Master 2 Internship Oral Presentation

Development of Monte Carlo tool for Radiation Protection

Under the supervision of
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Smartium Measurement Data Science

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master Physique Subatomique Astroparticules

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Smartium
Measurement Data Science

I. Introduction : Context and Smartium work

Need for **radionuclide** in **medical sector** (production, **manipulation** and storage)

Lead wall

Working stations

Measurement system

Laboratory front panel [1]

Smartium
Measurement Data Science

Spin-off from IPHC's works
Created in 2021
Develops numerical solutions for radiation protection and nuclear measurements

I. Introduction : Context and Smartium work

Need for **radionuclide** in **medical sector** (production, **manipulation** and storage)

Laboratory front panel [1]

Smartium work using **MC simulations**:

1) **Relationship** between **probe** and **staff** exposition to define warning threshold.

2) Radiological **exposure** as a function of the **position** for better probe placement.

I. Introduction : Context and Smartium work

Need for **radionuclide** in **medical sector** (production, **manipulation** and storage)

Lead wall

Working stations

Measurement system

Laboratory front panel [1]

Smartium work using **MC simulations**:

1) **Relationship** between **probe** and **staff** exposition to define warning threshold.

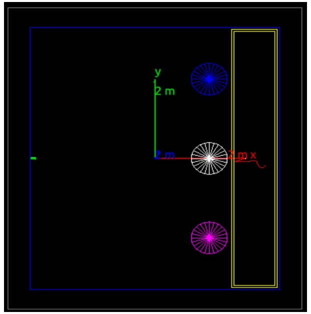
2) Radiological **exposure** as a function of the **position** for better probe placement.

Internship targets :

Make a **MC simulation** of a **laboratory front panel**

Find and implement **Variance Reduction Techniques** (VRTs) to **reduce as much as possible** the computation **time** while **limiting the impact** on the **result**

II. Materials & Methods

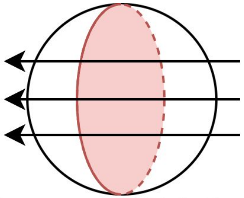


$$x = \bar{x} \pm \sigma_x$$

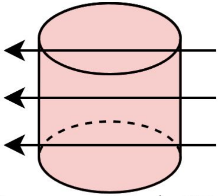
II. Materials & Methods : Dosimetric quantities

Physical quantities
Measurable

- Fluence (part.m^{-2})



$\phi = dN/dA$



$\phi \approx dl/dV$

- Absorbed dose (J/Kg or Gy) : dE/dm

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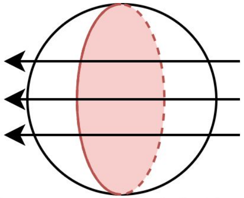

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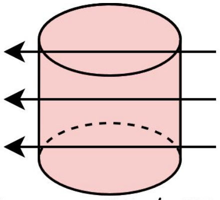

$\phi \approx dl/dV$

- Absorbed dose (J/Kg or Gy) : dE/dm

Protective quantities
Not measurable

- Equivalent dose for an organ T (Sv) : $H_T = D_{T,R} W_R$
  Takes into account the effect of a given radiation on tissues.
- Effective dose for the body (Sv): $E = \sum H_T W_T$
  Takes into account the organs sensibilities

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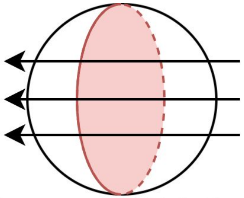

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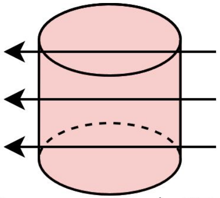

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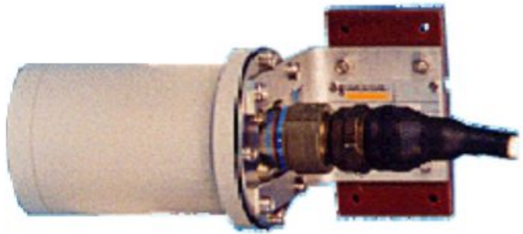
Protective quantities are not measurable : Introduce **operational quantities**
Measurable **approximations** of protective quantities

II. Materials & Methods : Dosimetric quantities

Operational quantity : Measurable approximations of protective quantities
Use for calibration of measurement system

Personal dosimeter



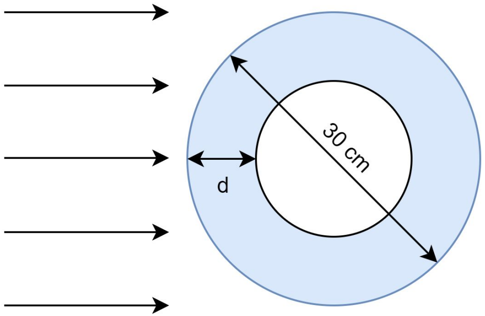
Probe

II. Materials & Methods : Dosimetric quantities

Operational quantity : Measurable approximations of protective quantities

The ambient dose equivalent : $H^*(d)$

Dose equivalent produced by radiation field
in the ICRU sphere of density 1 g/cm^3 at a depth d.



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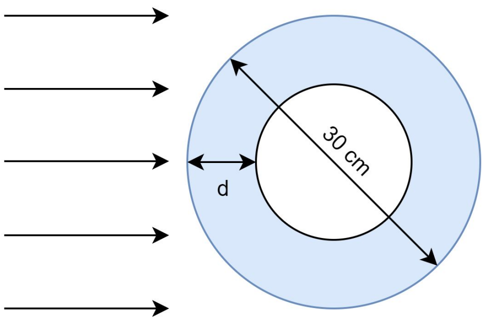
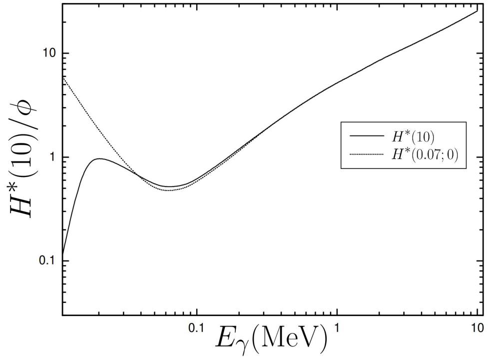


In this work we compute :

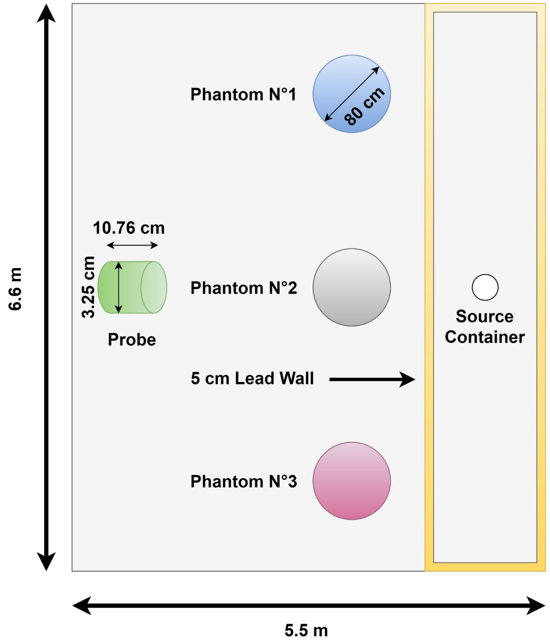
$$\dot{H}^*(10) = \dot{\phi} \sum_i CIPR_i I_i$$

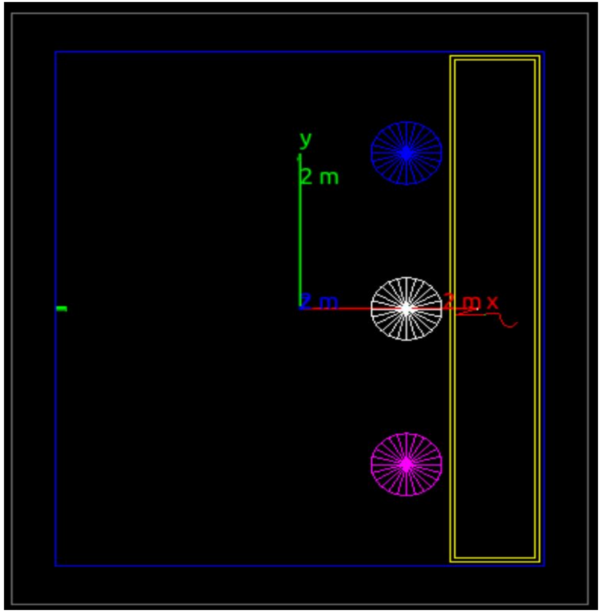


CIPR Coefficients [2]

II. Materials & Methods : Modeling of the laboratory

First work carried out : Learn the GATE software
Modelisation of the laboratory

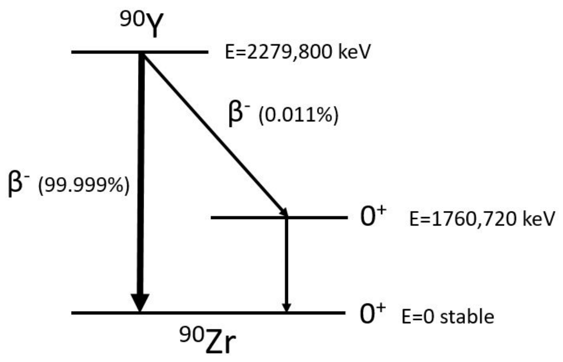


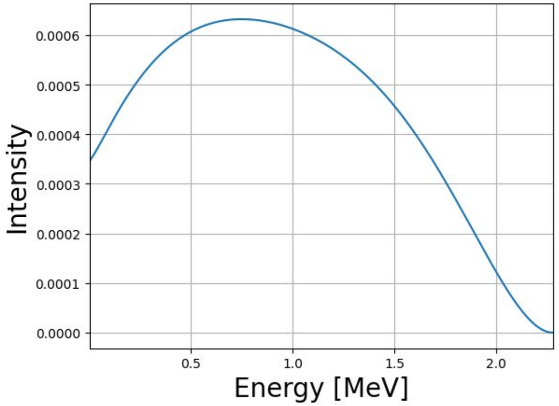


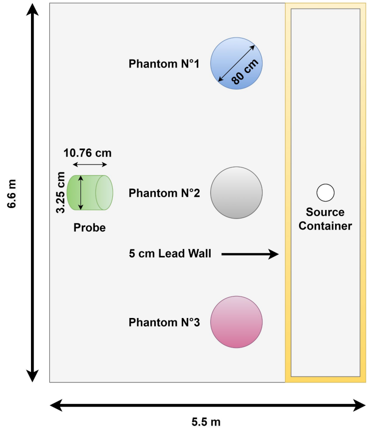
II. Materials & Methods : Modeling of the laboratory

Source : ^{90}Y of activity A = 1110 GBq

$$^{90}_{39}Y \rightarrow \beta^{-} + \bar{\nu}_e + ^{90}_{40}Zr^{(*)}$$







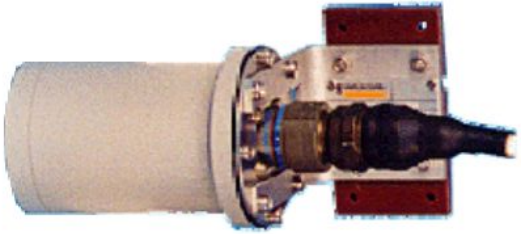
Decay scheme and spectrum data from [3]

β^{-} slowed in lead wall → **Bremsstrahlung photon irradiation**

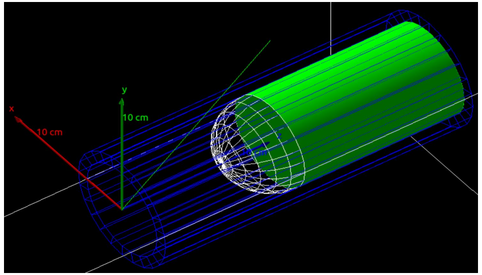
II. Materials & Methods : Modeling of the laboratory

Probe:

- Cylindrical shape
- Aligned with phantom N°2 and source
- Silicon : semiconductor
- Detection range : [0.01 µSv/h ; 1000 Sv/h]



SG/Si 11 probe



Probe model

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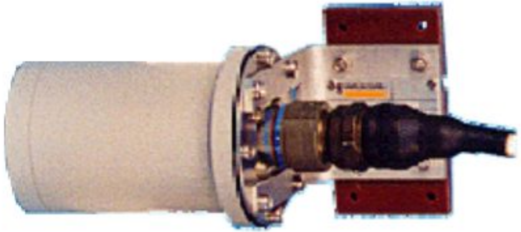

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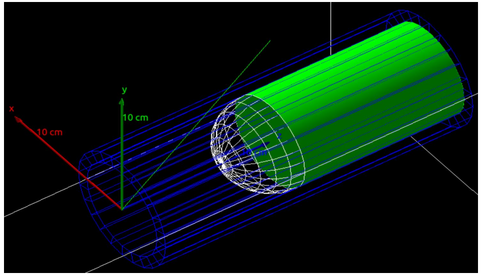


Probe model

To **ensure** the **accuracy** of the probe Monte Carlo modeling : **comparison** with **experimental** data.

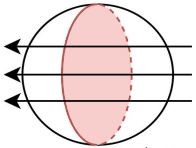
$$^{137}_{55}Cs \rightarrow \beta^- + \bar{\nu}_e + ^{137}_{56}Ba$$

Relative error ~1.5%
Validation of the modeling

II. Materials & Methods : Uncertainties calculations

Reminders : Compute H*(10) for probe and staff

Use the fluence approximation



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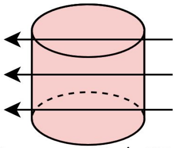

$\phi \approx dl/dV$

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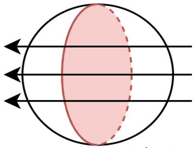

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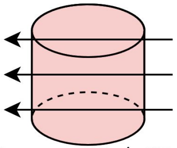

$\phi \approx dl/dV$

$$\frac{\sigma(\dot{H}^*(10))}{\dot{H}^*(10)} = \sqrt{\frac{\sum_i \sigma_{l_i}^2}{(\sum_i l_i)^2} + \frac{\sum_i (I_i^2 \sigma_{CIPR_i}^2 + CIPR_i^2 I_i)}{(\sum_i CIPR_i I_i)^2} + \frac{1}{N_{\text{hit}}}}$$

Unknown term /!

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Reminders : Compute H*(10) for probe and staff
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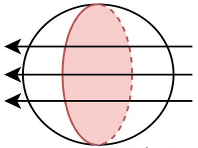

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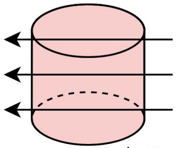

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1) **Compute** the relative uncertainty using the **classical definition**.

II. Materials & Methods : Uncertainties calculations

Reminders : Compute H*(10) for probe and staff

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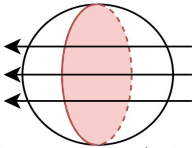

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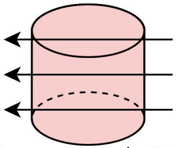

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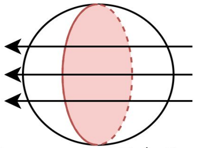
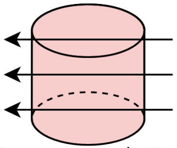
Unknown term /!

1) **Compute** the relative uncertainty using the **classical definition**.
2) **Estimate** the standard deviation of the **approximation** with **several simulations**

II. Materials & Methods : Uncertainties calculations

Reminders : Compute H*(10) for probe and staff
Use the fluence approximation





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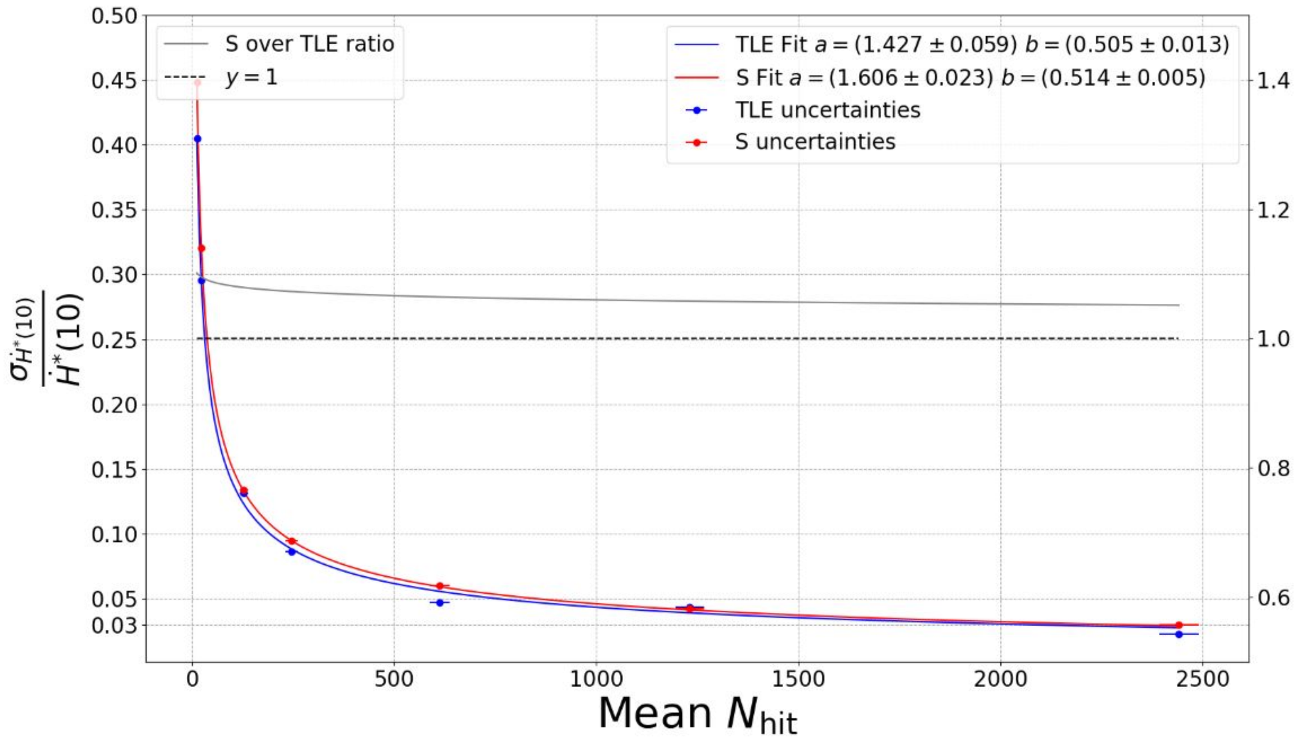
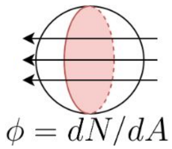
Unknown term /!

1) **Compute** the relative uncertainty using the **classical definition**.
2) **Estimate** the standard deviation of the **approximation** with **several simulations**
3) **Compare** the standard deviation of the approximation to the computed relative uncertainty of the classical definition

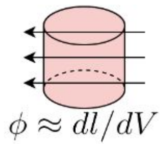
II. Materials & Methods : Uncertainties calculations



Red curve : Surface method, computed.



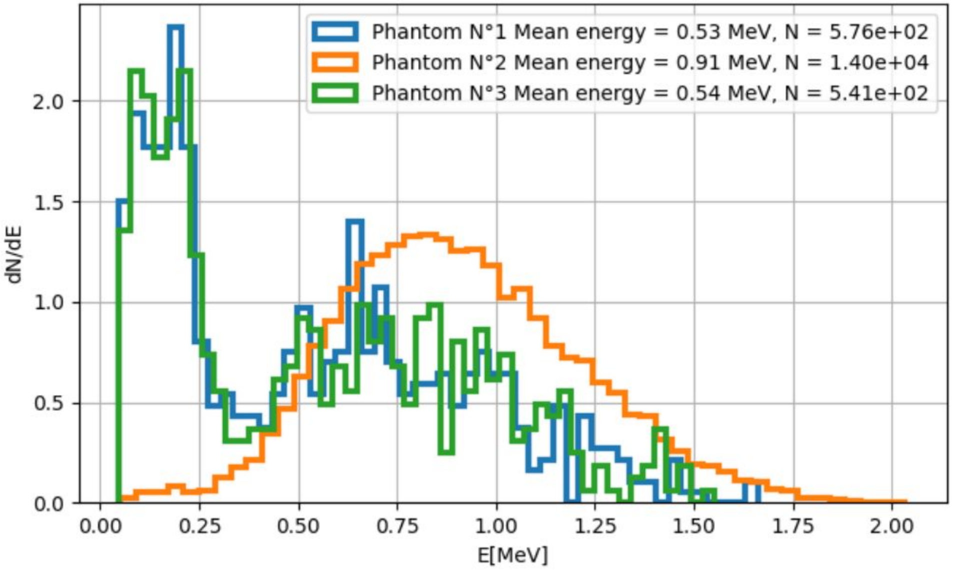
Blue curve : Lengths method, estimated with N simulations.



$$\frac{\sigma(\dot{H}^*(10))}{\dot{H}^*(10)} = \frac{a}{N_{\text{hit}}^b}$$

II. Materials & Methods : Modeling of the laboratory

Simulation results : $N_{sim} = 10^9$, ΔT = 23 h 35 min



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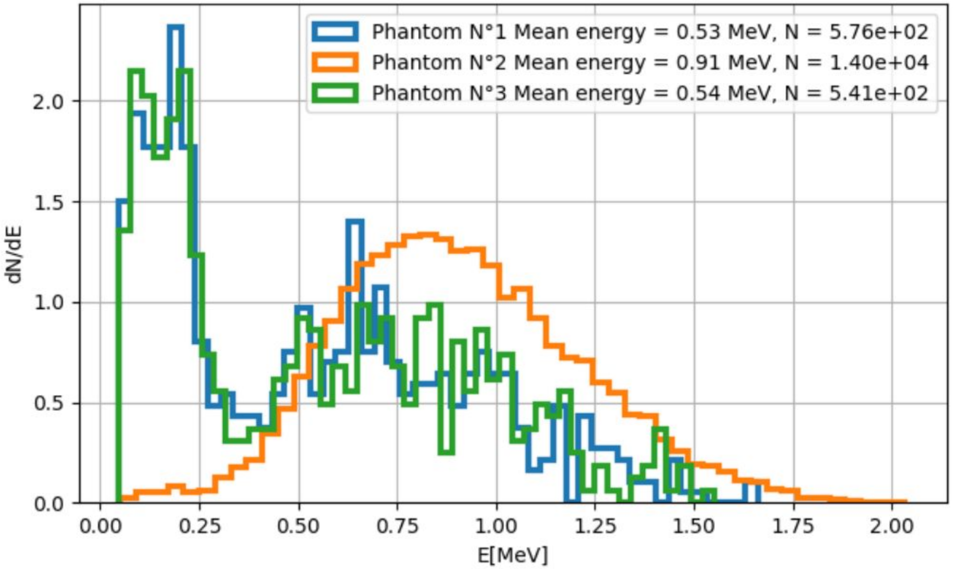

Phantom N°2 :

$$\dot{H}^*(10) = (20.1 \pm 0.30)\mu\text{Sv/h}$$

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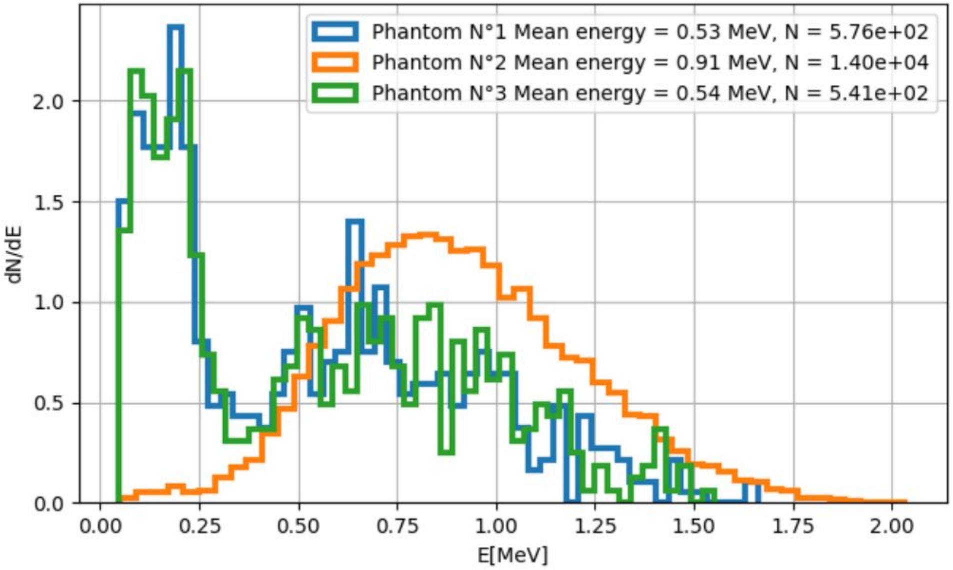

Phantom N°2 :

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Probe :
Only 3 hit !

$$\dot{H}^*(10) = (1.89 \pm 1.97)10^{-1}\mu\mathrm{Sv/h}$$

104% relative uncertainty for the probe : no reference value

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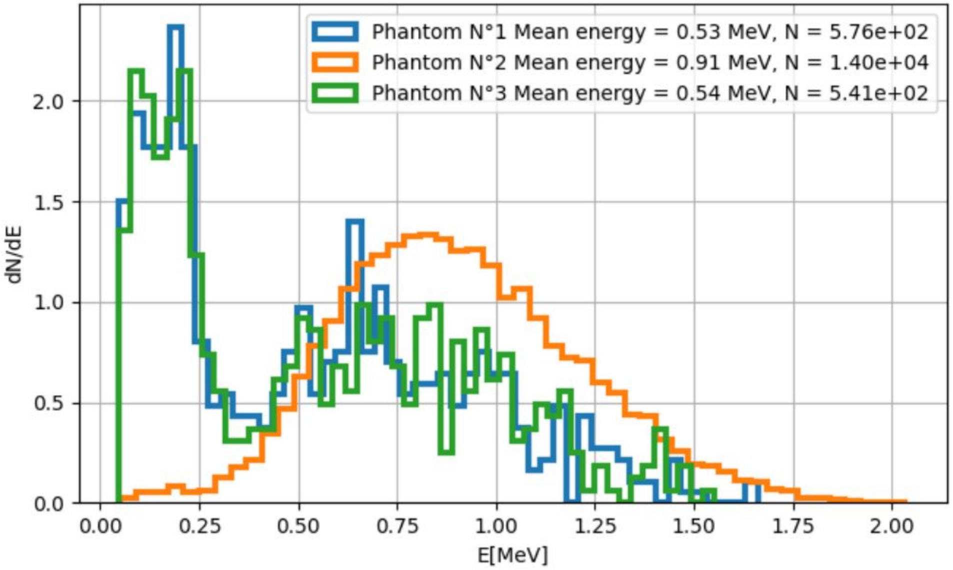


Phantom N°2 : ✓

$$\dot{H}^*(10) = (20.1 \pm 0.30)\mu\text{Sv/h}$$

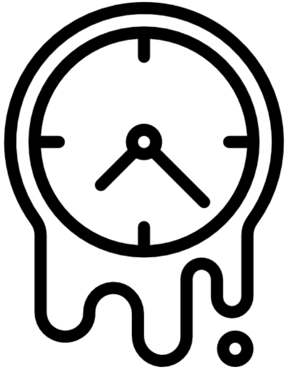
Probe :
Only 3 hit ! ✗

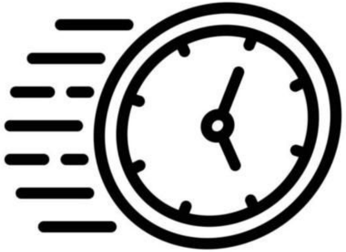
$$\dot{H}^*(10) = (1.89 \pm 1.97)10^{-1}\mu\text{Sv/h}$$

To have **5% error on the probe** : 9.65×10^3 hours or **1 year**, 1 month and 8 days

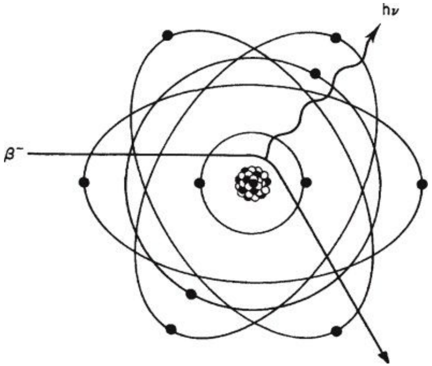
/!\ Low N_{hit}, only an approximation /!\

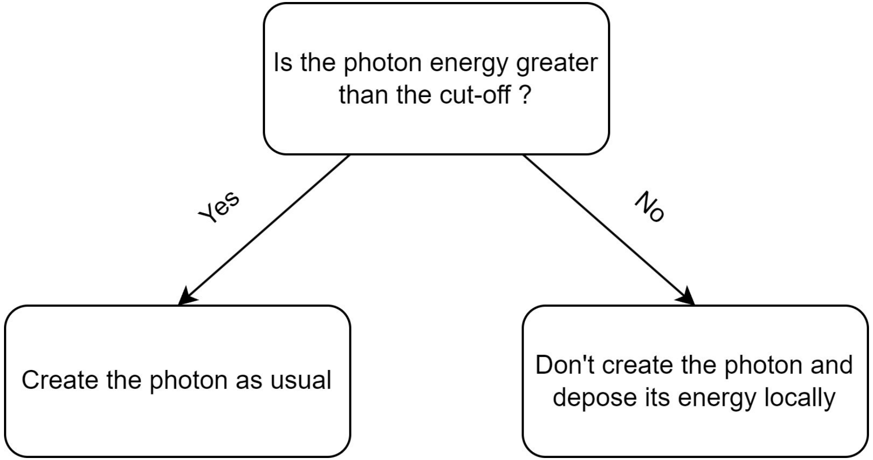
III. Variance Reduction Techniques (VRTs)





III. VRT : Secondary particles Cut-Off





In GEANT4 the cut-off is expressed in **distance** unit which corresponds to the **mean free path**.

Save time by **increasing the cut-off** (less particle to simulate)

III. VRT : Secondary particles Cut-Off

For N_{sim} = 2E8

Electron and Photon cut-off	$\dot{H}^*(10)$ (µSv/h)	ΔT	Volume
1 mm and 1 mm	$(2.02 \pm 0.05)10^{+1}$	26 h 51 m 36 s	Phantom 2
10 mm and 10 mm	$(1.98 \pm 0.06)10^{+1}$	4 h 43 min 12 s	Phantom 2
400 mm and 30 mm	$(1.99 \pm 0.06)10^{+1}$	3 h 21 m 36 s	Phantom 2

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Coherent results

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Coherent results
Reduction of the computation time

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Initially : 10 mm

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Coherent results
Reduction of the computation time
Initially : 10 mm
Results valid to (400, 30) mm

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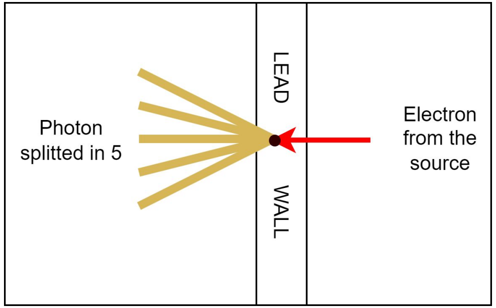
400 mm and 30 mm	$(1.99 \pm 0.06)10^{+1}$	3 h 21 m 36 s	Phantom 2

Coherent results
Reduction of the computation time
Initially : 10 mm
Results valid to (400, 30) mm

Conclusion : 1.4 times faster, no bias

III. VRT : Uniform Bremsstrahlung Splitting (UBS)

Instead of creating 1 photon, generate N_{split} **independent** photons with a statistical weight **$w = 1 / N_{split}$** to propagate through the results.



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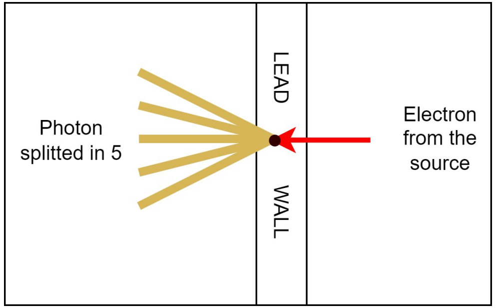

Theoretical evolution of the uncertainty : $R = \frac{\sigma_{\dot{H}*(10)}}{\dot{H}*(10)}$ $\quad R \sim 1/\sqrt{N_{\mathrm{hit}}}$

$$R \rightarrow R_{\mathrm{split}} = \frac{R}{\sqrt{N_{\mathrm{split}}}}$$

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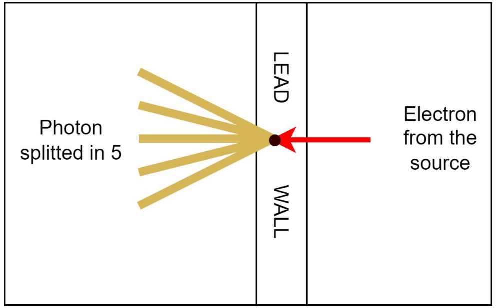

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$$\ln(R_{\mathrm{split}}) = \ln(R) - \frac{1}{2}\ln(N_{\mathrm{split}})$$

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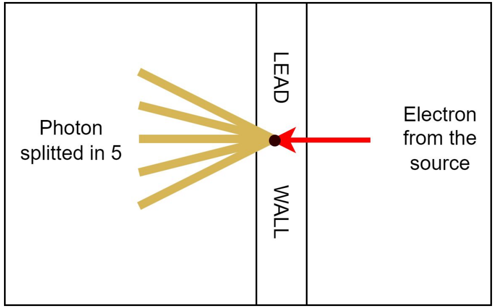

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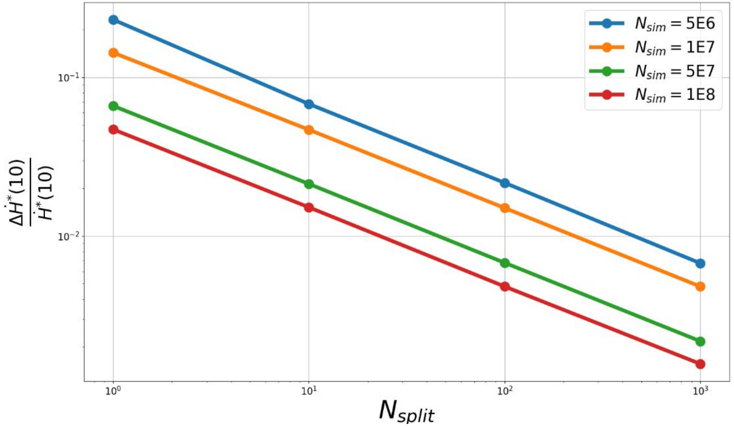

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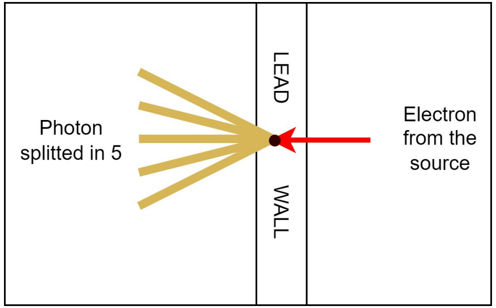

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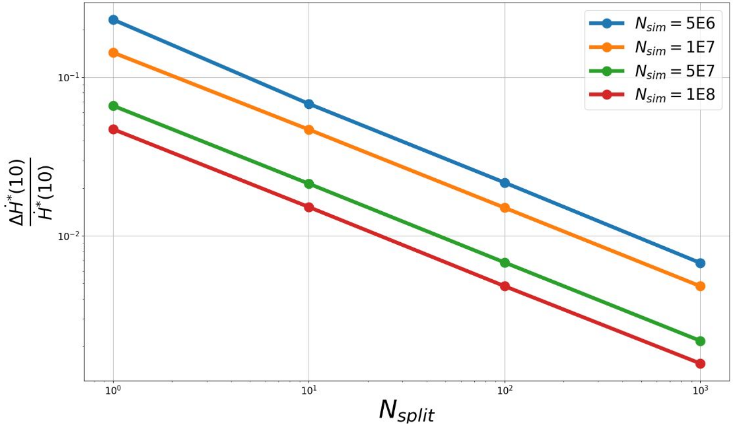
$$\ln(R_{\mathrm{split}}) = \ln(R) - \frac{1}{2}\ln(N_{\mathrm{split}})$$

Mean leading coefficient : 0.502 ± 1.93 10^{-3} %

Theoretical uncertainty evolves as expected



III. VRT : Uniform Bremsstrahlung Splitting (UBS)

Bias study on H*(10) and uncertainties

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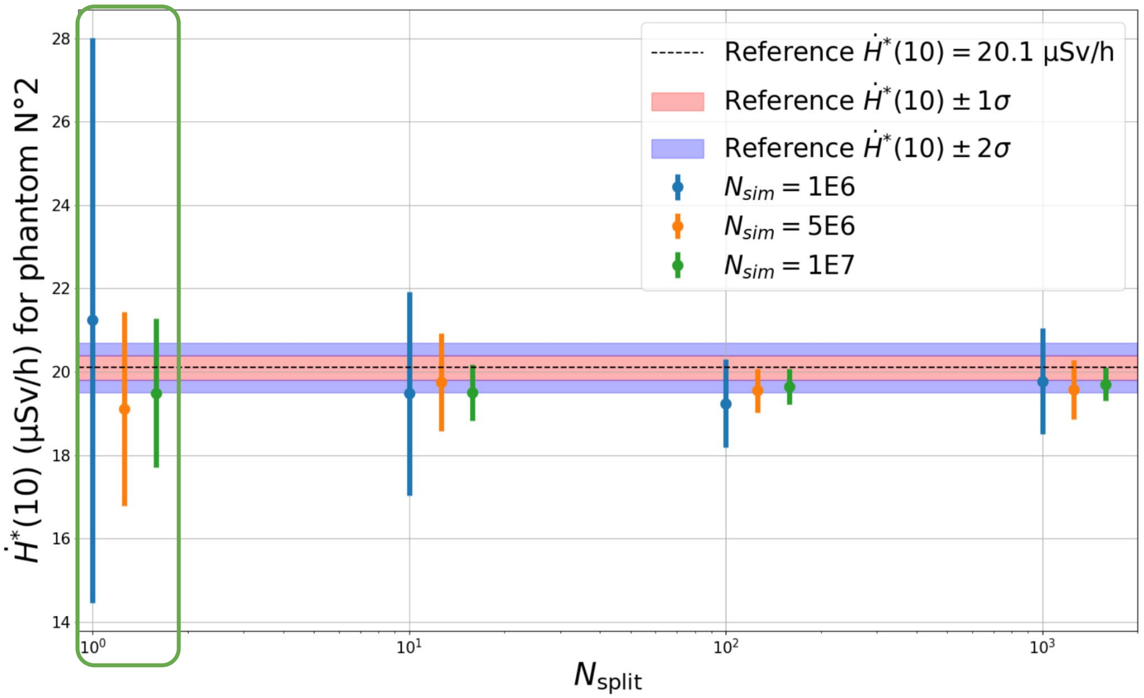

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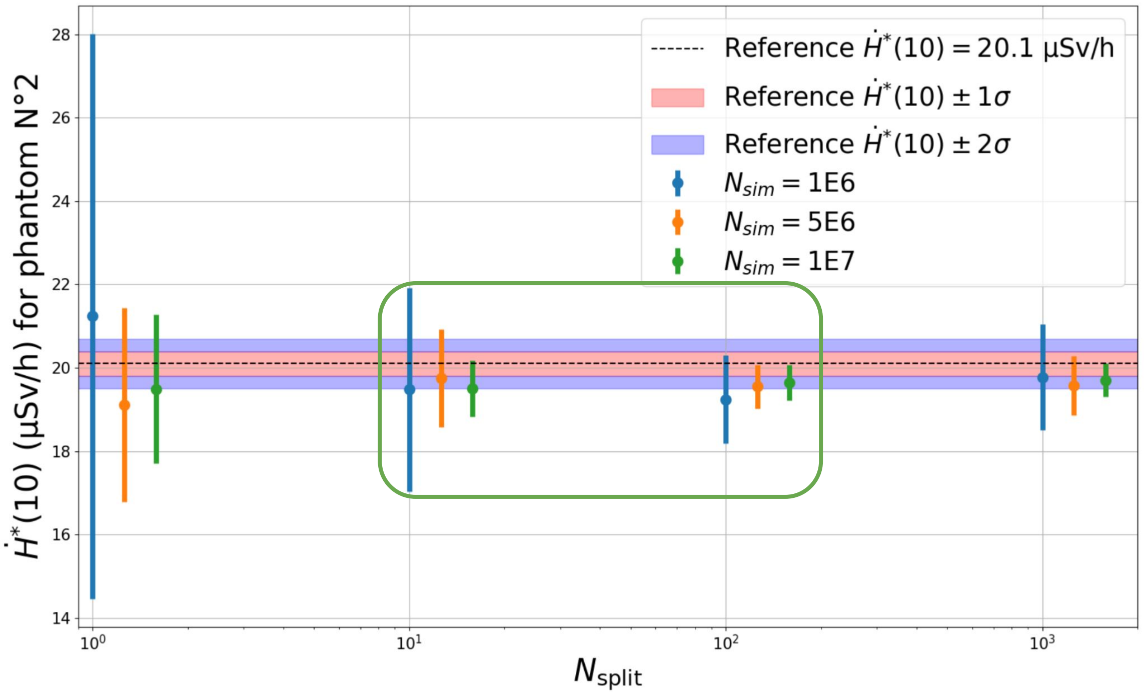

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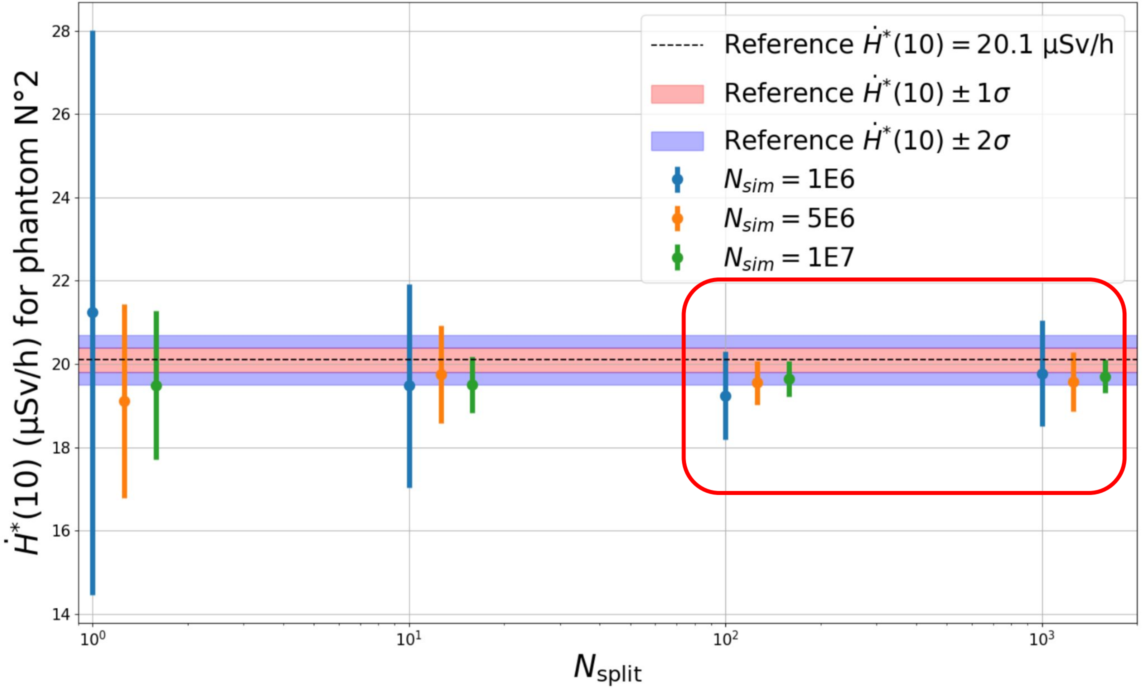

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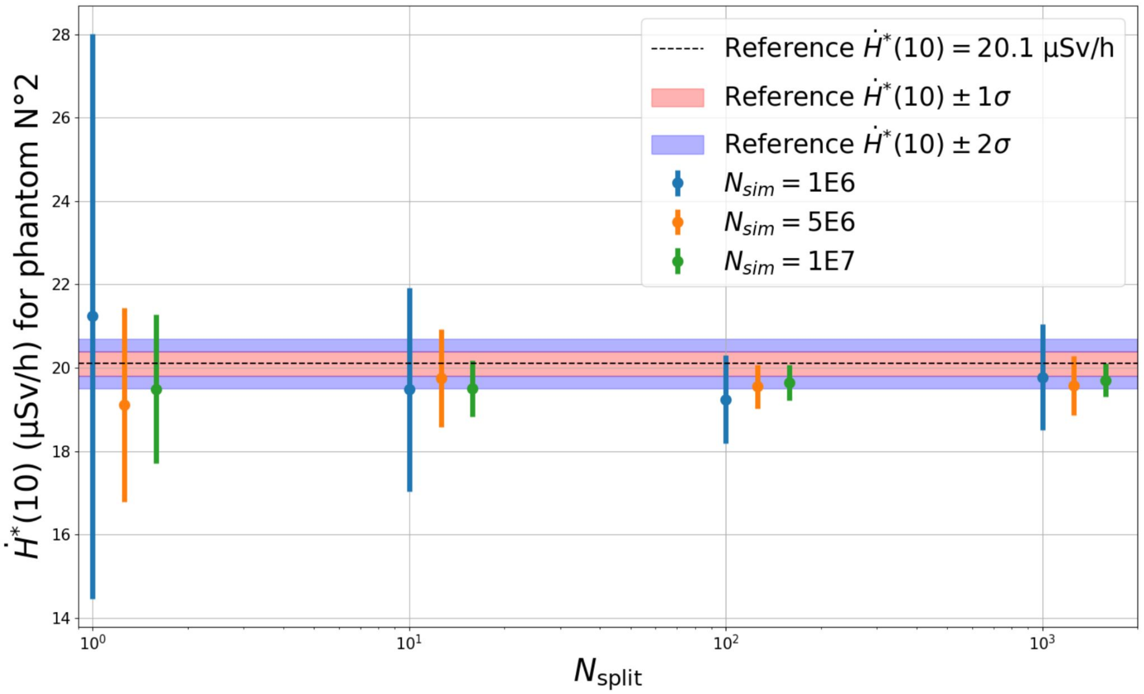


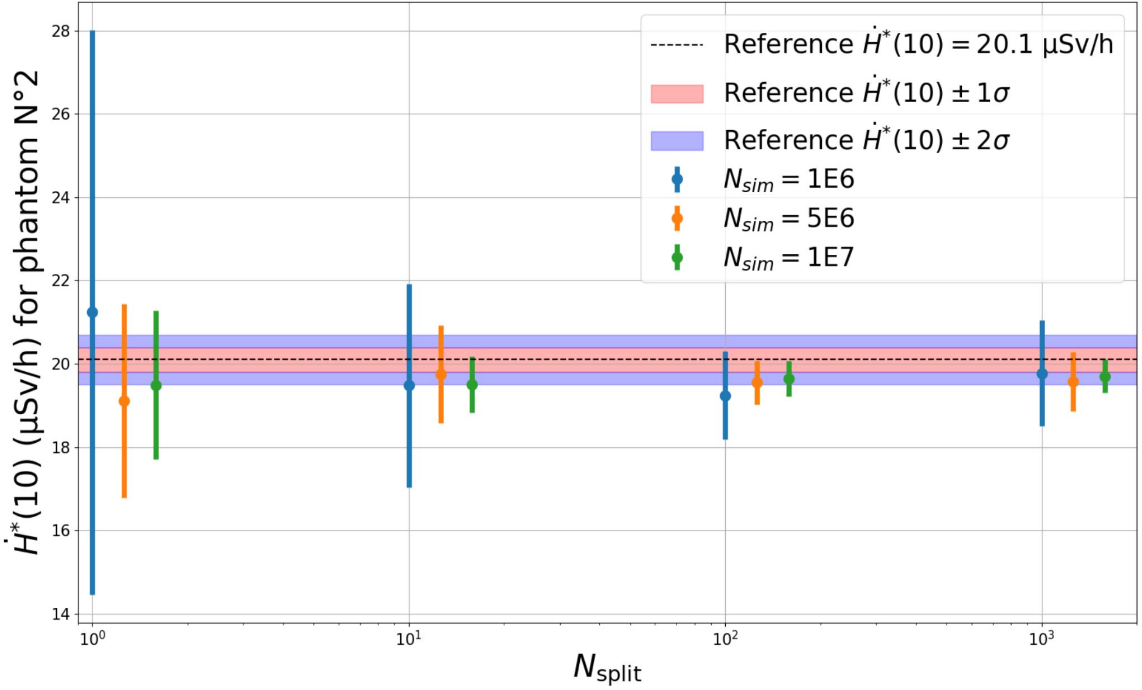
To avoid bias : N_{split} = 100 when $N_{sim} > 10^7$

Increase computation time by 5%.

Multiply number of hit by N_{split}.

III. VRT : Uniform Bremsstrahlung Splitting (UBS)

Bias study on H*(10) and uncertainties



To avoid bias : N_{split} = 100 when $N_{sim} > 10^7$

Increase computation time by 5%.

Multiply number of hit by N_{split}.

Conclusion : 100/1.05 times faster, no bias

III. VRT : Probe Radius Variation

$$\dot{H}^*(10) = \dot{\phi} \sum_i CIPR_i I_i$$

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Invariant by the changing the radius **for the probe** under some assumptions :

Unidirectional and **Homogeneous** radiation field, **invariant energy distribution**.

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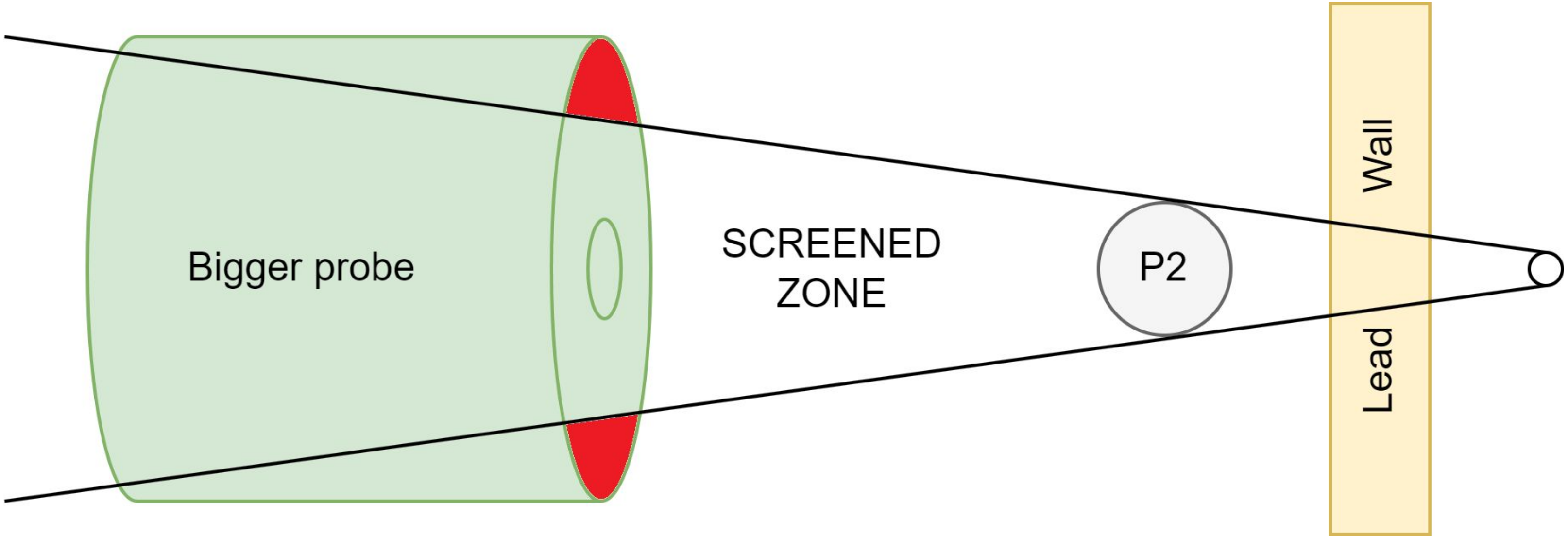
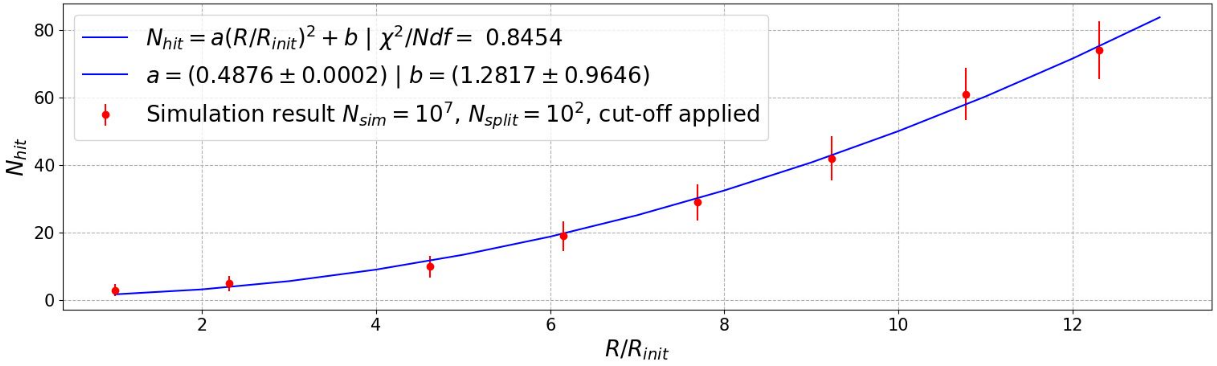


III. VRT : Probe Radius Variation

Under these assumptions N_{hit} should follow a square low.



N_{hit} follows a square low, **hypothesis validated**.

III. VRT : Probe Radius Variation

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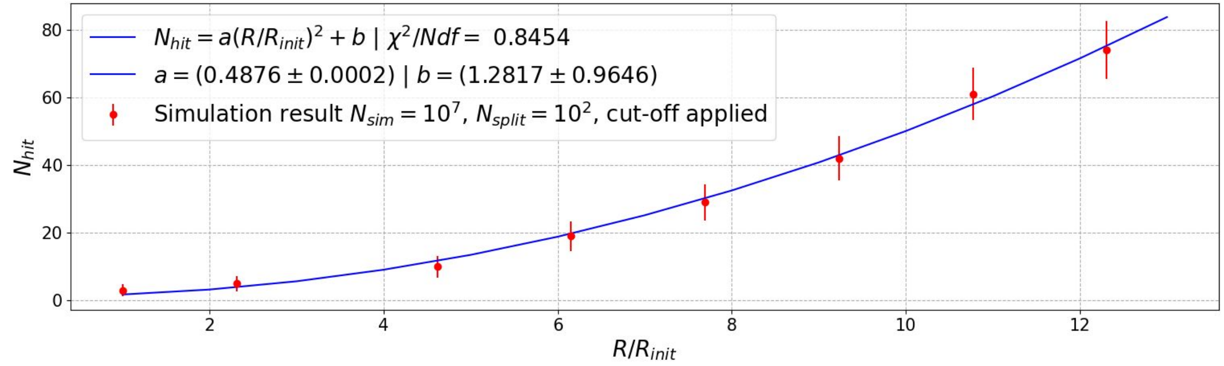

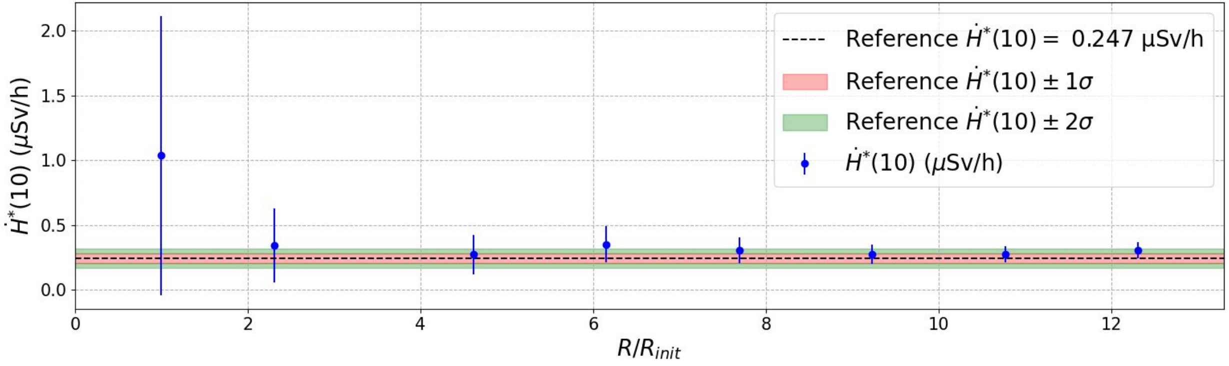

N_{hit} follows a square low, **hypothesis validated**.

Results **converge to a reference value** obtained with $N_{sim} = 10^9$, $N_{split} = 100$ and cut-off applied

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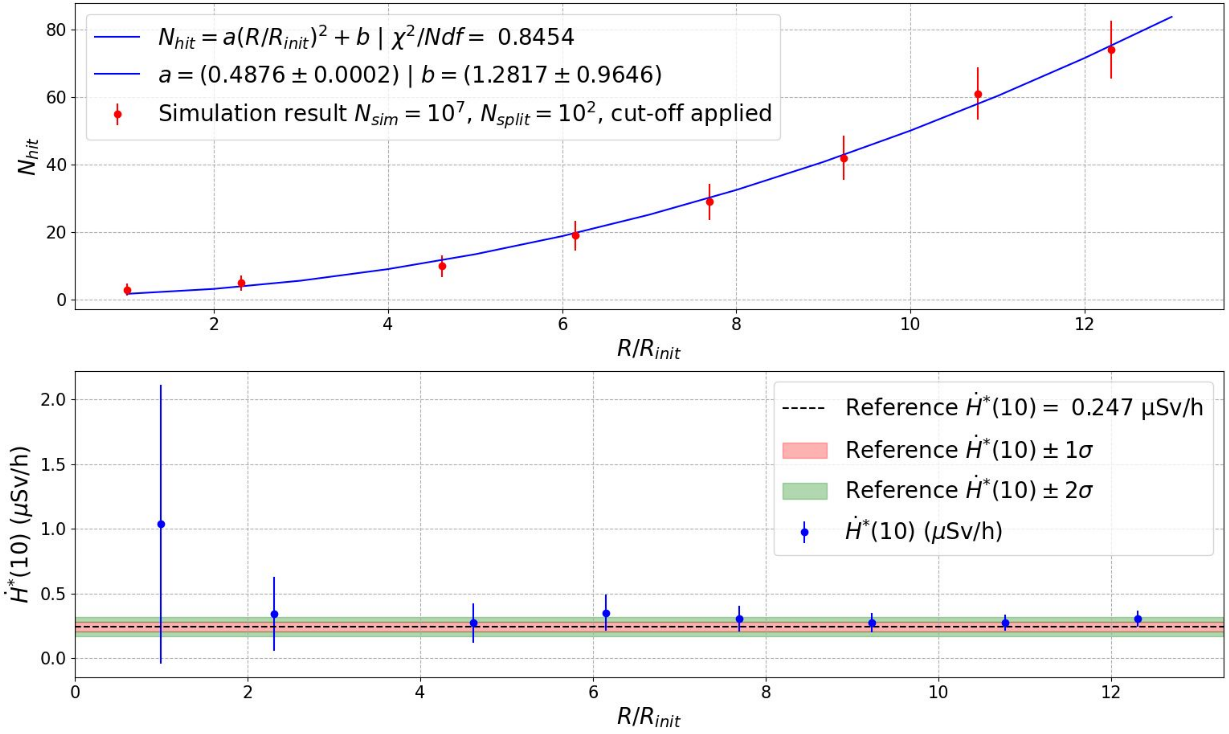


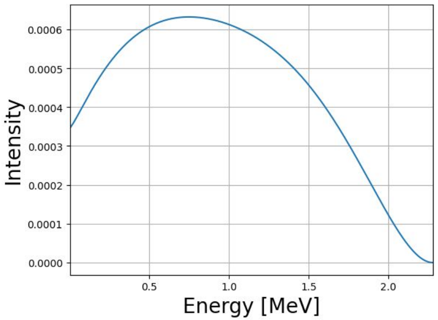
N_{hit} follows a square low, **hypothesis validated**.

Results **converge to a reference value** obtained with $N_{sim} = 10^9$, $N_{split} = 100$ and cut-off applied

Conclusion : 150 times faster, no bias, radius set to 40 cm

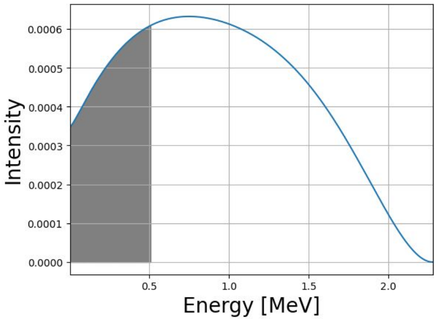
III. VRT : Cutting the energy spectrum

Low energy particles don't cross the lead wall : Simulating useless particles ?



Cut useless part

$P(cross) < 10^{-7}$



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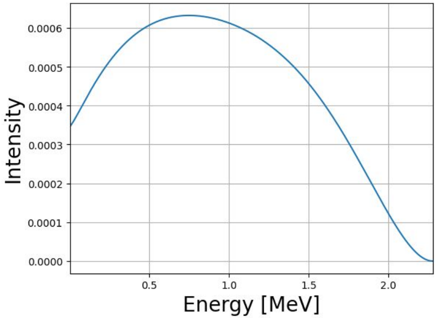

Cut useless part

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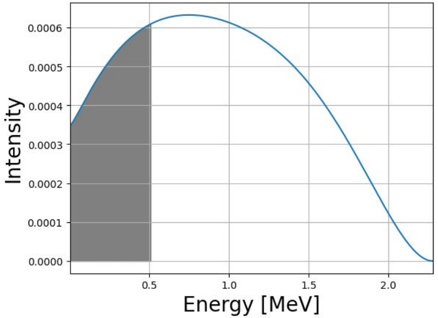

Correction on the activity $$A \rightarrow A \frac{\int_{E_{\text{cut}}}^{E_{\text{max}}} \frac{dN}{dE} dE}{\int_{0}^{E_{\text{max}}} \frac{dN}{dE} dE}$$

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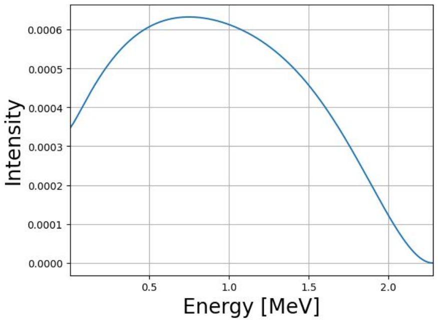

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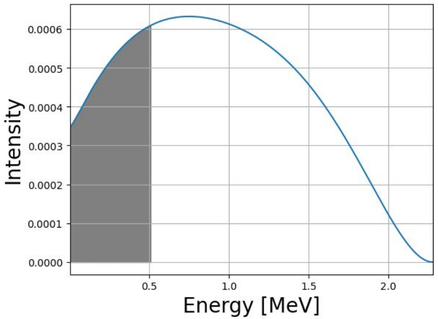

Correction on the activity

$$A \rightarrow A \frac{\int_{E_{\mathrm{cut}}}^{E_{\mathrm{max}}} \frac{dN}{dE} dE}{\int_{0}^{E_{\mathrm{max}}} \frac{dN}{dE} dE}$$

Method	N_{hit}	ΔT	$\dot{N}_{\mathrm{hit}}$ (particles.s^{-1})	$\dot{H}^*(10)$ (µSv/h)
Without spectrum cut	14003	23 h 35 min	$(1.65 \pm 0.01)10^{-1}$	$(2.01 \pm 0.03)10^{+1}$
With spectrum cut	19092	26 h 2 min	$(2.25 \pm 0.02)10^{-1}$	$(2.06 \pm 0.03)10^{+1}$

III. VRT : Cutting the energy spectrum

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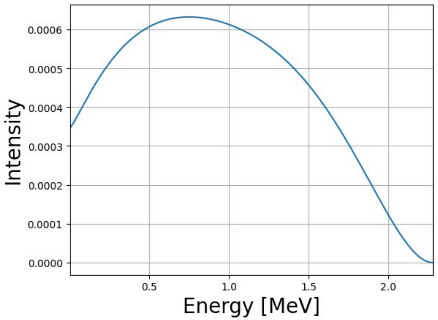

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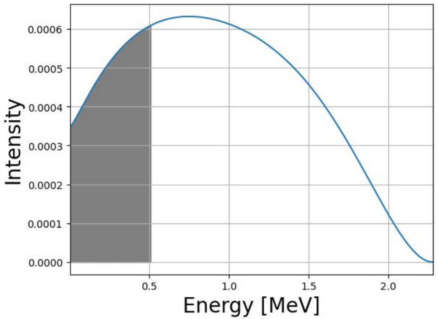

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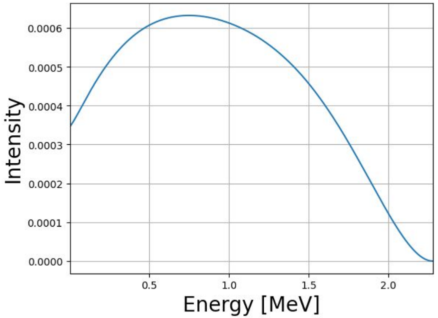

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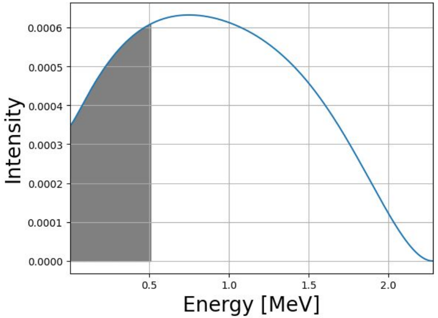

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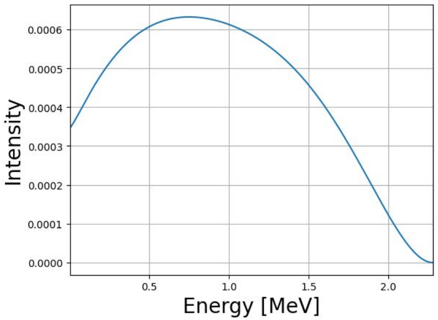

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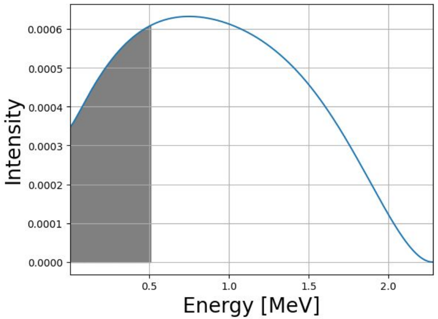

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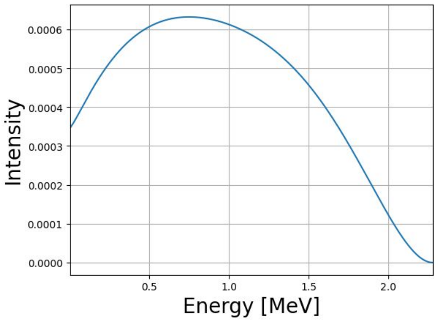

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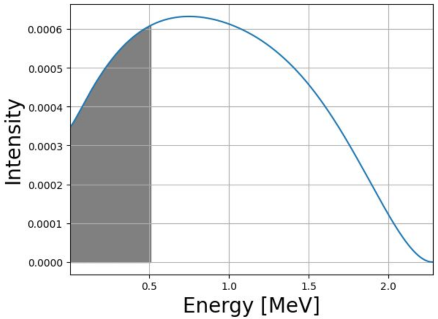

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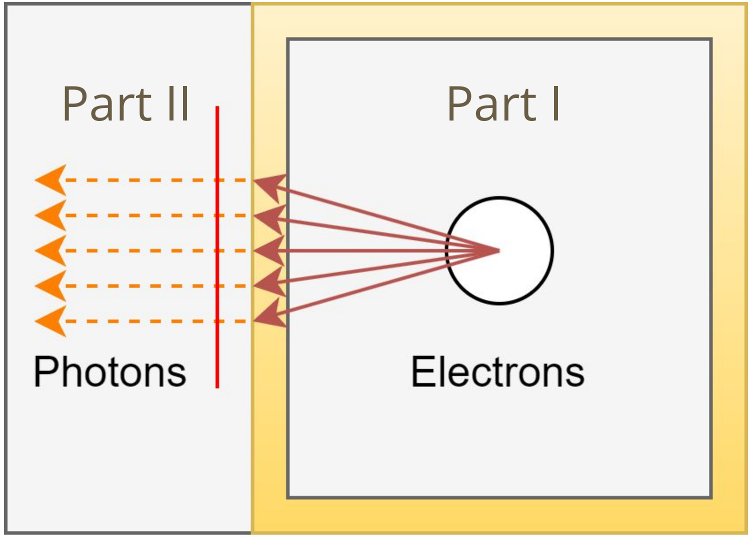
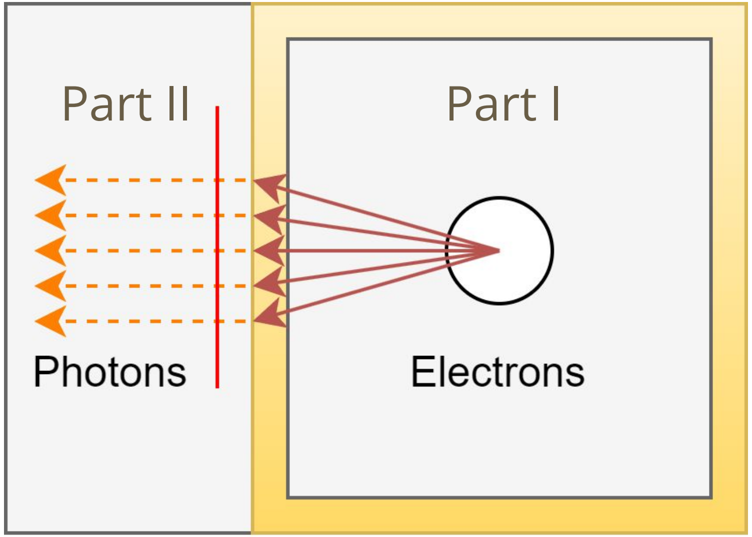
Conclusion : For same N_{hit}, (1.24 ± 0.01) faster, no bias

III. Photon Phase Space



Only need to simulate part II for different configurations

III. Photon Phase Space



New uncertainty term :

$$\frac{\sigma_{\dot{H}^*(10)}}{\dot{H}^*(10)} = \sqrt{\frac{\sum_i \sigma_{l_i}^2}{(\sum_i l_i)^2} + \frac{\sum_i \left(I_i^2 \sigma_{CIPR_i}^2 + CIPR_i^2 I_i\right)}{(\sum_i CIPR_i I_i)^2} + \frac{1}{N_{\text{hit}}} + \boxed{\frac{2}{N_\gamma}}}$$

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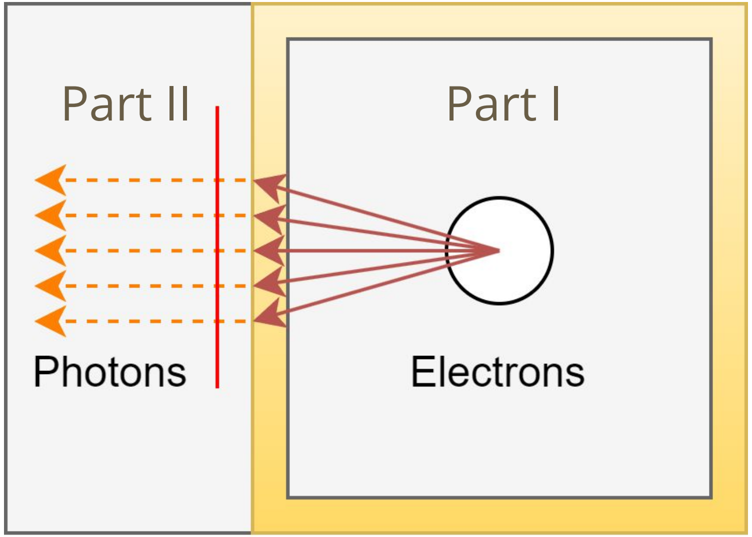

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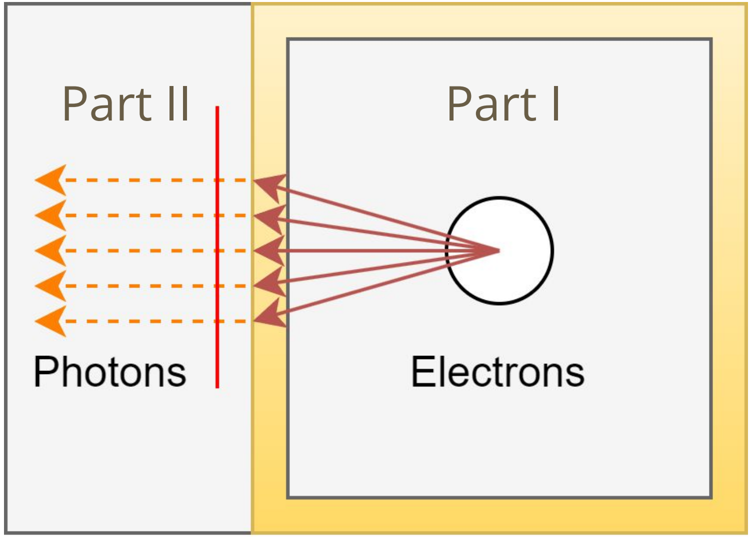
Method	$\dot{H}^*(10)$ (µSv/h)	ΔT
Without phase space	$(2.47 \pm 0.37)10^{-1}$	24 h 45 min
With phase space	$(2.70 \pm 0.39)10^{-1}$	34 s

III. Photon Phase Space



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Method	$\dot{H}^*(10)$ (µSv/h)	ΔT
Without phase space	$(2.47 \pm 0.37)10^{-1}$	24 h 45 min
With phase space	$(2.70 \pm 0.39)10^{-1}$	34 s

Conclusion : 2.6 10^3 times faster, no visible bias
Only possible after a first simulation

III. VRT : Total time gain

Secondary particles cut-off : g(Cut-Off) = 1.4

III. VRT : Total time gain

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Uniform Bremsstrahlung splitting : g(UBS) = 100/1.05

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Probe radius variation : g(Radius) = 151.48

III. VRT : Total time gain

Secondary particles cut-off : g(Cut-Off) = 1.4
Uniform Bremsstrahlung splitting : g(UBS) = 100/1.05
Probe radius variation : g(Radius) = 151.48
Energy spectrum cut : g(Spectrum) = 1.24 ± 0.01

III. VRT : Total time gain

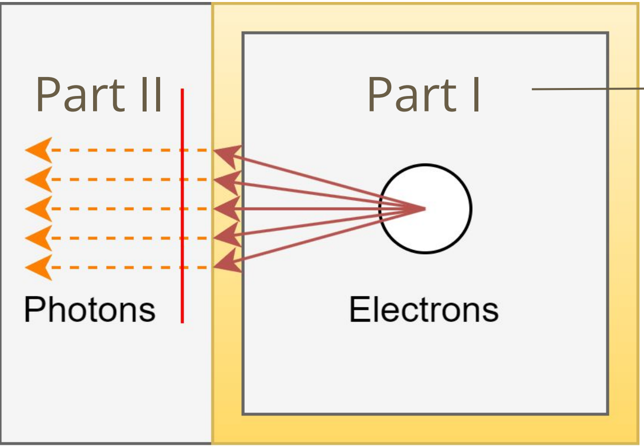
Secondary particles cut-off : g(Cut-Off) = 1.4
Uniform Bremsstrahlung splitting : g(UBS) = 100/1.05
Probe radius variation : g(Radius) = 150
Energy spectrum cut : g(Spectrum) = 1.24 ± 0.01

Total gain : $G = (2.504 \pm 0.020)10^4$

III. VRT : Total time gain

Secondary particles cut-off : g(Cut-Off) = 1.4
Uniform Bremsstrahlung splitting : g(UBS) = 100/1.05
Probe radius variation : g(Radius) = 151.48
Energy spectrum cut : g(Spectrum) = 1.24 ± 0.01

Total gain : G = $(2.504 \pm 0.020)10^4$

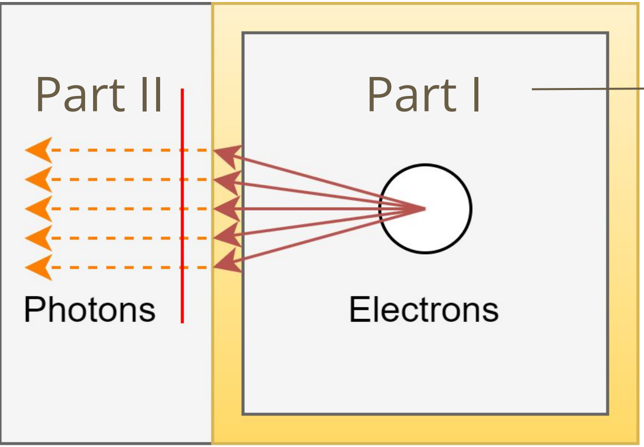


1 year 1 month (5% probe) to 20 min

III. VRT : Total time gain

Secondary particles cut-off : g(Cut-Off) = 1.4
Uniform Bremsstrahlung splitting : g(UBS) = 100/1.05
Probe radius variation : g(Radius) = 151.48
Energy spectrum cut : g(Spectrum) = 1.24 ± 0.01

Total gain : $G = (2.504 \pm 0.020)10^4$

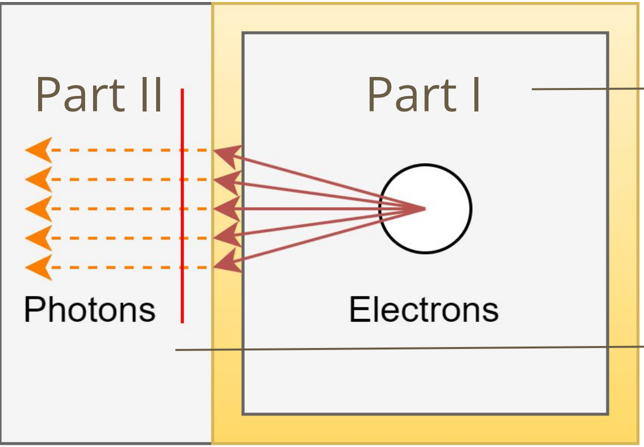


1 year 1 month (5% probe) to ~~20 min~~
Test $\lesssim$ 2 hours

III. VRT : Total time gain

Secondary particles cut-off : g(Cut-Off) = 1.4
Uniform Bremsstrahlung splitting : g(UBS) = 100/1.05
Probe radius variation : g(Radius) = 151.48
Energy spectrum cut : g(Spectrum) = 1.24 ± 0.01

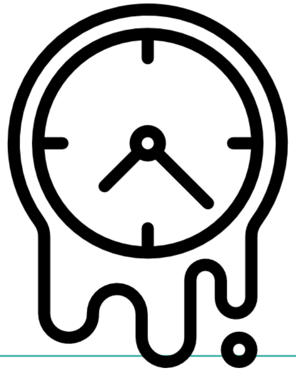
Total gain : G = $(2.504 \pm 0.020)10^4$

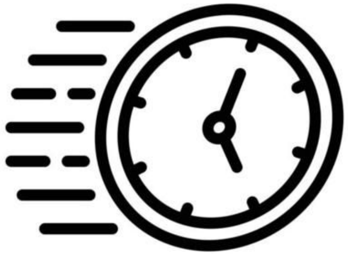


1 year 1 month (5% probe) to ~~20 min~~
Test ≲ 2 hours

~ 30 seconds

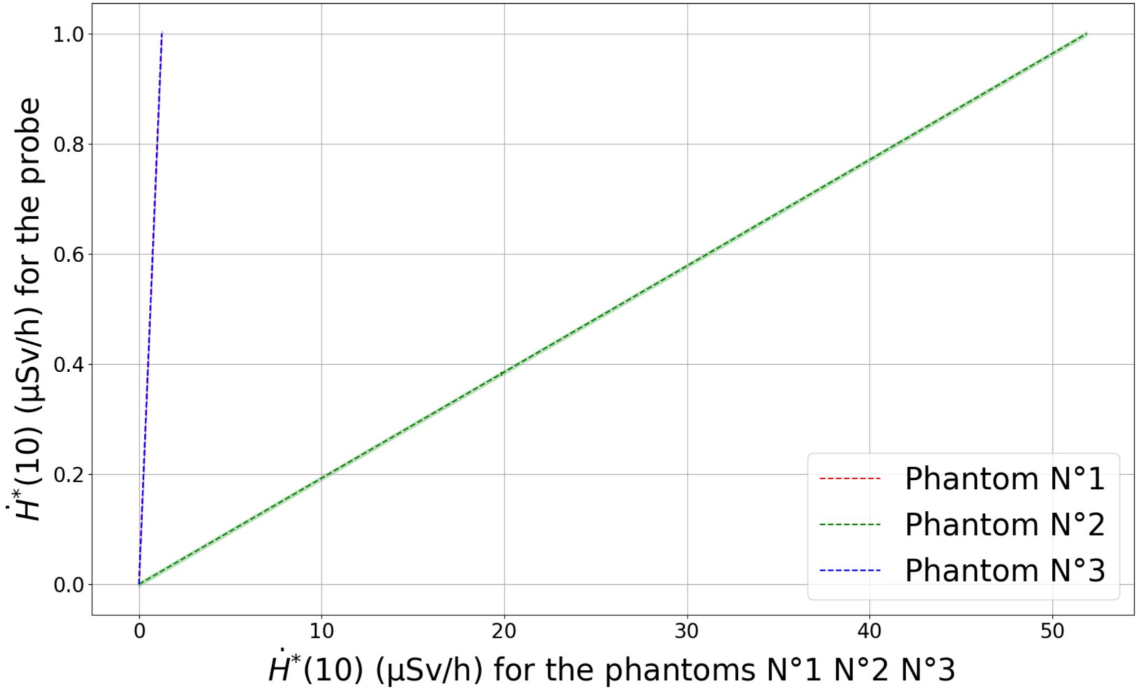
IV. Application of the methods





IV.A Threshold signal

N_{sim} = 3 10^9, N_{split} = 10^2, R_{probe} = 40 cm, Cut-Off applied, Energy spectrum cut :



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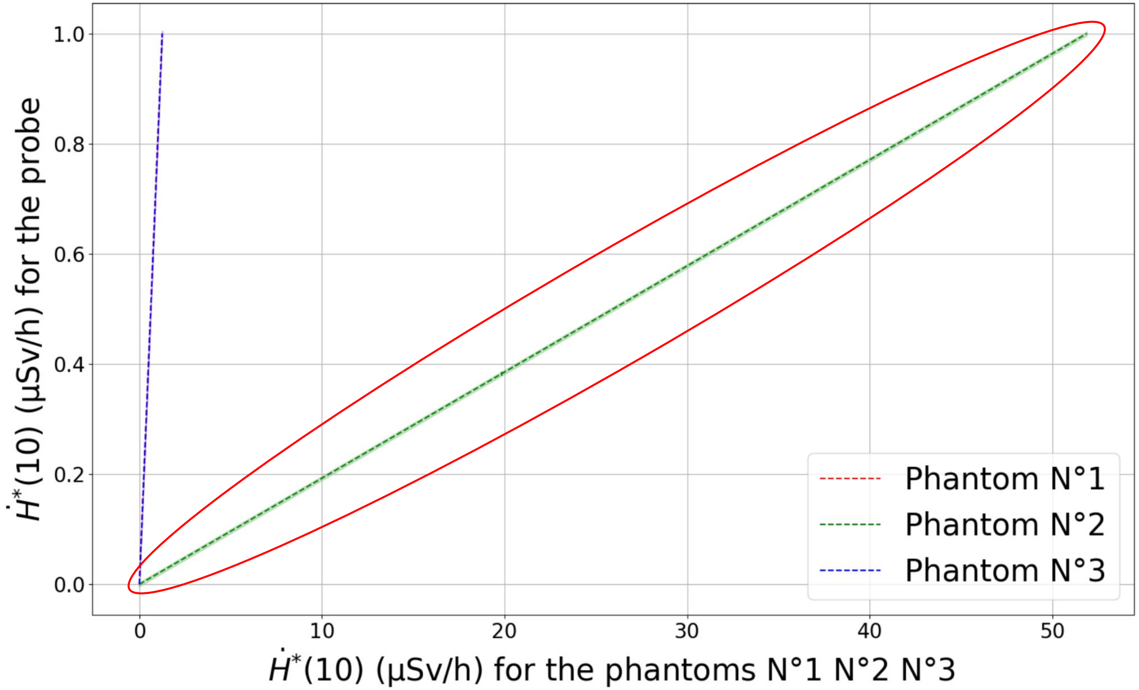

Phantom N°2 : **(51.32 ± 0.53)** times more than the probe.

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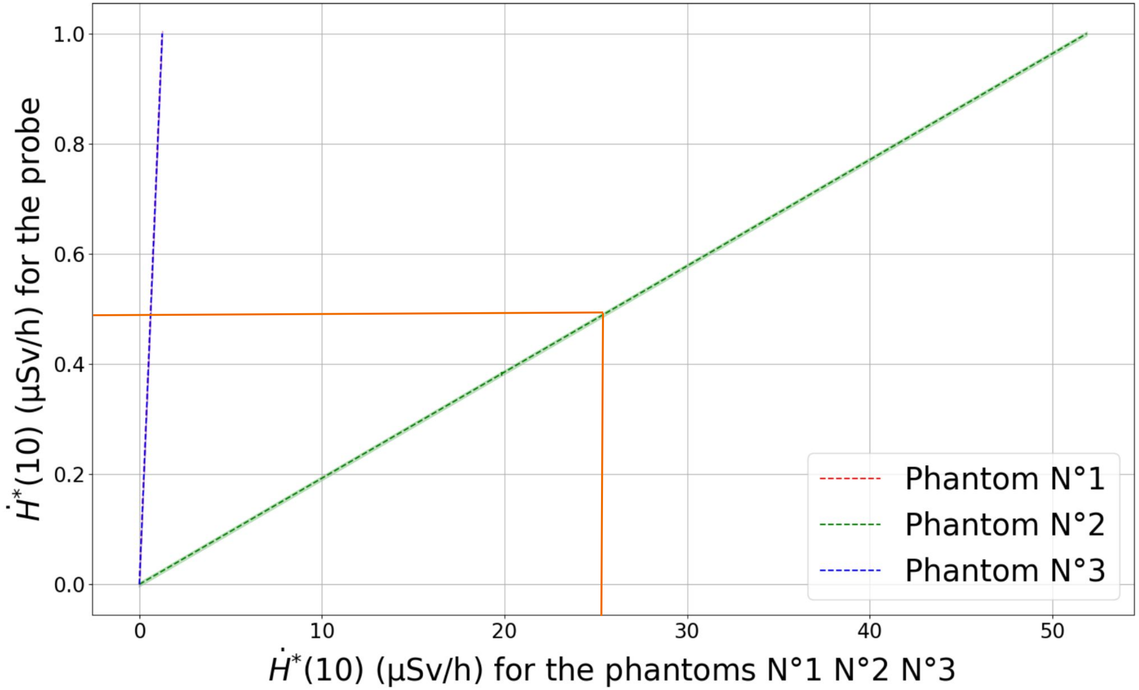

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~ **0.5 µSv/h threshold** for 25µSv/h

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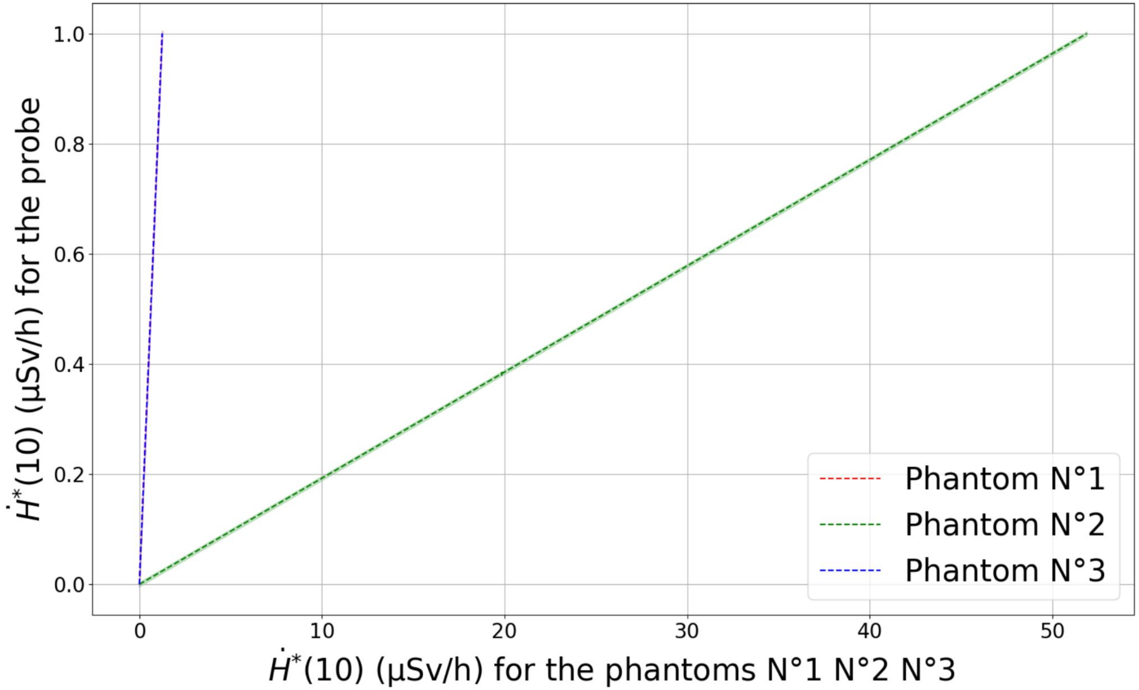


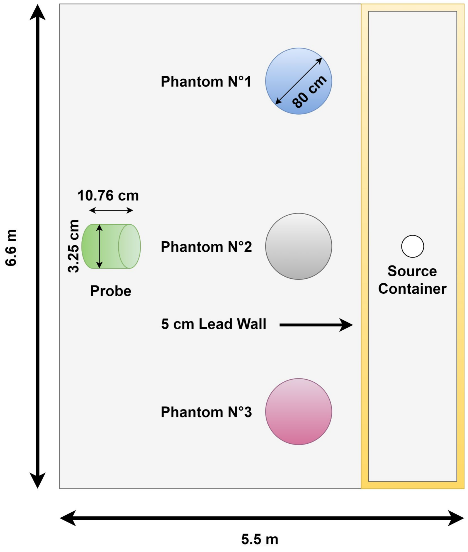
Phantom N°2 : **(51.32 ± 0.53)** times more than the probe.

~ **0.5 µSv/h threshold** for 25µSv/h

Variation of 43% for the probe
Correlation between individual bias ?

IV.B Optimization of probe placement

N_{sim} = 3 10^9, N_{split} = 10^2, R_{probe} = 40 cm, Cut-Off applied, Energy spectrum cut :



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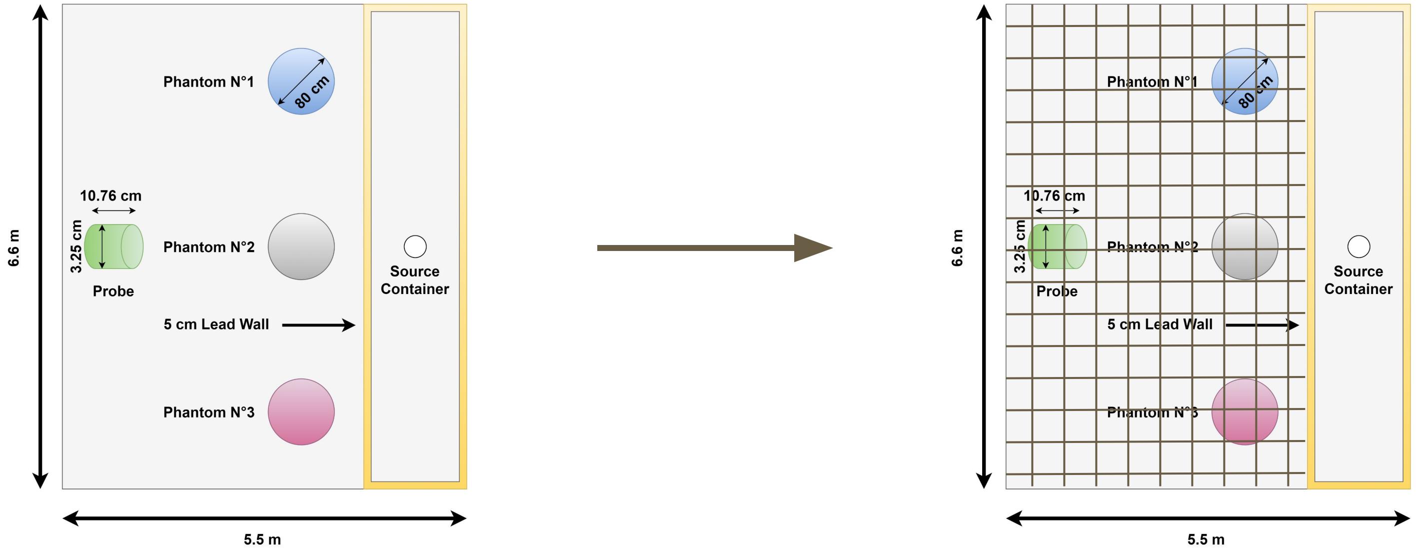

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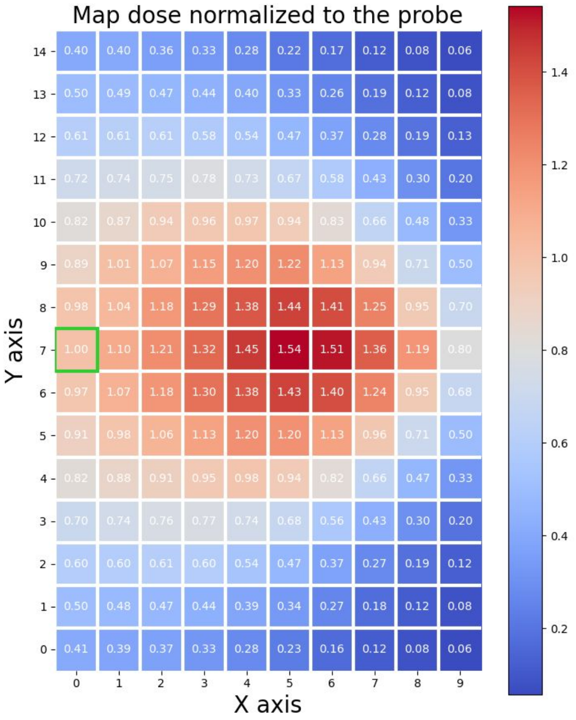

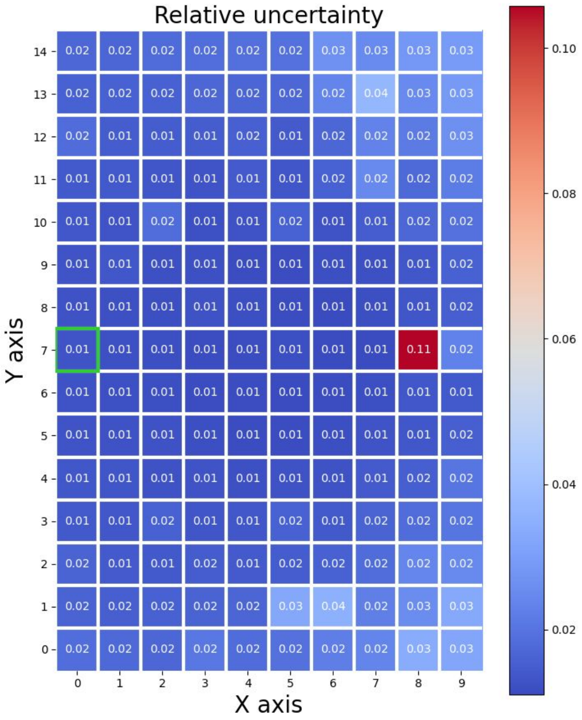

Possibility to increase the signal by a factor **(1.54 ± 0.02)**

V. Conclusion

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- Simulation of laboratory front panel
- Uncertainty calculation → More than a year for good statistical results
- Introduction VRTs → 2 hours to generate a phase space
- Using phase space → ~ 30 seconds for any configuration

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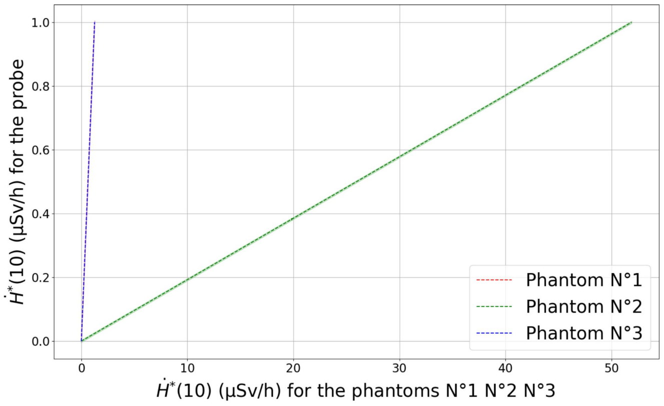
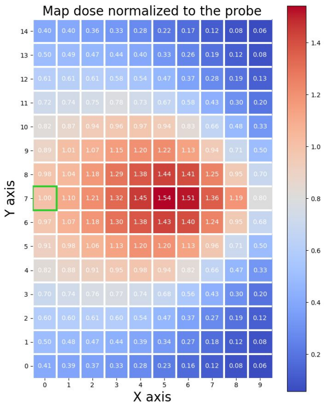
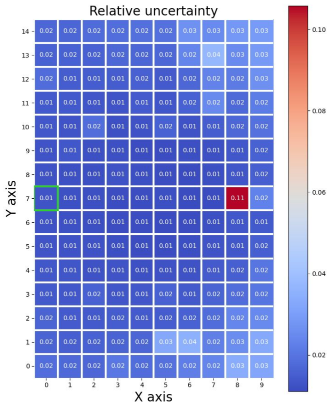
Establish relationship between probe and staff exposure
Establish radiological exposure as a function of position







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- Simulation of laboratory front panel
- Uncertainty calculation → More than a year for good statistical results
- Introduction VRTs → 2 hours to generate a phase space
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Establish relationship between probe and staff exposure
Establish radiological exposure as a function of position

Openings :

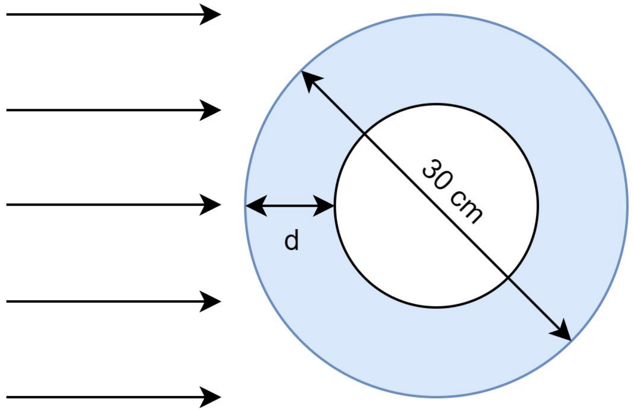
- Investigate single VRT bias correlation
- Obtain experimental reference value for the probe
- Find other VRTs

Sources

[1] - Arronax Nantes
https://www.arronax-nantes.fr/chimie-et-radiopharmacie/thematique/radiopharmacie/
[2] - CIPR Coefficients
International Commission on Radiological Protection, 1995, Conversion coefficients for use in Radiological Protection Against External Radiation, publication 74
[3] - ^{90}Y Decay scheme and energy spectrum data
International Atomic Energy Agency

Backups : ICRU Sphere

ICRU = Internal Commission on Radiation Units & Measurements



76.2 % O, 11.1% C, 10.1% H, 2.6% N

Backups : Radiation protection factors

dE/dm Absorbed dose (Gy or J/Kg)

Ideal dE/dx to kill DNA : 100 keV/µm

Even if two types of particles deposited dE/dm their dE/dx is different

$$H_T = D_{T,R} W_R$$

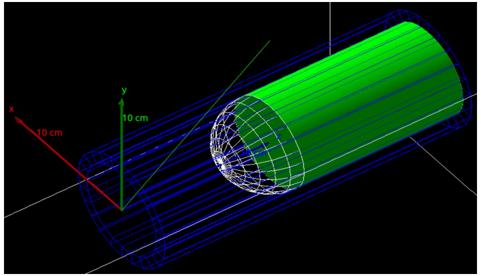
Different organs sensibilities (experimental)

$$E = \sum H_T W_T$$

Backups : Materials & Methods : The GATE software

GATE software developed by the international OpenGATE collaboration

Define volumes and geometries with associated material



Cylindrical Si probe

Select physical processes : EM type in our case
Photoelectric, Compton, pair production, Bremsstrahlung, Annihilation...

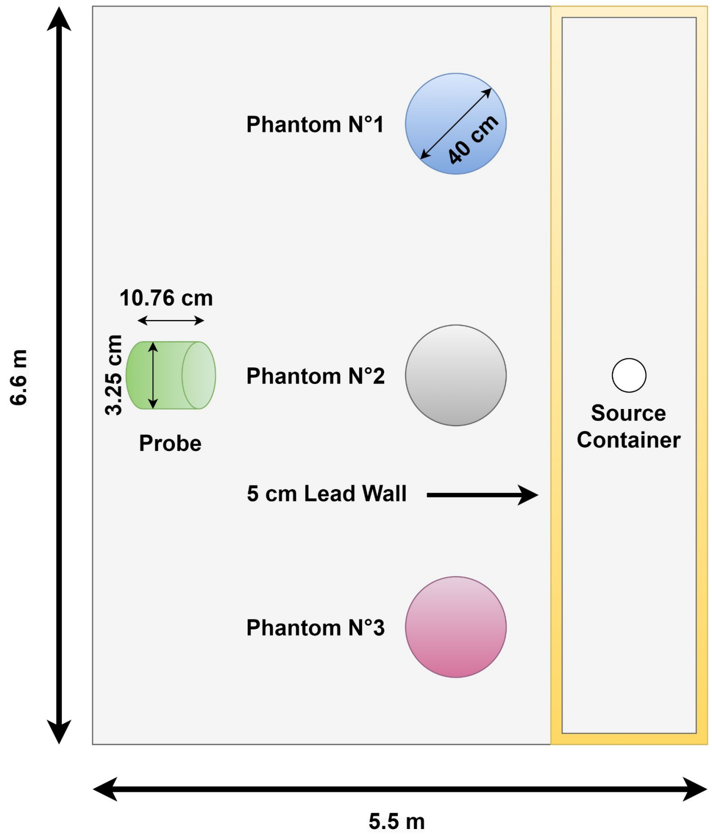
Source : Particles type, energy range, angular distribution.

Attach actors to volumes (TLE Dose Actor, Energy Spectrum, Fluence actor, Phase Space Actor...)

GATE
opengatecollaboration.org

Backups : More details about the simulation

Distance Probe - Phantom N°2 : 3.9 m
Distance Phantom N°2 - Source : 0.8 m
Distance Probe - Source : 4.7 m



Backups : Probe modeling validation

	Theoretical (given)	Measurement (given)	Simulated
$\dot{H}^*(10)$ (µSv/h)	37.5	36.84	37.40 ± 0.03

To **ensure** the **accuracy** of the probe Monte Carlo modeling : **comparison** with **experimental** data.

$$^{137}_{55}Cs \rightarrow \beta^- + \bar{\nu}_e + ^{137}_{56} Ba$$

Relative error ~1.5 10^{-2}
Validation of the modeling

Backups : H*(10) invariance

Invariant by the changing the radius **for the probe** under some assumptions :
Unidirectional and **Homogeneous** radiation field, photon spectrum invariant.

$$\dot{H}^*(10) = \dot{\phi} \sum_i CIPR_i I_i$$

$$\phi(r) = \frac{dl(r)}{dV(r)} = \frac{1}{V(r)} \sum_i l_i(r)$$

$$\phi(R) = \frac{dl(R)}{dV(R)} = \frac{1}{V(R)} \sum_i l_i(R)$$

$$\sum_i l_i(R) = \sum_i l_i(r) \left(\frac{R}{r}\right)^2$$

$$\phi(R) = \frac{1}{V(R)} \sum_i l_i(r) \left(\frac{R}{r}\right)^2$$

$$\phi(R) = \frac{1}{\pi h} \sum_i l_i(r) \frac{1}{r^2}$$

$$\phi(R) = \frac{1}{V(r)} \sum_i l_i(r)$$

$$\phi(R) = \phi(r)$$

Backups : Radiological zonage

Zone type		Zone identification	Maximum total effective dose (external plus internal)
Unregulated		White	80 µSv/month
Supervised		Blue	7.5 µSv/hr
Controlled	Limited	Green	25 µSv/hr
	Specially regulated	Yellow	2 mSv/hr
	Forbidden without specific authorization	Orange	100 mSv/hr
		Red	above 100 mSv/hr

Karlsruhe Institute of Technology

Cancer risk : 0.5% / 100 mSv

Public limit : 1 mSv/yr
Worker limit : 20 mSv/yr

III. VRT : Probe Radius Variation

$$\dot{H}^*(10) = \dot{\phi} \sum_i CIPR_i I_i$$

Invariant by the changing the radius **for the probe** under some assumptions :

Unidirectional and **Homogeneous** radiation field, **invariant energy distribution**.