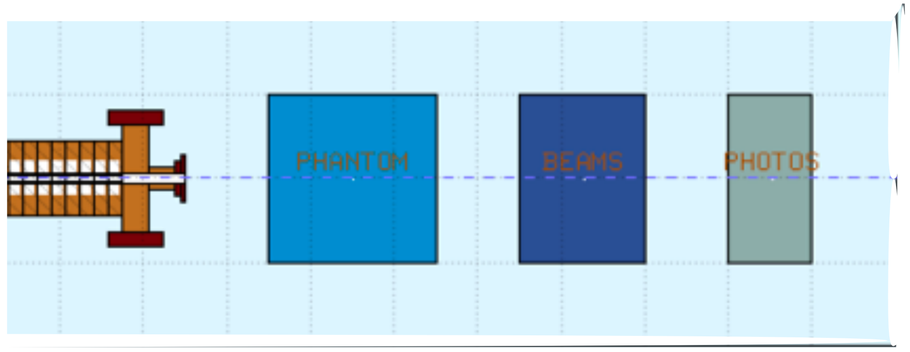
TOTAL DOSE RELEASE

	Mean Dose [Gy/primary]	Stdev [Gy/primary]
A	$3.75 \cdot 10^{-18} \pm 1.76 \cdot 10^{-19}$	$1.97 \cdot 10^{-18}$
B	$5.99 \cdot 10^{-19} \pm 7.61 \cdot 10^{-20}$	$8.51 \cdot 10^{-19}$
C	$8.49 \cdot 10^{-19} \pm 9.31 \cdot 10^{-20}$	$1.04 \cdot 10^{-18}$
D	$3.48 \cdot 10^{-19} \pm 4.63 \cdot 10^{-20}$	$5.18 \cdot 10^{-19}$

With a statistics of $1 \cdot 10^{7}$ primary electrons

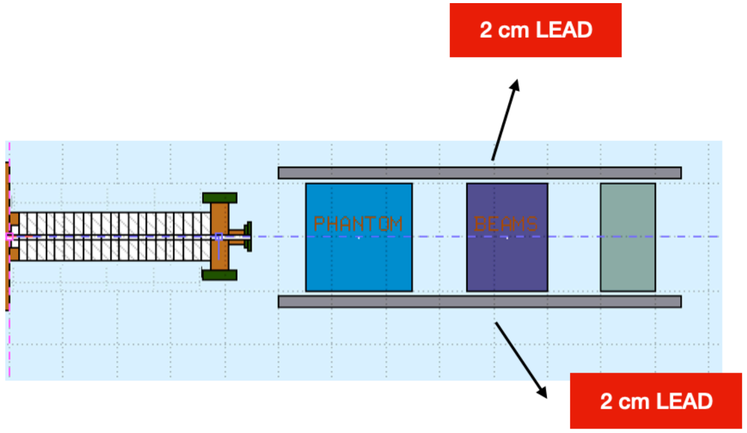
Dose evaluation for Radioprotection protocols

TOTAL DOSE RELEASE WITHOUT SHIELDING



	Mean Dose [Gy/primary]	Stdev [Gy/primary]
A	$9.73 \cdot 10^{-18} \pm 3.06 \cdot 10^{-19}$	$3.42 \cdot 10^{-18}$
B	$7.28 \cdot 10^{-18} \pm 3.28 \cdot 10^{-19}$	$3.67 \cdot 10^{-18}$
C	$7.82 \cdot 10^{-18} \pm 3.48 \cdot 10^{-19}$	$3.89 \cdot 10^{-18}$
D-soffitto	$3.86 \cdot 10^{-18} \pm 2.27 \cdot 10^{-19}$	$2.54 \cdot 10^{-18}$

TOTAL DOSE RELEASE WITH SHIELDING



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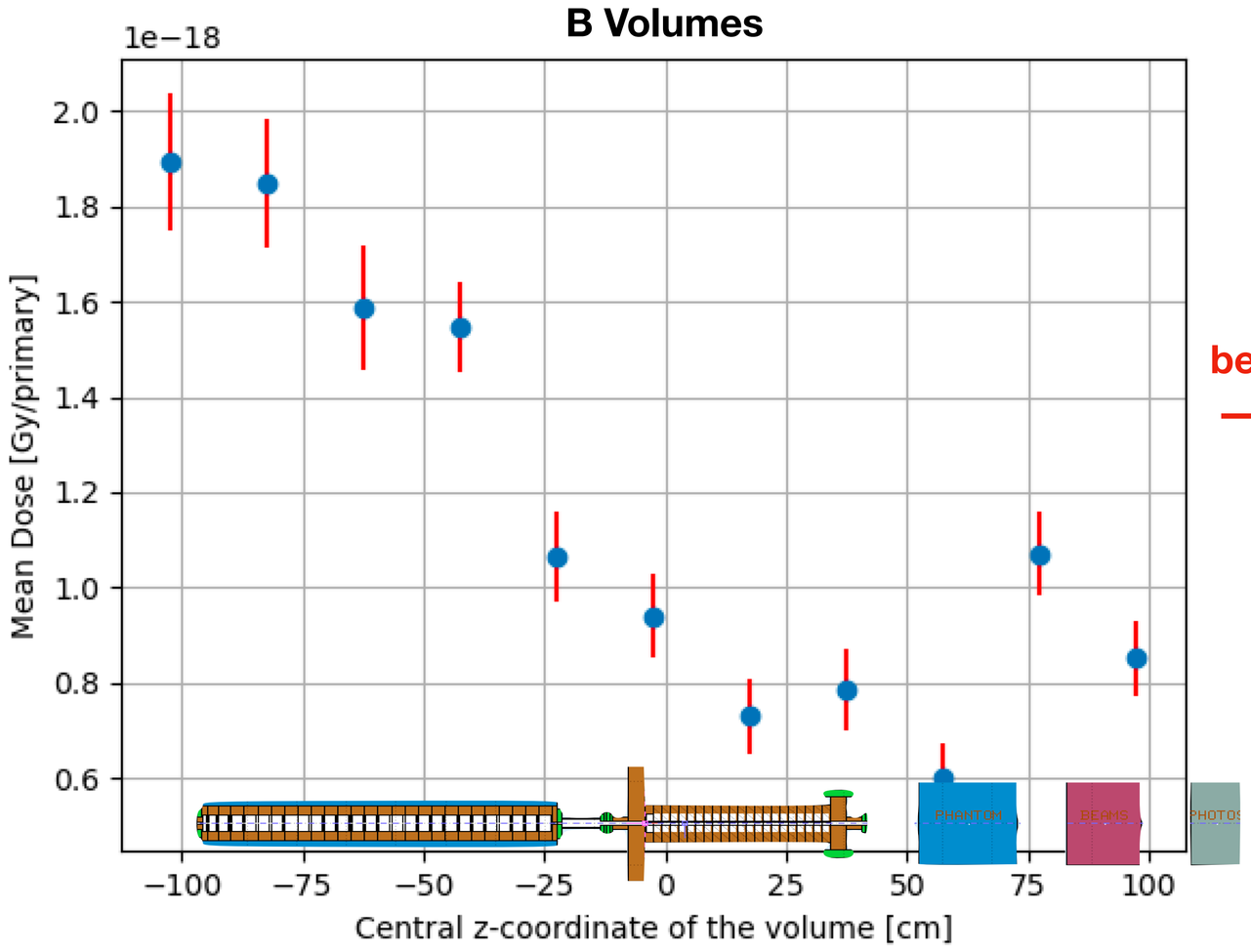

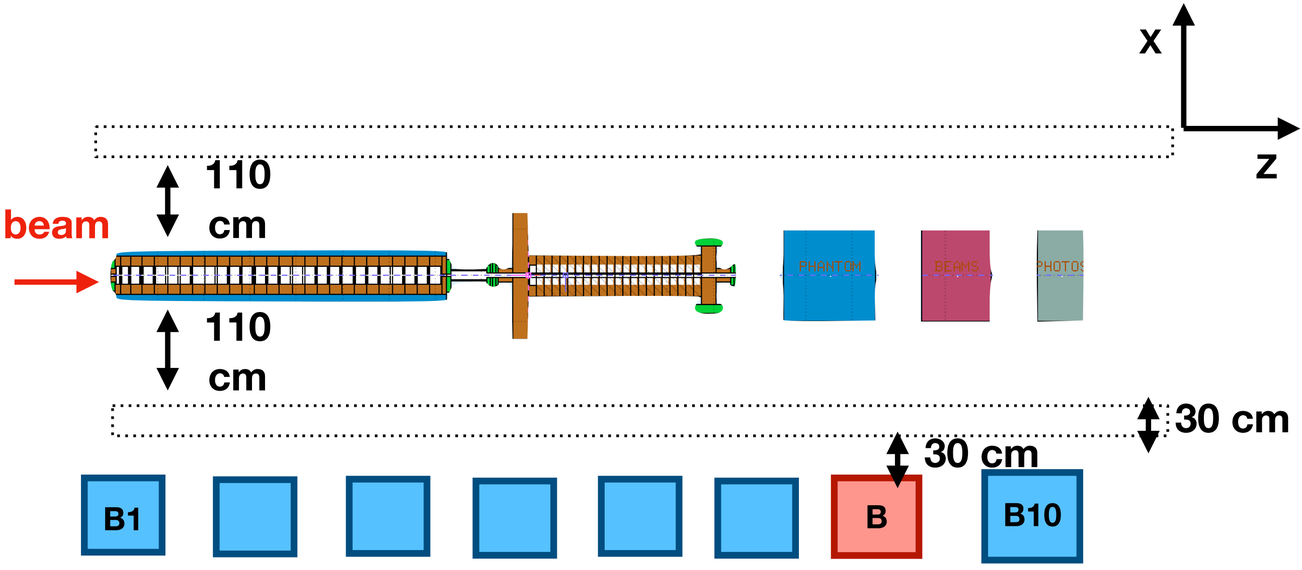

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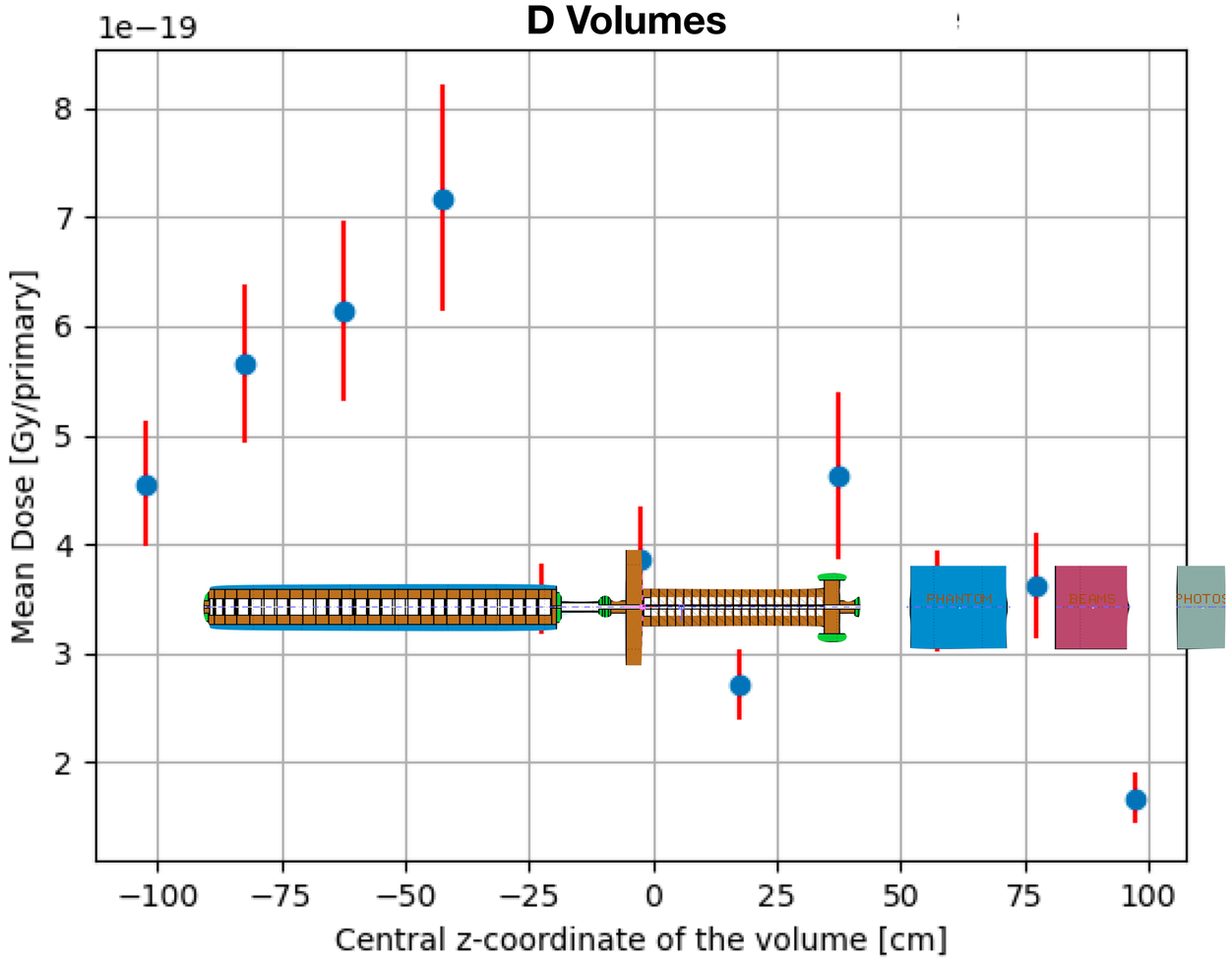

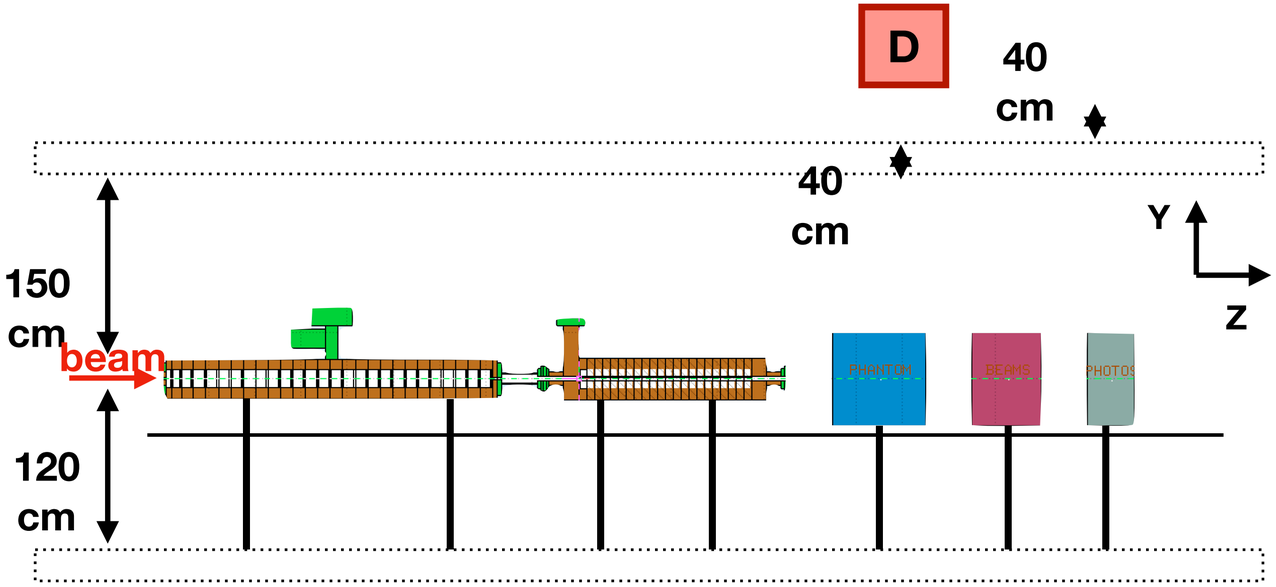

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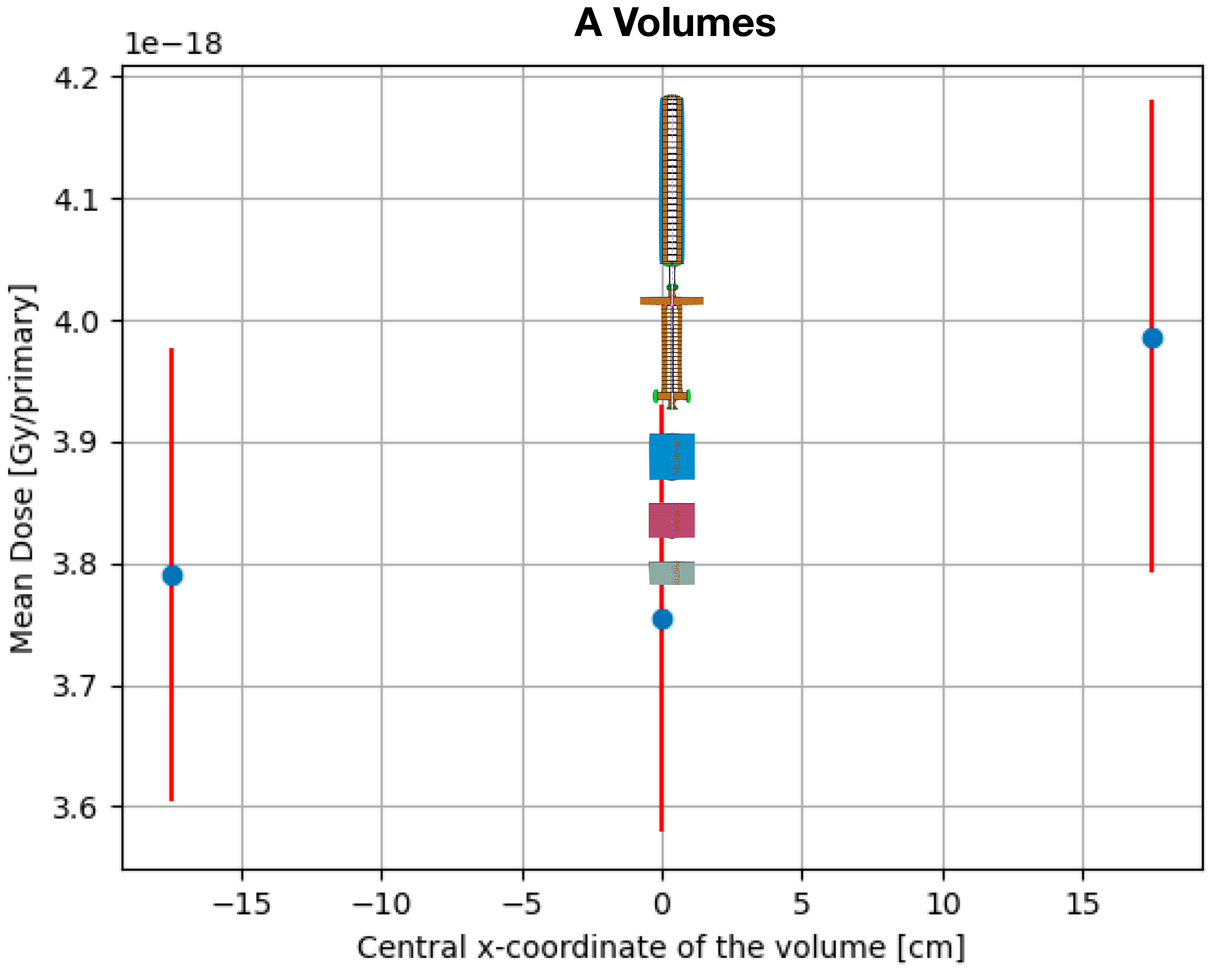
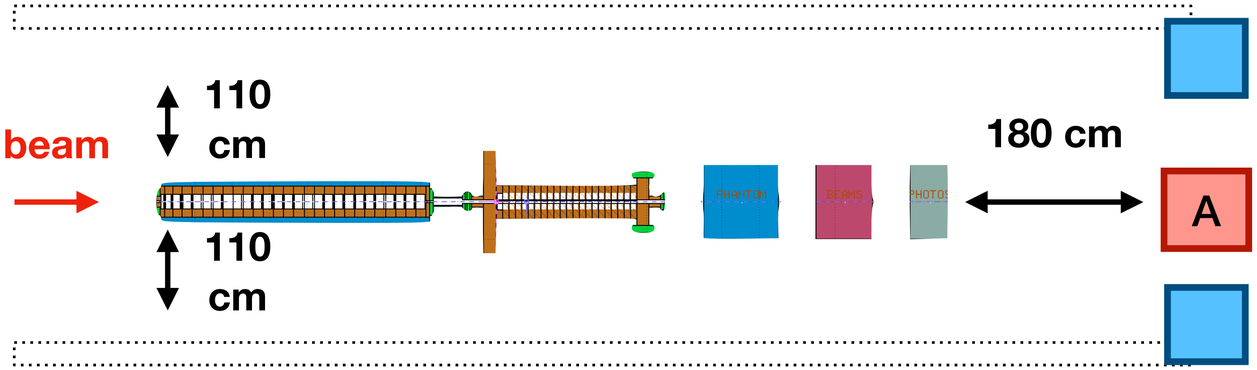
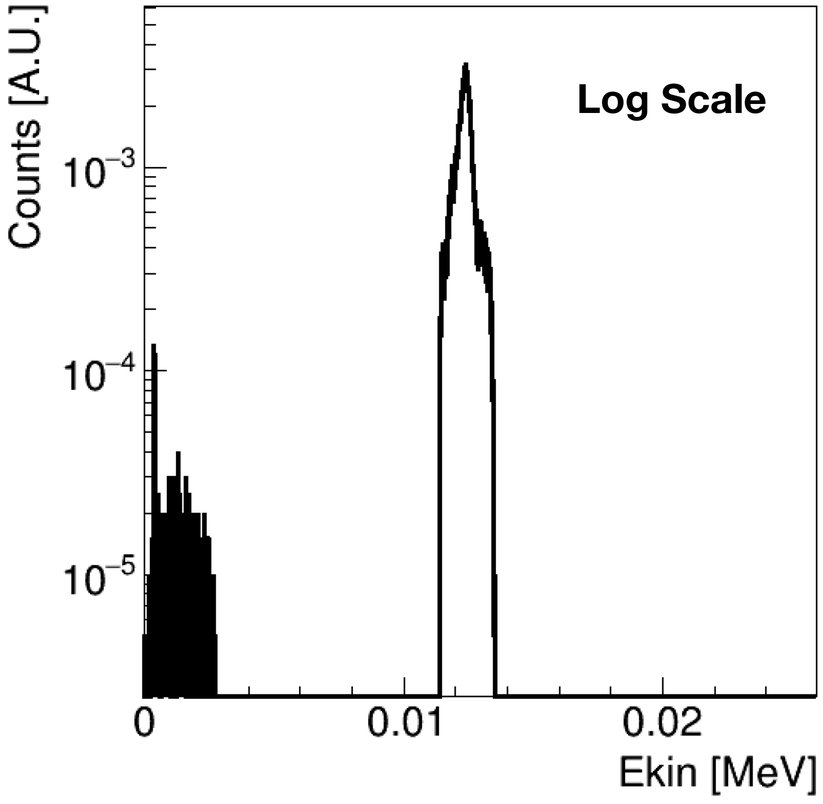




Spare slides

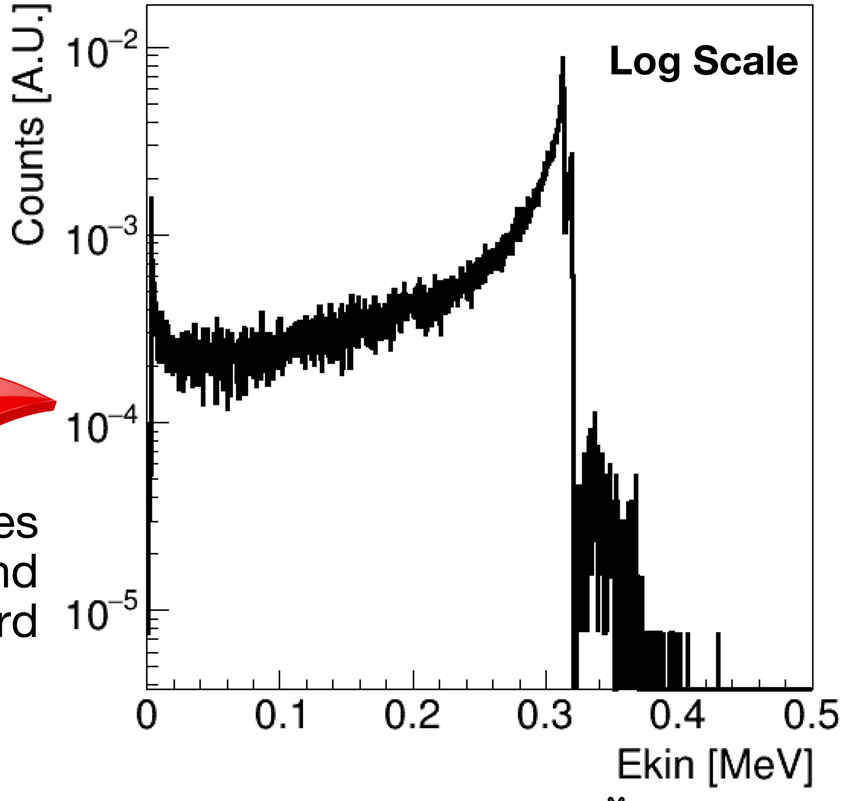
Backscattered primaries

Inside a standing wave structure, approximately half of the particles within the first cell will experience a decelerating electric field, causing these particles to be **transported backward towards the cathode**. It is not possible to access the geometric and energetic information of these particles, but we know that they travel in the opposite direction to the accelerated beam and that their energy distribution is, at most, that of the particles accelerated forward from the second cavity onwards.



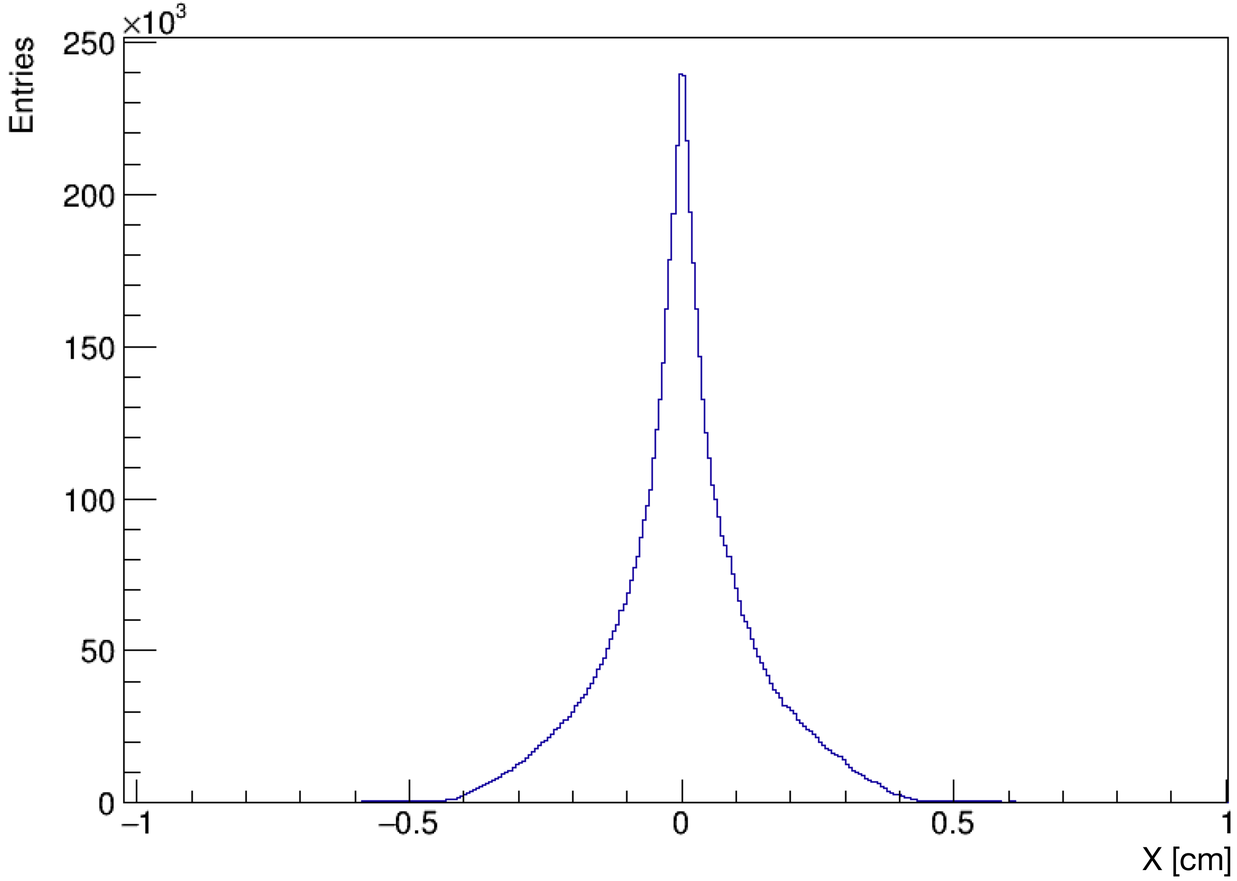
Energy distributions of the particles accelerated forward at the first cavity (where we still have the information about all the particles).

Energy distributions of the particles accelerated forward at the second cavity (where only the forward particles are present).

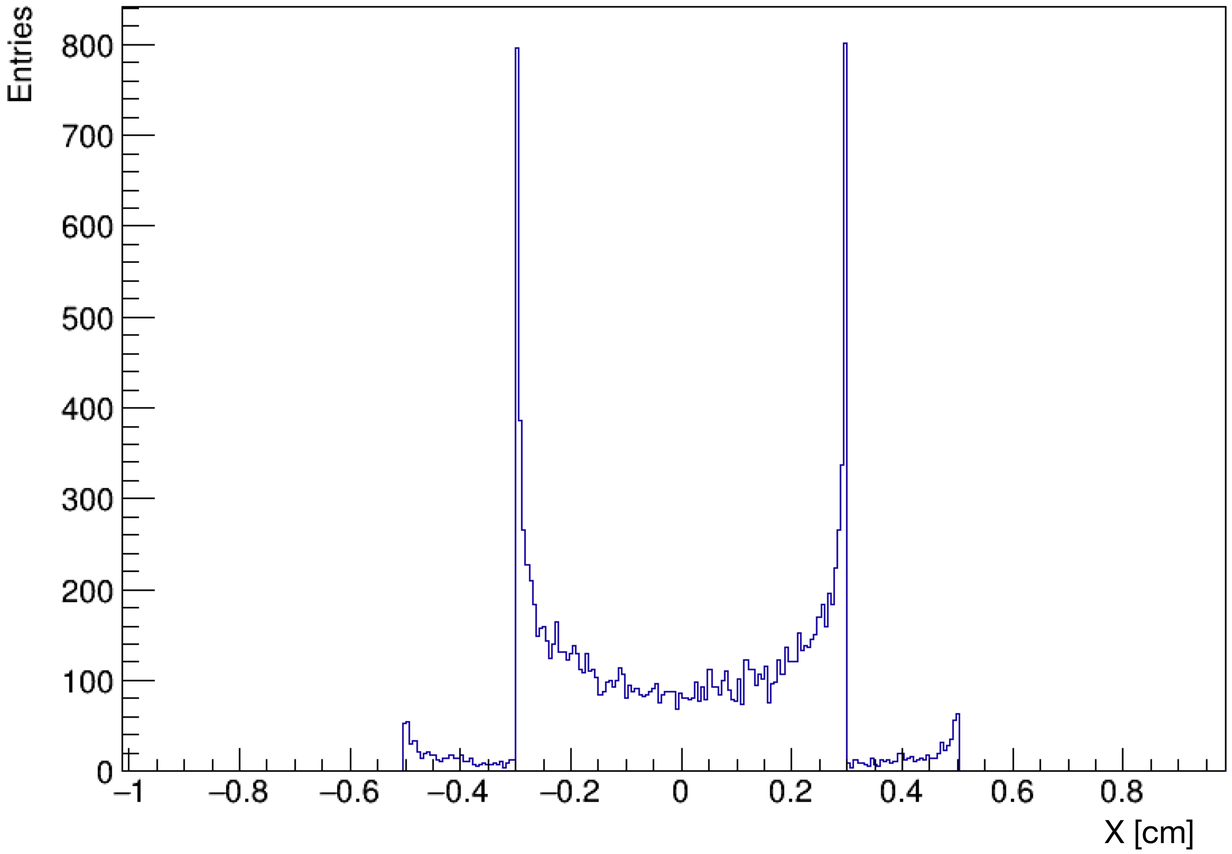


Input file: from Parmela to FLUKA

Distribution in x of all particles read from the output file of Parmela.



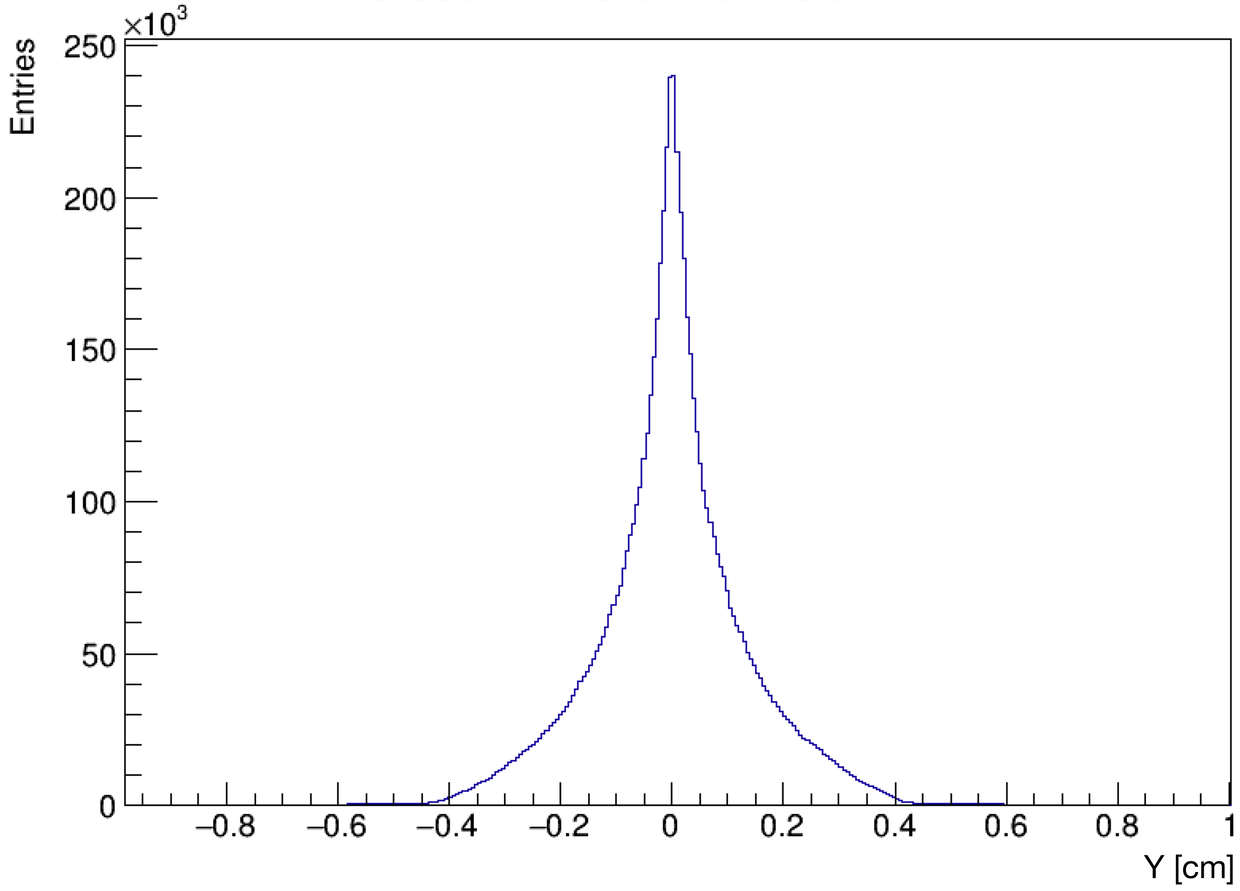
Distribution in x of all particles exiting the accelerator.



Note: The radius of the standing wave structure is different from the traveling wave one, so we have 2 different cylinders.

Input file: from Parmela to FLUKA

Distribution in y of all particles read from the output file of Parmela.



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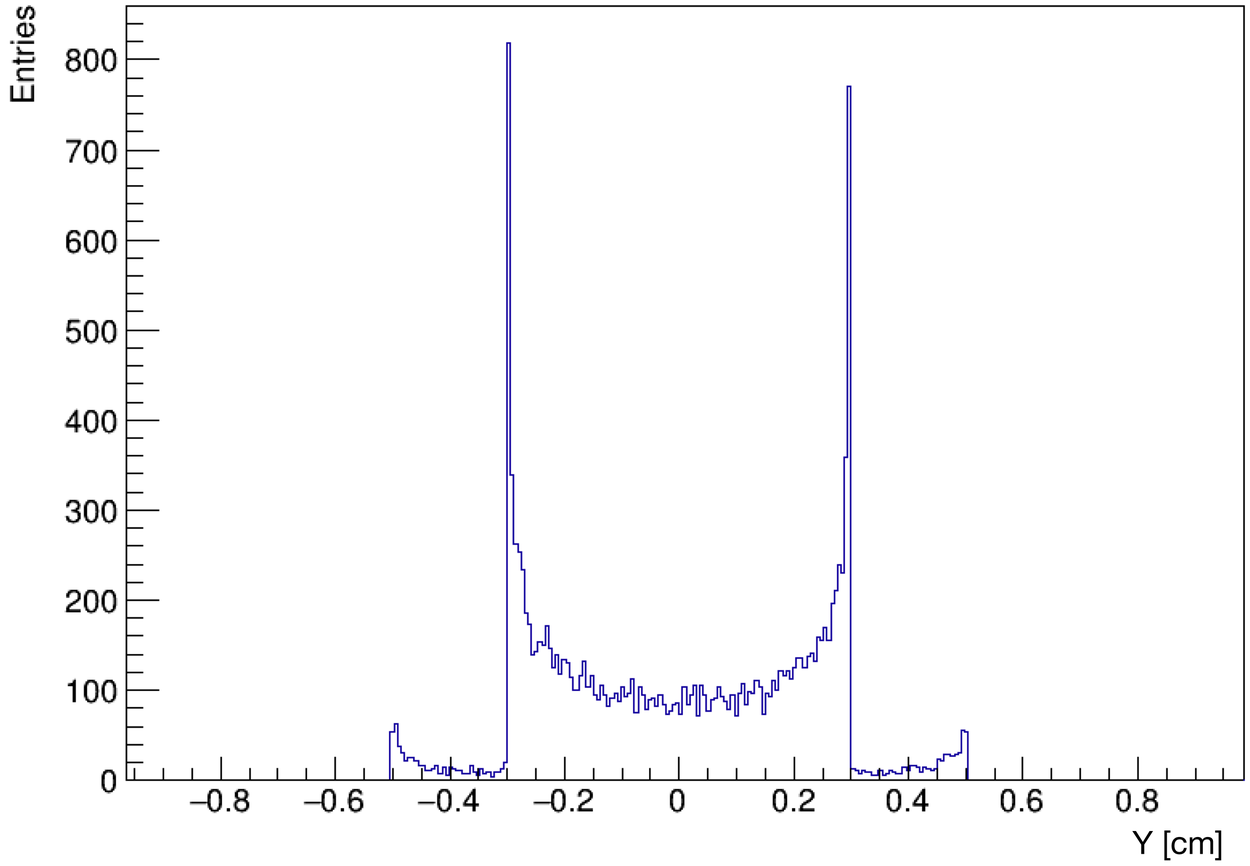

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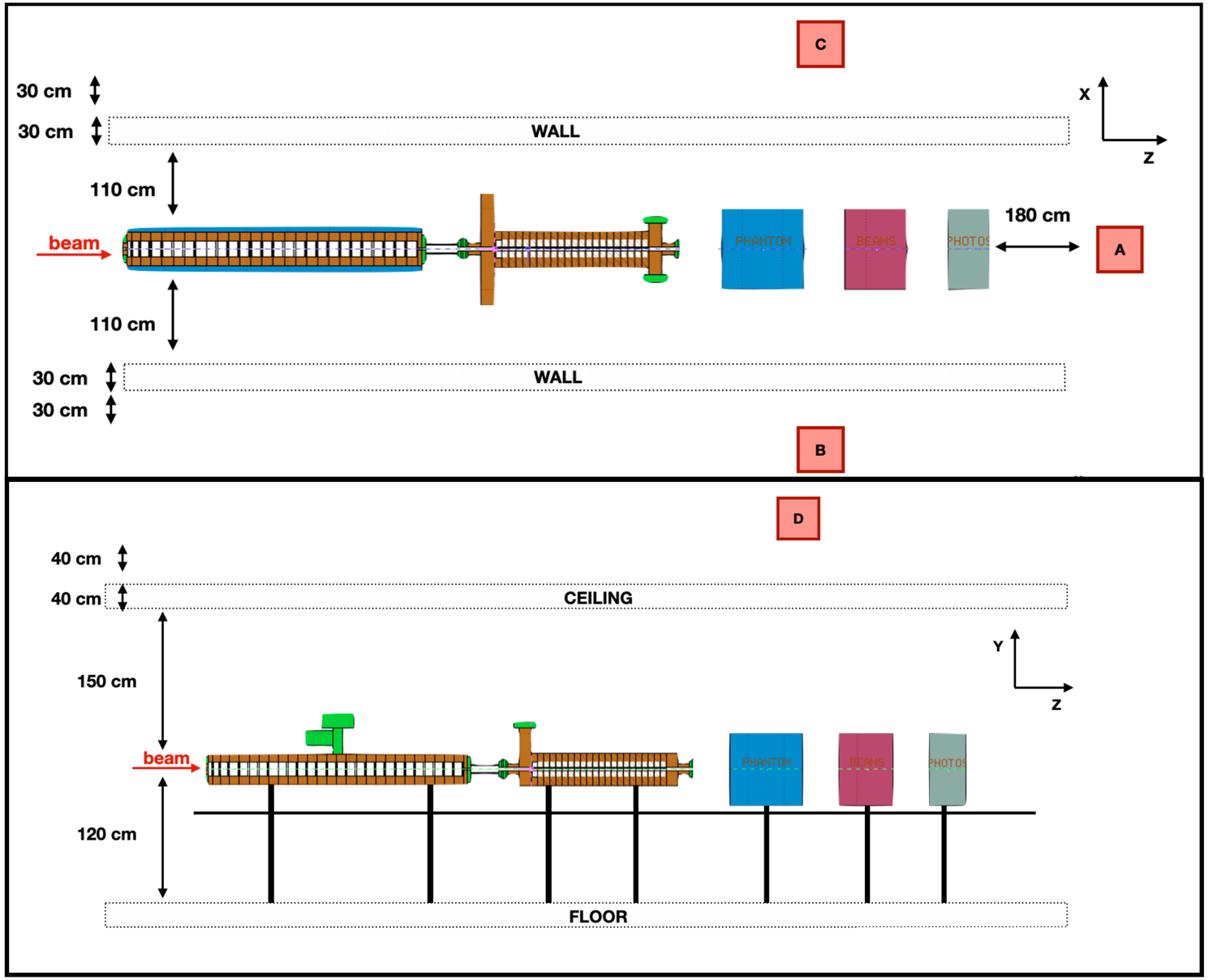
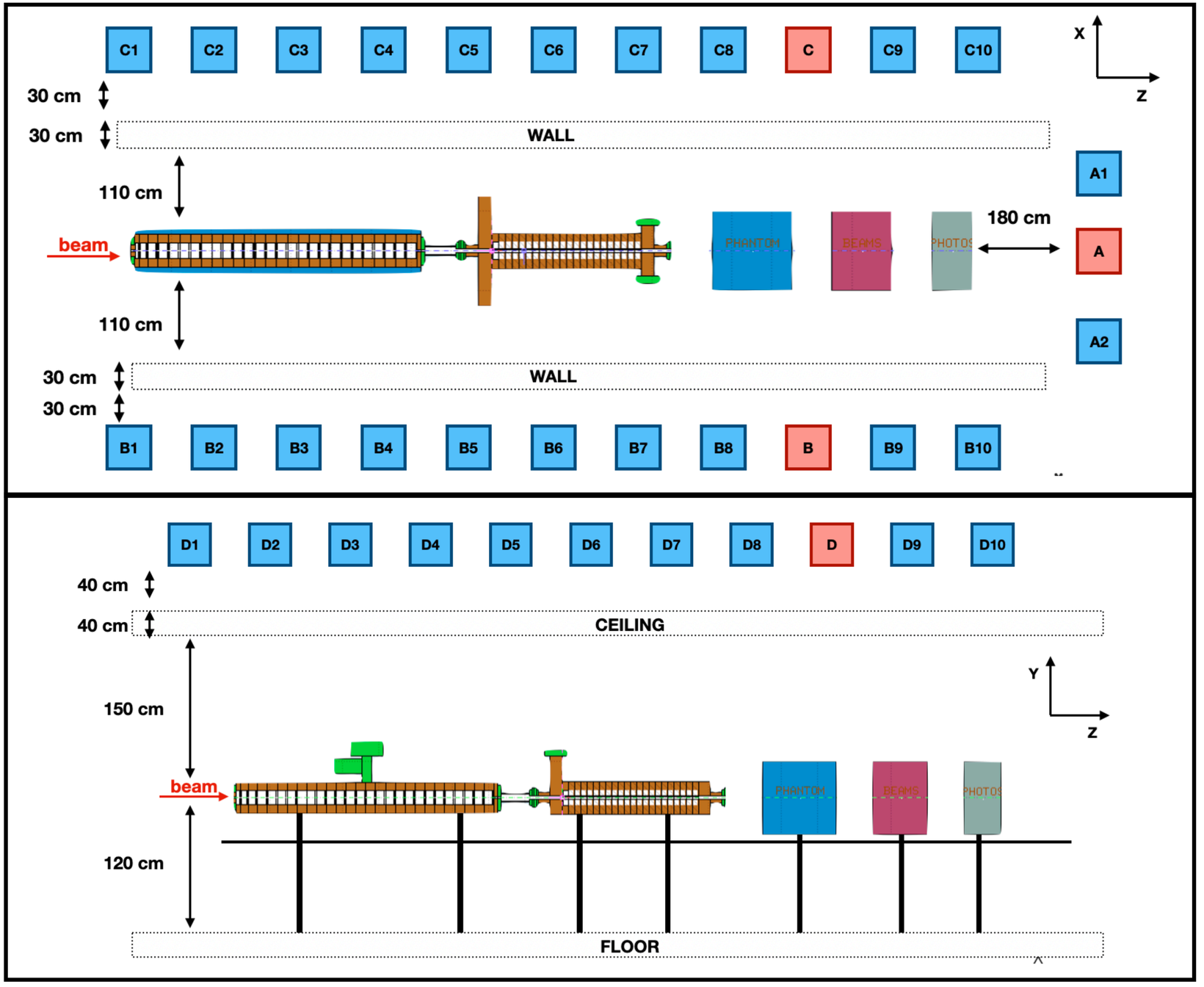

C
30 cm
30 cm
WALL
X
Z
110 cm
beam
PHANTOM
BEAMS
PHOTOS
180 cm
A
110 cm
30 cm
WALL
30 cm
B
D
40 cm
40 cm
CEILING
Y
Z
150 cm
beam
PHANTOM
BEAMS
PHOTOS
120 cm
FLOOR


C1
C2
C3
C4
C5
C6
C7
C8
C
C9
C10
X
Z
30 cm
30 cm
WALL
110 cm
beam
PHANTOM
BEAMS
PHOTOS
180 cm
A1
A
A2
110 cm
30 cm
WALL
30 cm
B1
B2
B3
B4
B5
B6
B7
B8
B
B9
B10
D1
D2
D3
D4
D5
D6
D7
D8
D
D9
D10
40 cm
40 cm
CEILING
Y
Z
150 cm
beam
PHANTOM
BEAMS
PHOTOS
120 cm
FLOOR