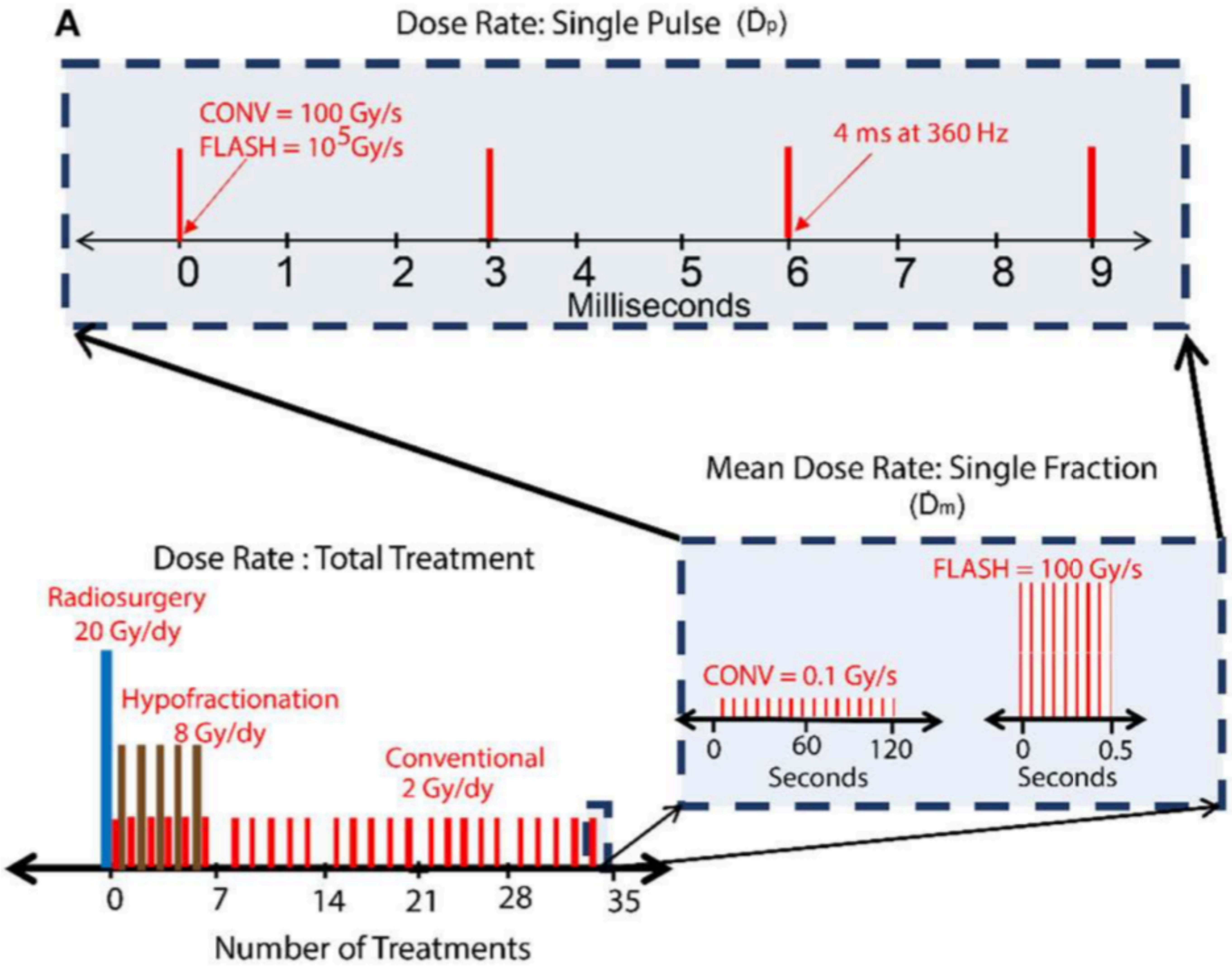
Beam Monitor for FLASH

16.06.2021

Conventional vs Flash Beams

Ashraf MR, Rahman M, Zhang R, Williams BB, Gladstone DJ, Pogue BW and Bruza P (2020) Dosimetry for FLASH Radiotherapy: A Review of Tools and the Role of Radioluminescence and Cherenkov Emission. Front. Phys. 8:328. doi: 10.3389/fphy.2020.00328



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Beam Characteristics	CONV	FLASH
Dose Per Pulse D_p	~0.4 mGy	~1 Gy
Dose Rate: Single Pulse $\dot{D}_p$	~100 Gy/s	~10^5 Gy/s
Mean Dose Rate: Single Fraction $\dot{D}_m$	~0.1 Gy/s	~ 100 Gy/s
Total Treatment Time T	~days/minutes	< 500 ms

1 pulse ~

1 pulse ~

Parameters in Flash Beams

Beam	Accelerator	Energy [MeV/u]	Average Dose Rate [Gy/s]	Repetition Rate	Pulse Duration	Dose per Pulse [Gy]	Max Dose in 100 ms
p	*Cyclotron (FLASH mode)*	60 - 250	40-200	~ 100 MHz	Almost continuous in a full treatment of 200 ms		
^{12}C	*Synchrotron (FLASH mode)*	300	80 Gy/s				>8 Gy
p	*Synchro-Cyclotron (FLASH mode)*	60 - 250	100-200	~ 650 Hz	1-10 µs	0.1-0.3	
e-	*Conventional electron LINAC (FLASH mode)*	8-20	40-200	100-200 Hz	~µs		
e-	*IORT LINAC (FLASH mode)*	7-9	up to 500	1-30 Hz	~ µs	up to 20	50 Gy
e-	*Electron FLASH*	~ 5-7	0.1-4000 Gy/s	100 Hz	~ µs	~ 40	
p	*Laser/driven*	10 - 60	1 - 70 Gy/min @ 1 or 10 Hz	~ 1 Hz	10 - 100 ns	1-10	not applicable
e-	*Laser/driven*	20-250	1 Gy/s	10 Hz	200 fs	> 0.5	>1 Gy

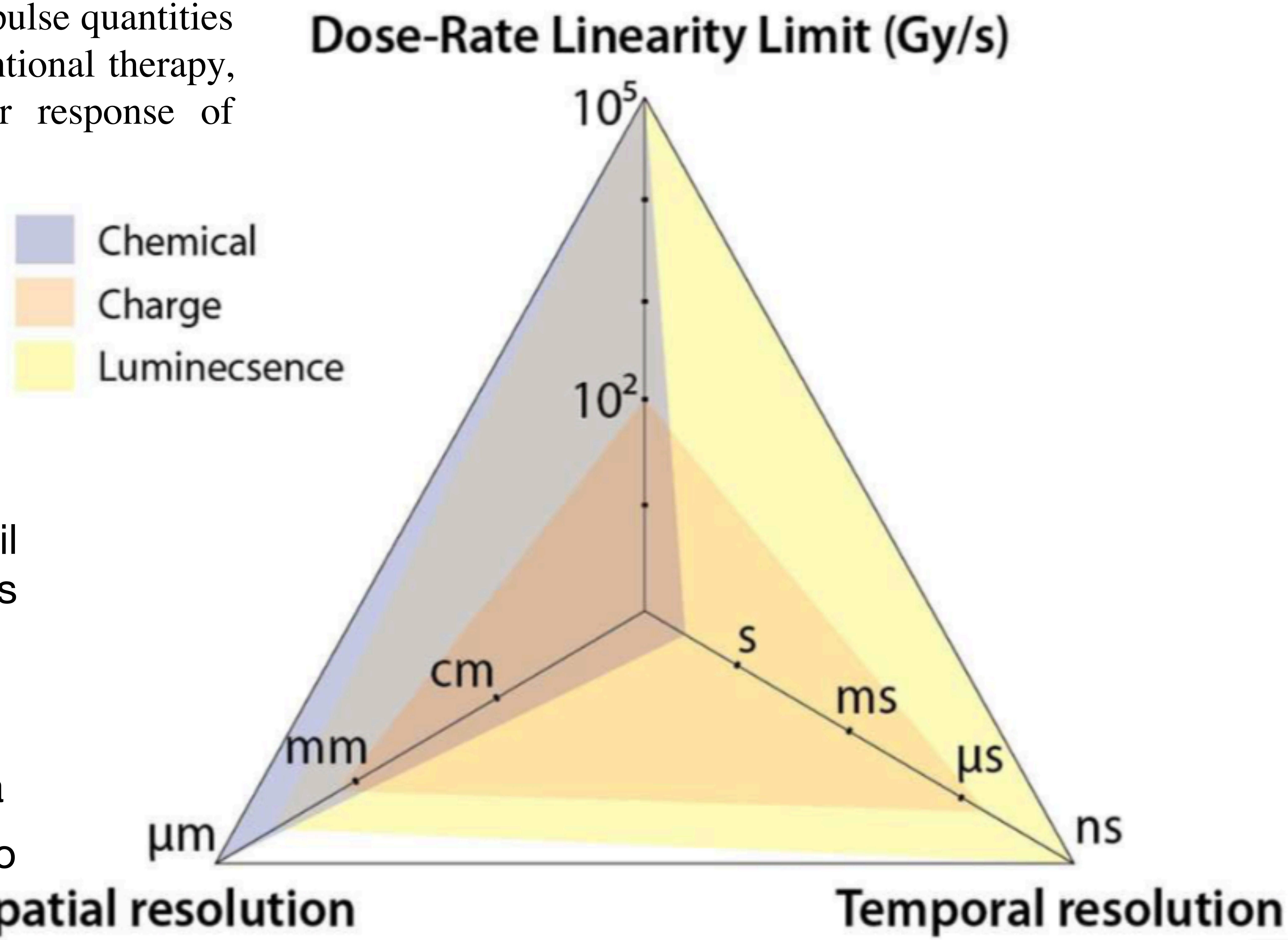
Review di detectors

Ashraf MR et al . doi: 10.3389/fphy.2020.00328

For FLASH, instantaneous dose and the dose per pulse quantities can be orders of magnitude higher than in conventional therapy, leading to issues of saturation, and non-linear response of standard dosimeters at large doses.

- **Dose Rate Linearity**
- **Spatial Resolution**
- **Time Resolution**

1. Risoluzione spaziale ~ 1 mm
2. Risoluzione temporale compatibile con il fascio (1 Hz di fascio, pulse di 1 μm) ~ns
3. Risoluzione sulla dose.. 3%?
4. Indipendente dall'energia del fascio
5. Indipendente dalla dose-rate istantanea
6. Sensibile alla quantità di ossigeno punto per punto



From Ashraf MR et al . doi: 10.3389/fphy.2020.00328

Response	Detectors	Measurement type	FLASH study	Instantaneous dose-rate/dose per pulse (D_p) dependence	Spatial resolution	Time-resolution	Energy dependence
Luminescence	TLD/OSLD	**1D,** 2D	e [15, 37, 71]	Independent (~10^9 Gy/s) [80, 137]	~ 1 mm	Passive	Tissue-equivalent
	Scintillators	1D, **2D**, 3D	p [13, 18]	Independent (~10^6 Gy/s) [29]	~ 1 mm	~ns	Tissue-equivalent
	Cherenkov	**1D**, 2D, 3D	e [29]	Independent (~10^6 Gy/s) [29]	~ 1 mm	~ps	Energy dependent
	FNTD	2D	NA	Independent (~10^8 Gy/s) [85]	~ 1 µm	Passive	Energy dependent
Charge	Ionization chambers	**1D**, **2D**	p [13, 18, 19] e [15, 37, 71] ph [16, 17]	Dependent on D_p [48, 52] (>1 Gy/pulse),	~3–5 mm	~ms	Energy dependence shows up > 2 MeV
	Diamonds	**1D**	p [18]	Dependent on D_p (>1 mGy/pulse) [49]	~ 1 mm	~µs	Tissue-equivalent
	Si diode	**1D**, 2D	NA	Dependent on D_p [54] (Independent ~0.2 Gy/s) [138]	~ 1 mm	~ms	Energy dependent
Chemical	Alanine pellets	**1D**	e [12, 15, 37, 139]	Independent (10^8 Gy/s) [69]	~ 5 mm	Passive	Tissue-equivalent
	Methyl viologen/fricke	**1D**	e [29, 48]	Depends on the decay rate and diffusion of radiation induced species	~ 2 mm	~ns	Tissue-equivalent
	Radiochromic film	**2D**	p [18, 19] e [10–12, 15, 30, 37, 71, 140] ph [16]	Independent (10^9 Gy/s) [70, 71]	~1 µm	Passive	Tissue-equivalent
	Gel dosimeters	3D	NA	Strong dependence below 0.001 Gy/s [141] and above 0.10 Gy/s [142]	~1 mm	Passive	Tissue-equivalent

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best passive detectors

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best detectors but with threshold

Fluorescence in Air

PHD Thesis: The Fluorescence Yield of Air excited by Electron measured with the AIRFLY Experiment

BTF: F.Arciprete et al. AIRFLY: Measurement of the fluorescence yield in atmospheric gases January 2006 Czechoslovak Journal of Physics 56:A361-A367

The fluorescence yield Y is the **number of photons produced by one electron per 1 m of path-length**. The unit of the fluorescence yield, [photons/m], has practical reasons and was introduced to use the fluorescence yield for air shower measurements.

In order to get a hold on the fluorescence yield, another quantity, the fluorescence efficiency Φ has to be defined. The fluorescence efficiency is the ratio of radiated energy to deposited energy at a given wavelength (with number of emitted photons n_λ):

$$\Phi_\lambda = \frac{\text{radiated energy}}{\text{deposited energy}} = \frac{n_\lambda \cdot E_\lambda}{E_{dep}},$$

If the number of excited molecules is proportional to the deposited energy, the fluorescence efficiency can also be formulated as:

$$\Phi_\lambda = \frac{n_\lambda \cdot E_\lambda}{n_e \cdot \frac{dE}{dX}\rho\Delta x}.$$

Here, n_e is the number of electrons and dEρΔx the deposited energy of one electron according to the Bethe-Bloch equation along a path of length Δx in a gaseous medium of density ρ. **The fluorescence yield can be determined for the number of emitted photons nλ per electron and path length.**

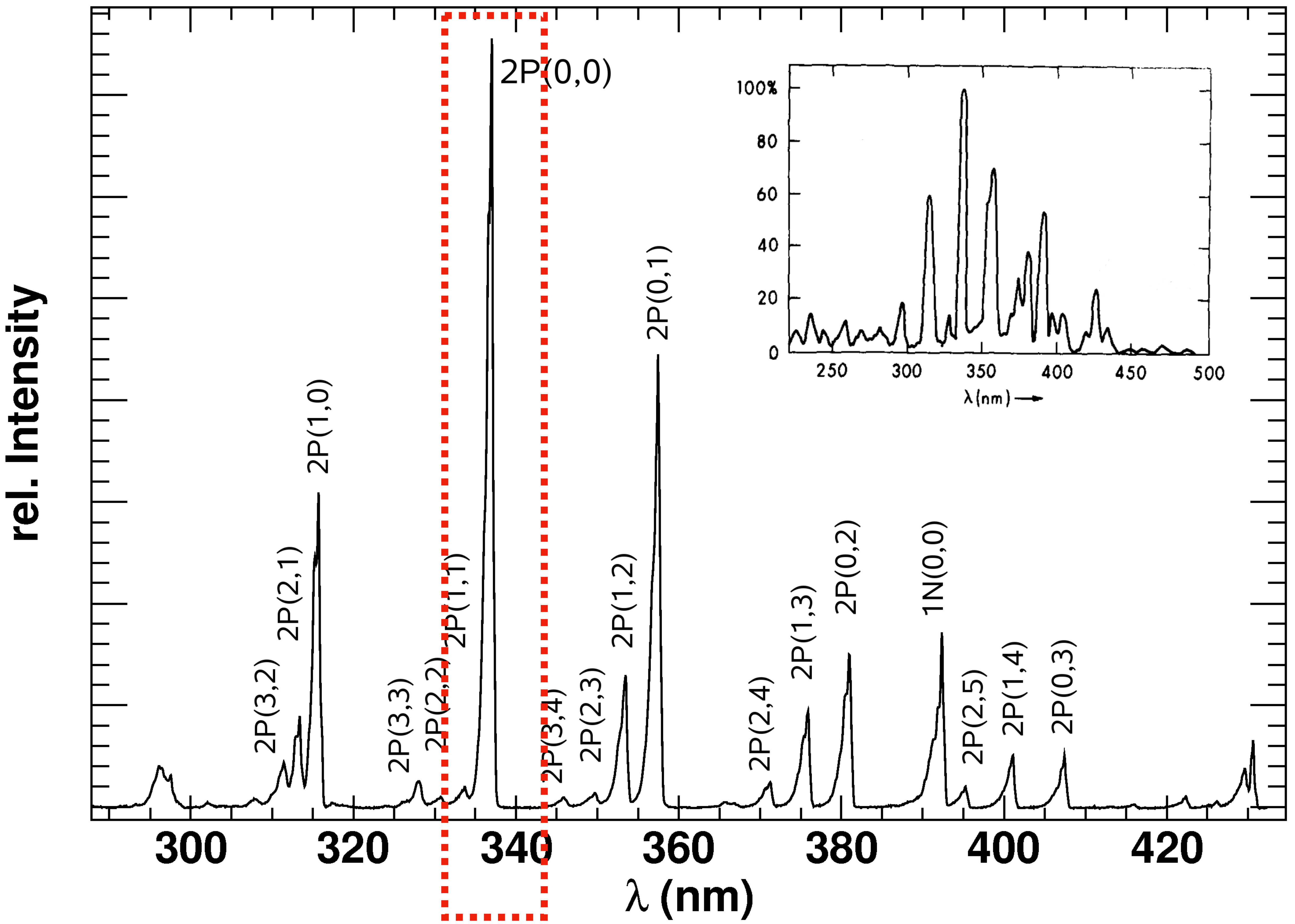
The fluorescence yield is always, unless explicitly mentioned, defined in units of photons/m but some authors express it in photons/MeV:

$$Y\left[\frac{\text{photons}}{\text{m}}\right] = Y\left[\frac{\text{photons}}{\text{MeV}}\right] \cdot \frac{dE}{dX}\rho.$$

Fluorescence in Air

- **Photons energy spectrum in the range 300-430 nm**

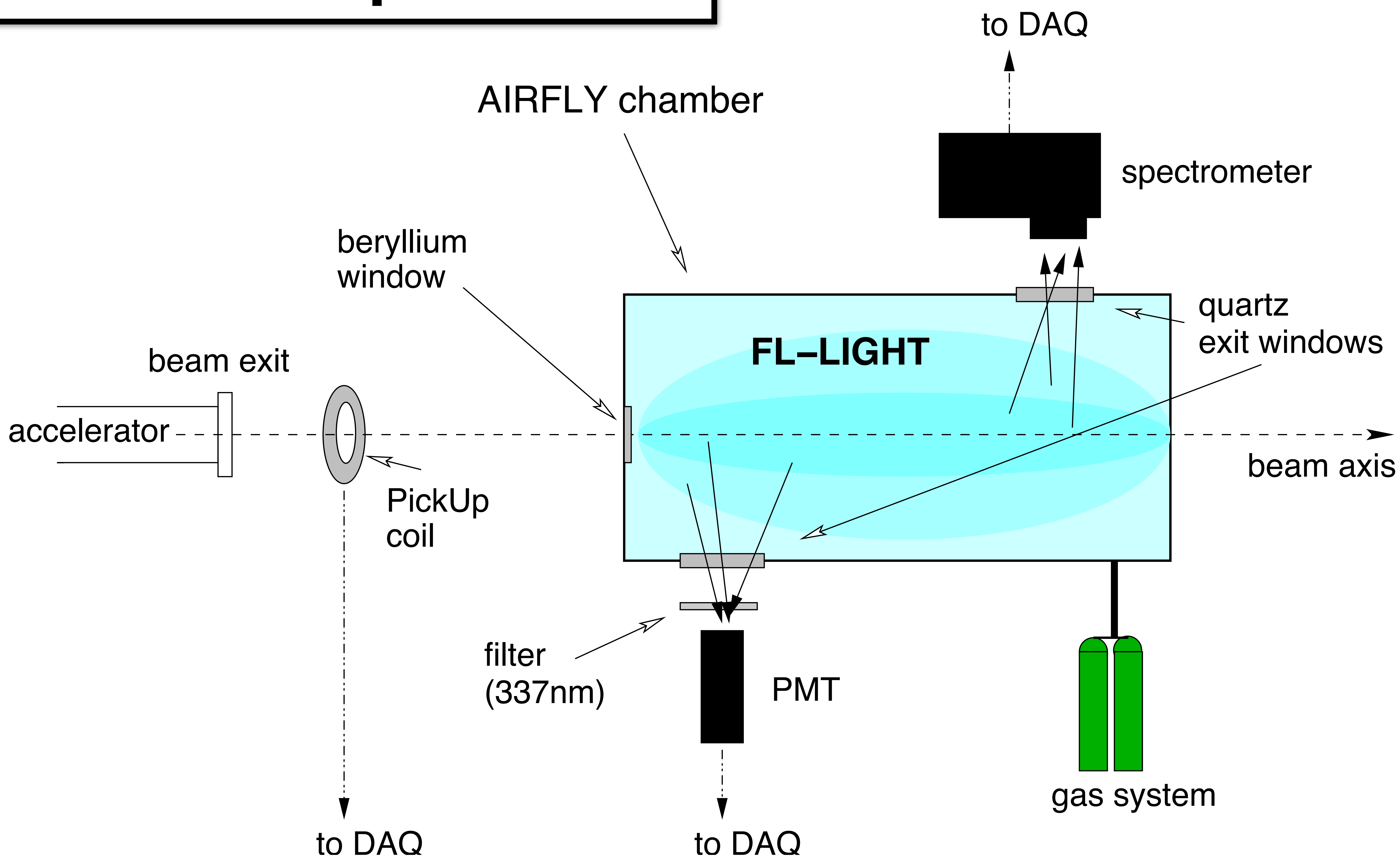
Figure 2.8: Fluorescence spectrum of air between 280 nm and 430 nm recorded by AIRFLY with transition labels. The gas was excited by 3 MeV electrons at a pressure of 800 hPa. In the right upper corner, the spectrum reported by Bunner (1967) is shown [15].



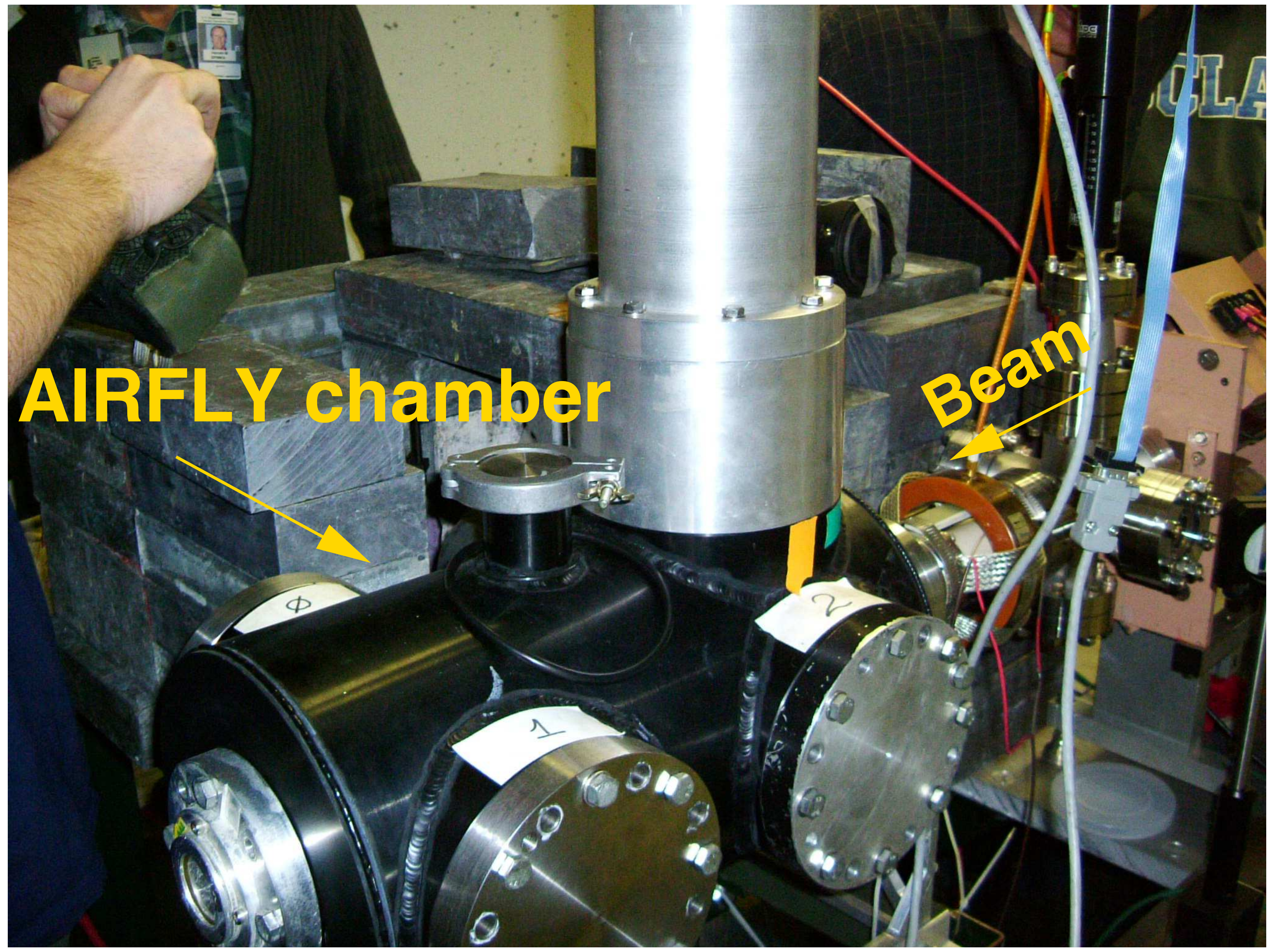
Details on band heads of N_2 and N_2^+ between 300nm and 430nm

λ (nm)	System(ν_i, ν_f)	A_{ν_i,ν_f} (10^6 s^{-1})	λ (nm)	System(ν_i, ν_f)	A_{ν_i,ν_f} (10^6 s^{-1})
310.40	2P(4,3)	3.02	358.21	1N(1,0)	5.76
†311.67	2P(3,2)	5.94	364.17	2P(4,6)	1.00
†313.60	2P(2,1)	10.1	367.19	2P(3,5)	2.35
†315.93	2P(1,0)	11.9	†371.05	2P(2,4)	4.04
326.81	2P(4,4)	3.71	†375.54	2P(1,3)	4.93
†328.53	2P(3,3)	2.85	†380.49	2P(0,2)	3.56
329.34	1N(4,2)	3.19	385.79	2P(4,7)	2.33
329.84	1N(3,1)	2.08	385.79	1N(2,2)	0.93
330.80	1N(2,0)	0.90	388.43	1N(1,1)	4.03
†330.90	2P(2,2)	0.80	389.46	2P(3,6)	3.00
†333.90	2P(1,1)	0.59	†391.44	1N(0,0)	11.4
†337.13	2P(0,0)	13.1	†394.30	2P(2,5)	3.14
344.60	2P(4,5)	0.12	†399.84	2P(1,4)	2.43
†346.90	2P(3,4)	0.12	†405.94	2P(0,3)	1.10
†350.05	2P(2,3)	1.71	409.48	2P(4,8)	2.09
353.26	1N(5,4)	6.63	414.18	2P(3,7)	2.01
†353.67	2P(1,2)	5.54	416.68	1N(3,4)	2.32
353.83	1N(4,3)	7.46	419.91	1N(2,3)	3.47
354.89	1N(3,2)	8.09	420.05	2P(2,6)	1.57
356.39	1N(2,1)	7.88	423.65	1N(1,2)	4.28
†357.69	2P(0,1)	8.84	427.81	1N(0,1)	3.71

AIRFLY Exp. SetUP



- Beam (BTF):
- 50-450 MeV electrons
- Multiplicity approximately constant

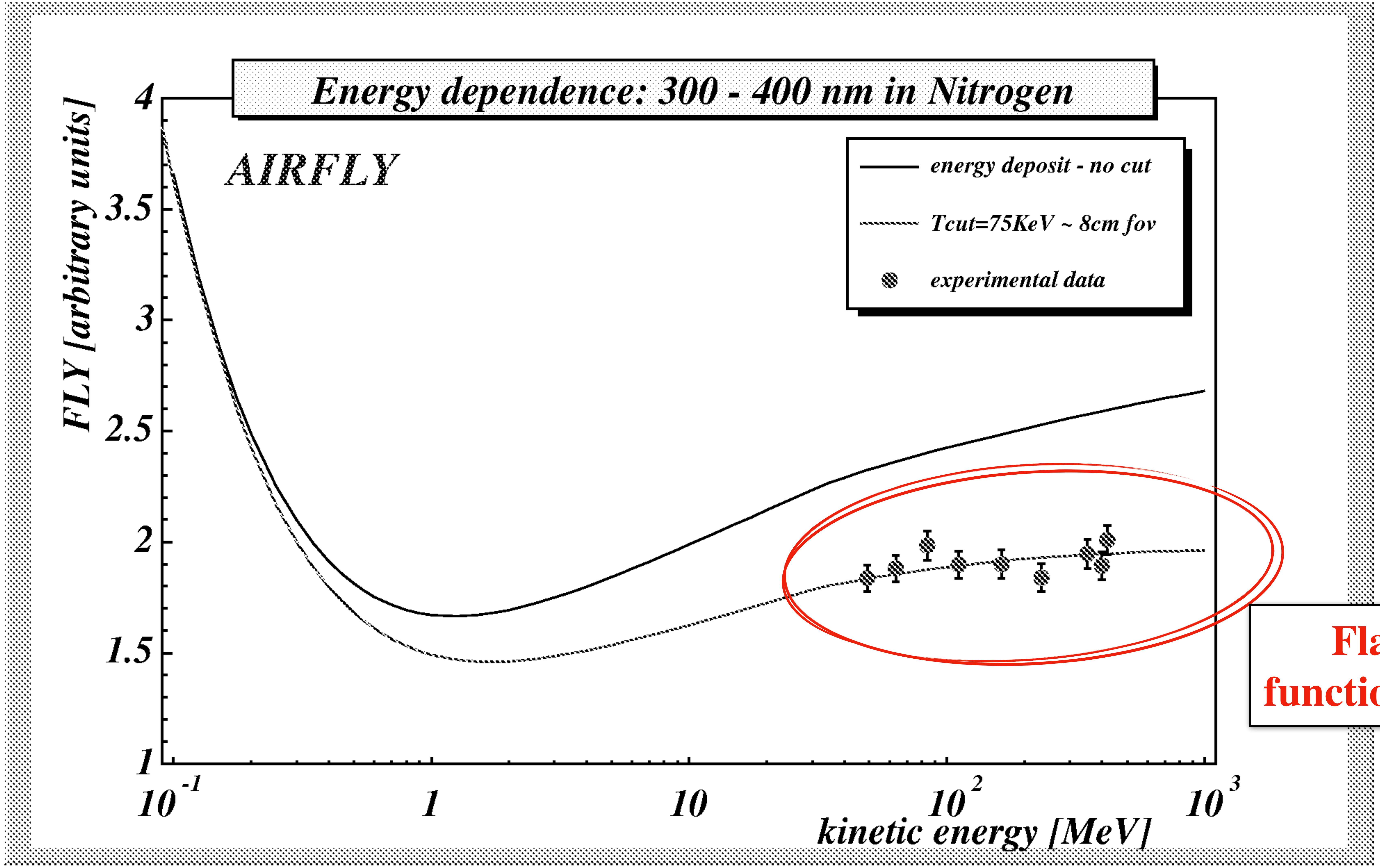


- PMT H7195P (integration gate 100 ns)
- During the measurements, the spectrometer and the PMT were shielded with lead bricks to reduce background.

- Hamamatsu H7195P model and was chosen for low background. It has a bialkali photocatode with a diameter of 46 mm and a peak sensitivity at 420 nm. The bialkali catode has a quantum efficiency at 337 nm of about 8% and a very low dark current.

- The interference filter, used to delimit the wavelength region of the light reaching the PMT, has a peak transmission of about 50% at 340 nm and a width of 10 nm (FWHM). With this filter, the light reaching the PMT originates to 98.3% from the 2P(0,0)-transition at 337 nm.

Energy Dependence

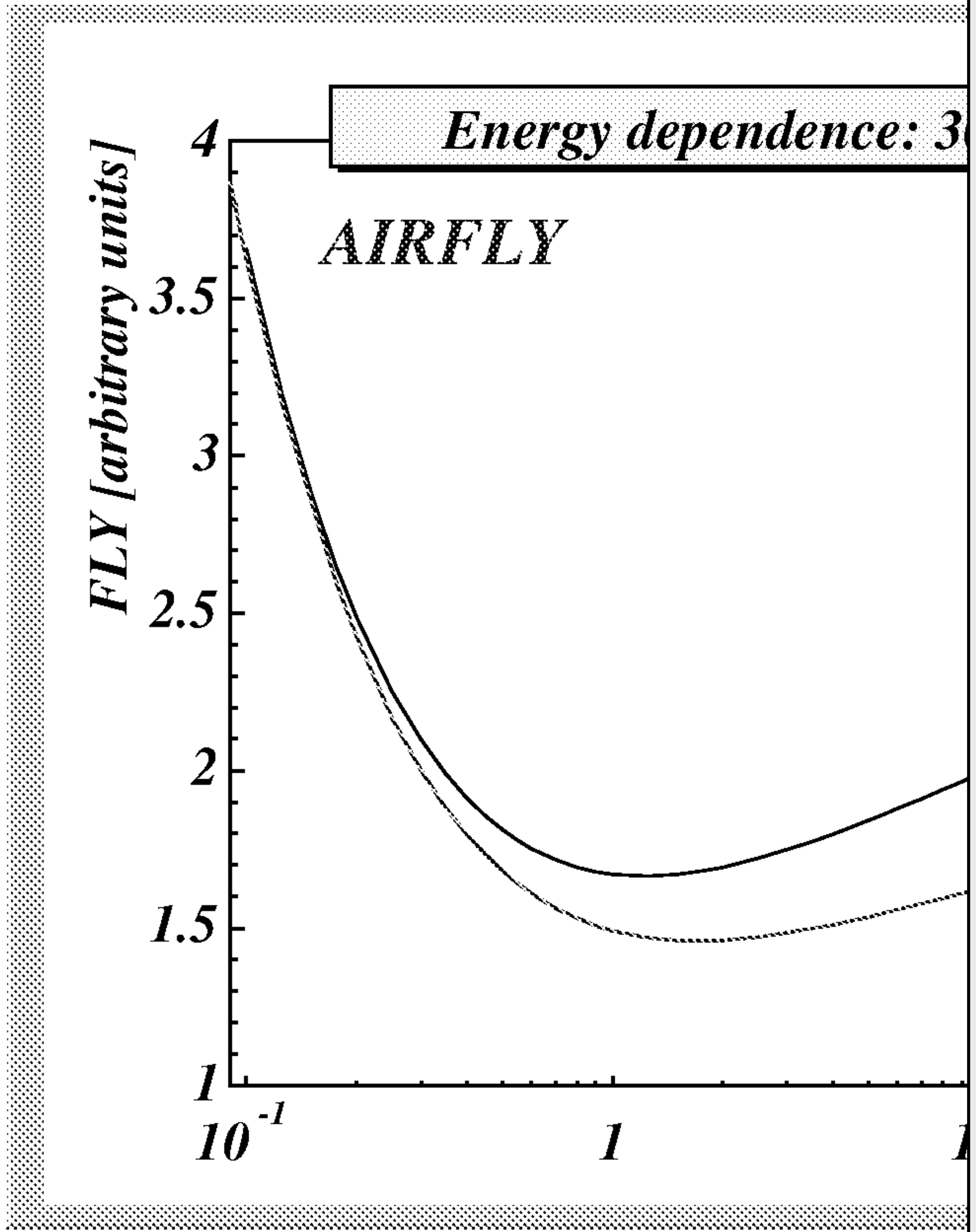


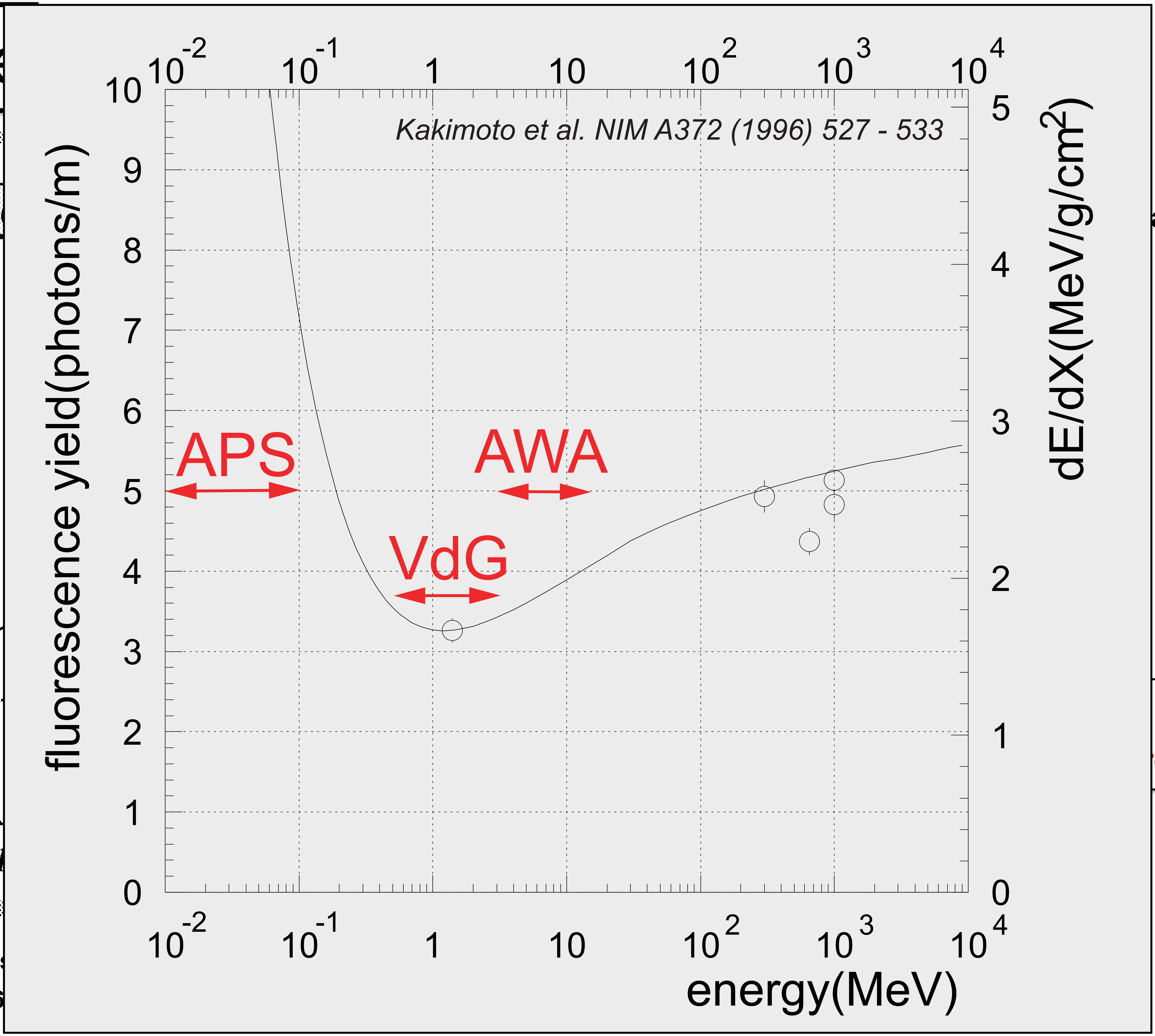
- Beam (BTF):
- 50-450 MeV electrons
- Multiplicity approximately constant
- 1-10^{10} particles/bunch
- 1Hz

Flat in dE/dx.. => linear response, function of kinetic energy of the electrons

F.Arciprete et al. AIRFLY: Measurement of the fluorescence yield in atmospheric gases January 2006 Czechoslovak Journal of Physics 56:A361-A367
https://www.researchgate.net/publication/215566660_AIRFLY_Measurement_of_the_fluorescence_yield_in_atmospheric_gases

Energy Dependence





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rons

F.Arciprete et al. AIRFLY: Measurement of the fluores

https://www.researchgate.net/publication/21556666

Expected photons

Per elettroni da “13” MeV ci aspettiamo:
- 4 ph. al m di fluorescenza (@4π)
- Cherenkov sotto soglia

Per elettroni da 20 MeV ci aspettiamo:
- 4 ph. al m di fluorescenza (@4π)
- 6 ph. al m di Cherenkov (~ 0.1^{o})

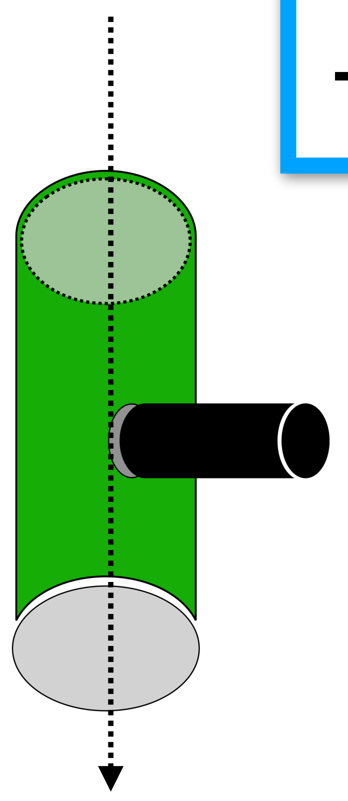
Per elettroni da 130 MeV ci aspettiamo:
- 5 ph. al m di fluorescenza (@4π)
- 70 ph. al m di Cherenkov (~ 1.4^{o})

Expected photons

According to the detector we decide to implement.. SIT LIAC machine

Per elettroni da “13” MeV ci aspettiamo:
- 4 ph. al m di fluorescenza (@4π)
- Cherenkov sotto soglia

(1)



PERISCOPIO

(1):
- 0.04 ph x 10 cm x 0.1 x 10^10 (elet./pulse) ~ 4 10^8 ph
- ~ 8 10^7 ph.el

Periscopio@SIT: 30.7.2020

According to the detector we decide to implement.. SIT LIAC machine

PMT: H10580

Per elettroni da “13” MeV ci aspettiamo:
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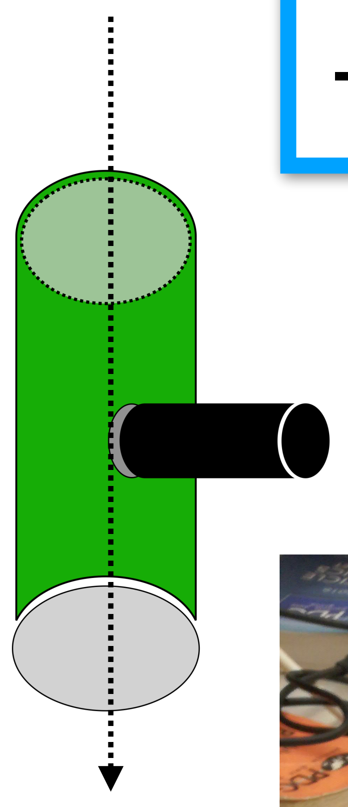
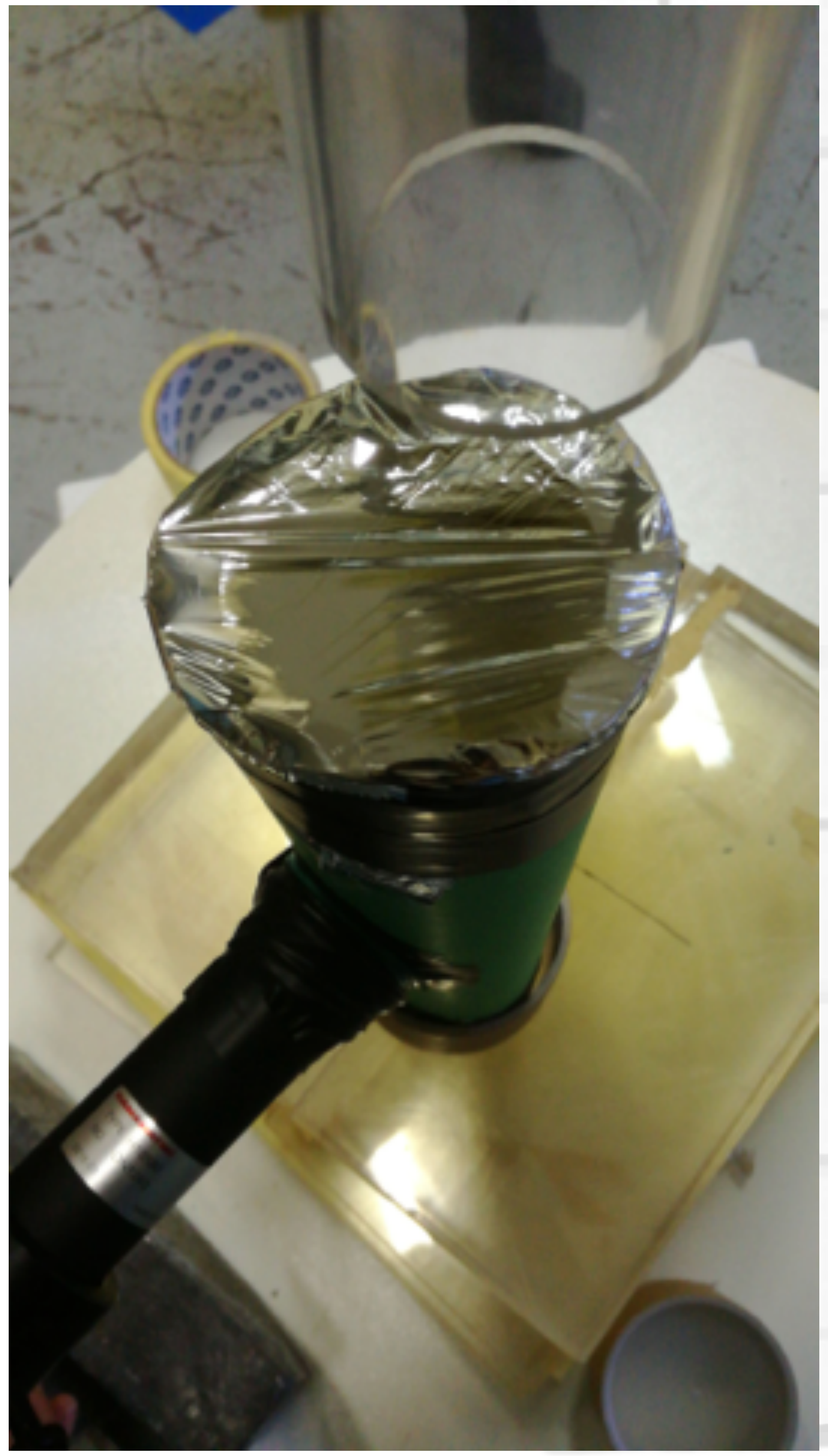
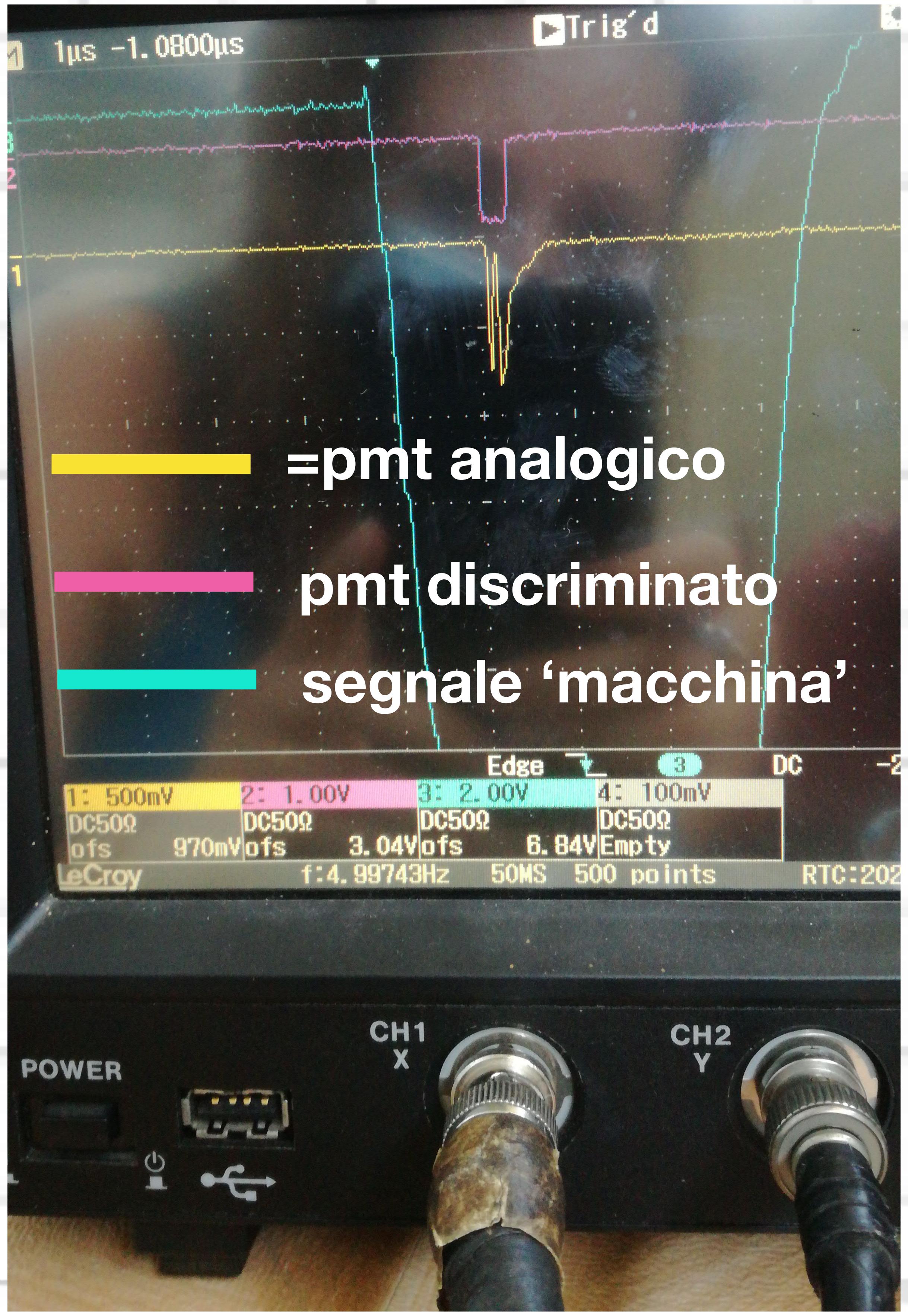


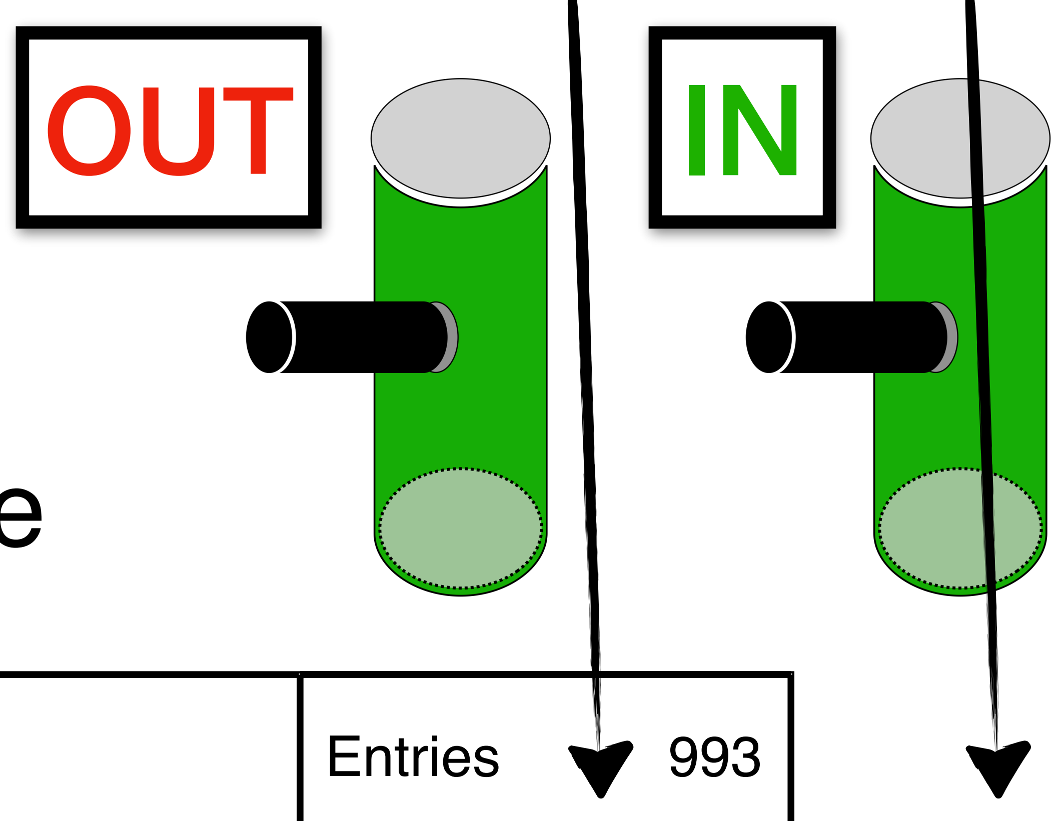
PERISCOPIO

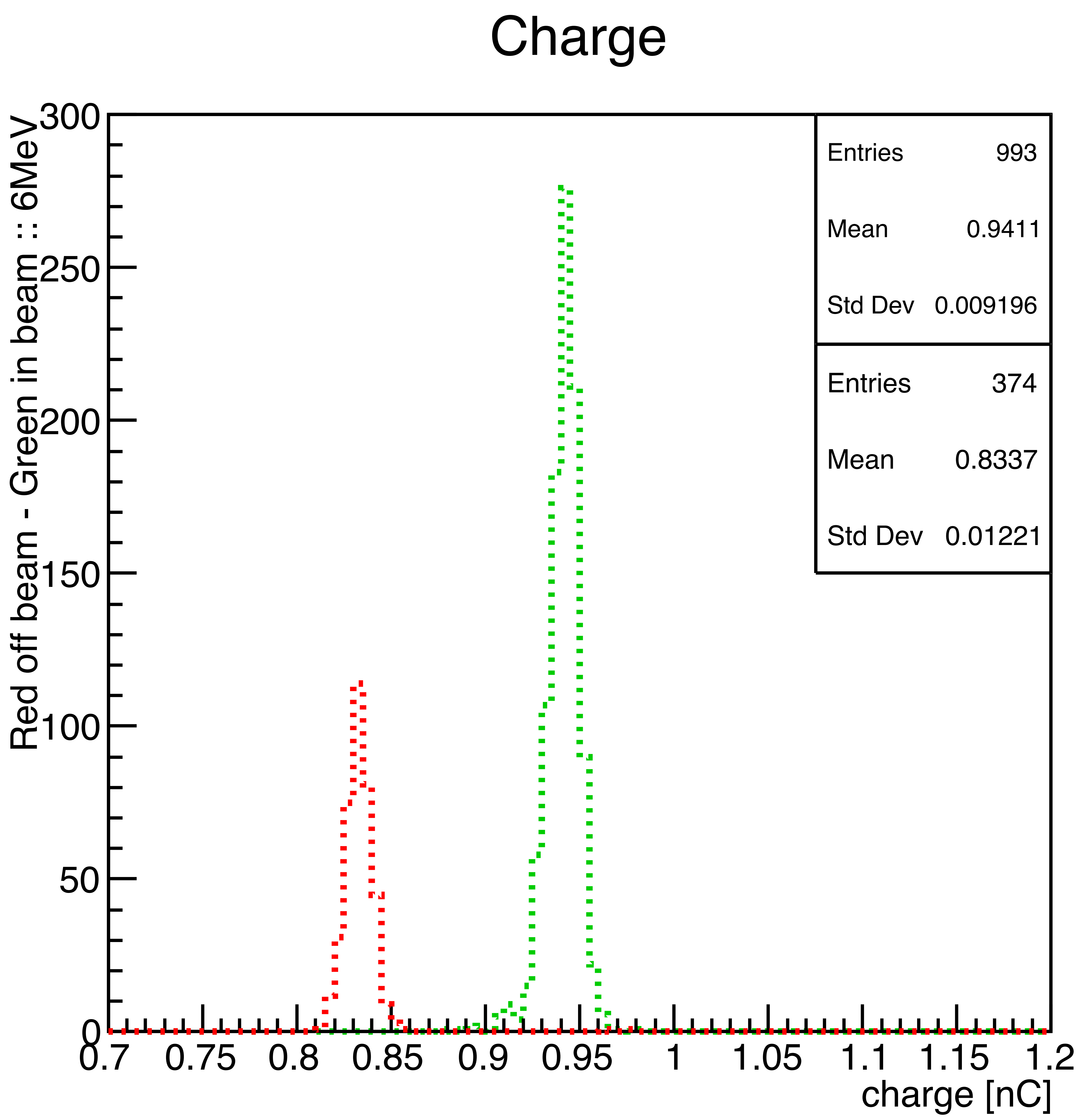


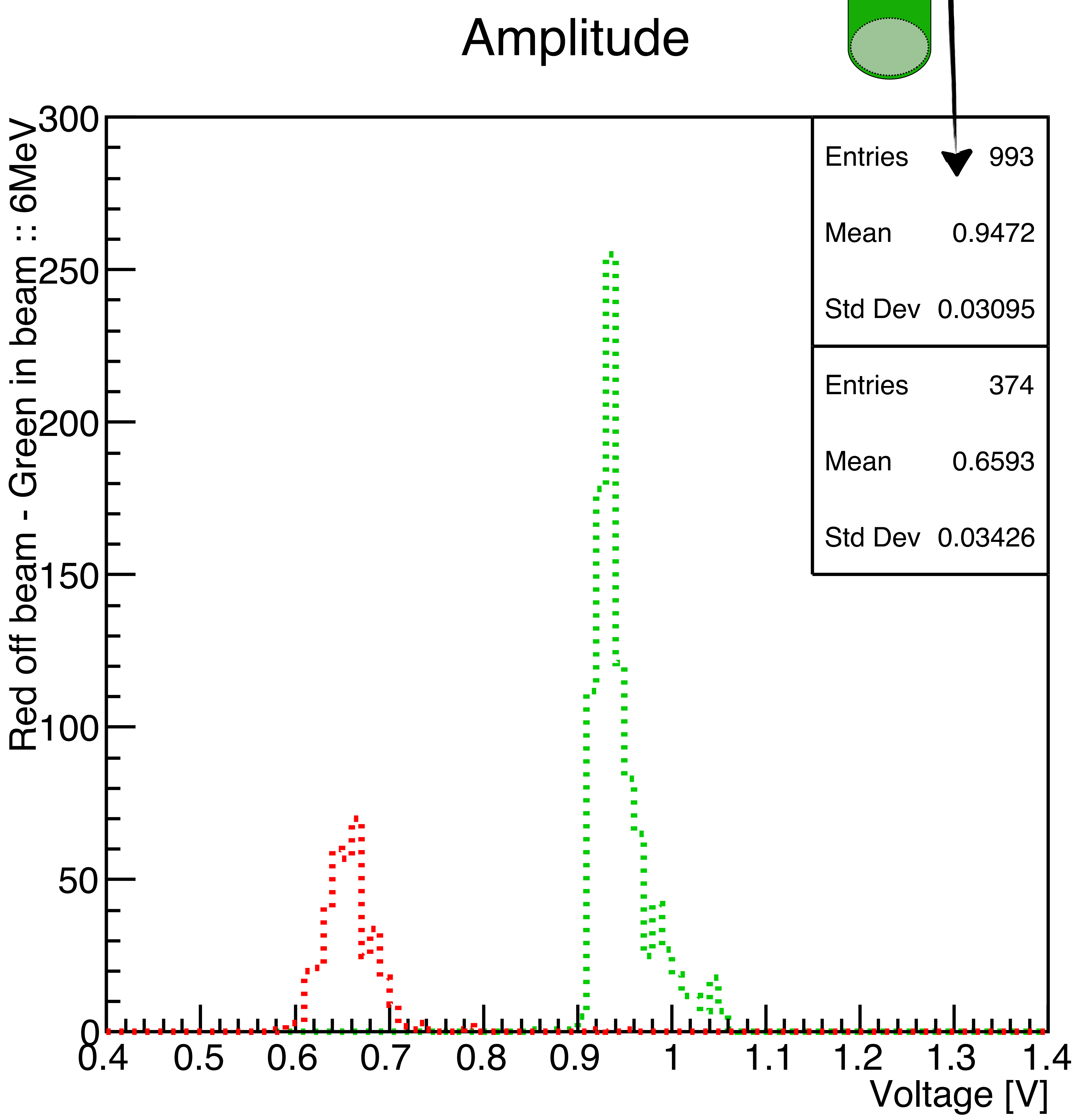


Preliminary analysis

Beam IN and OUT of the detector







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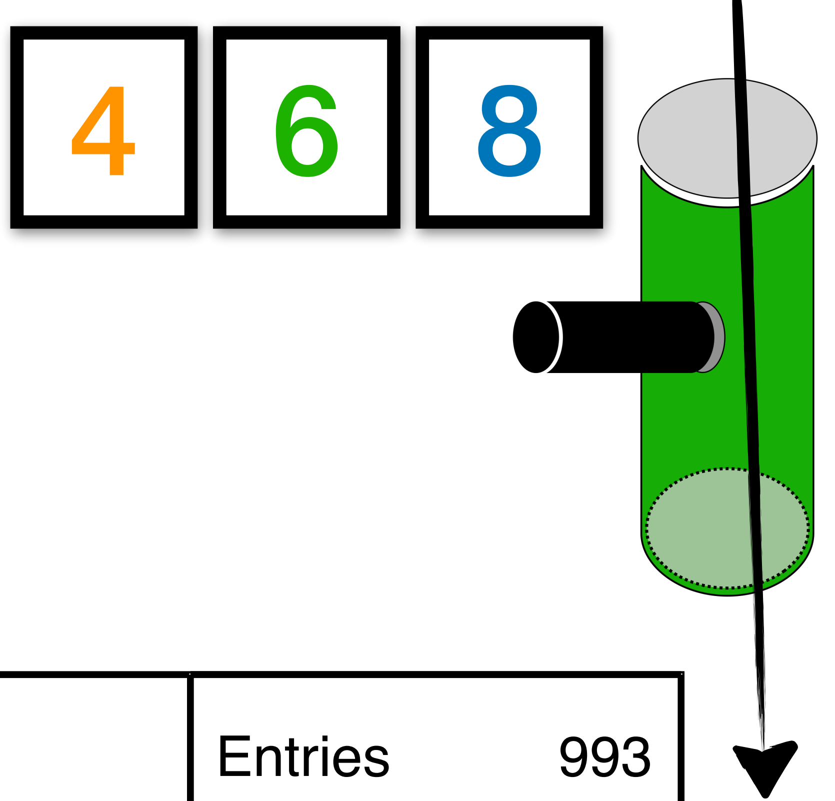
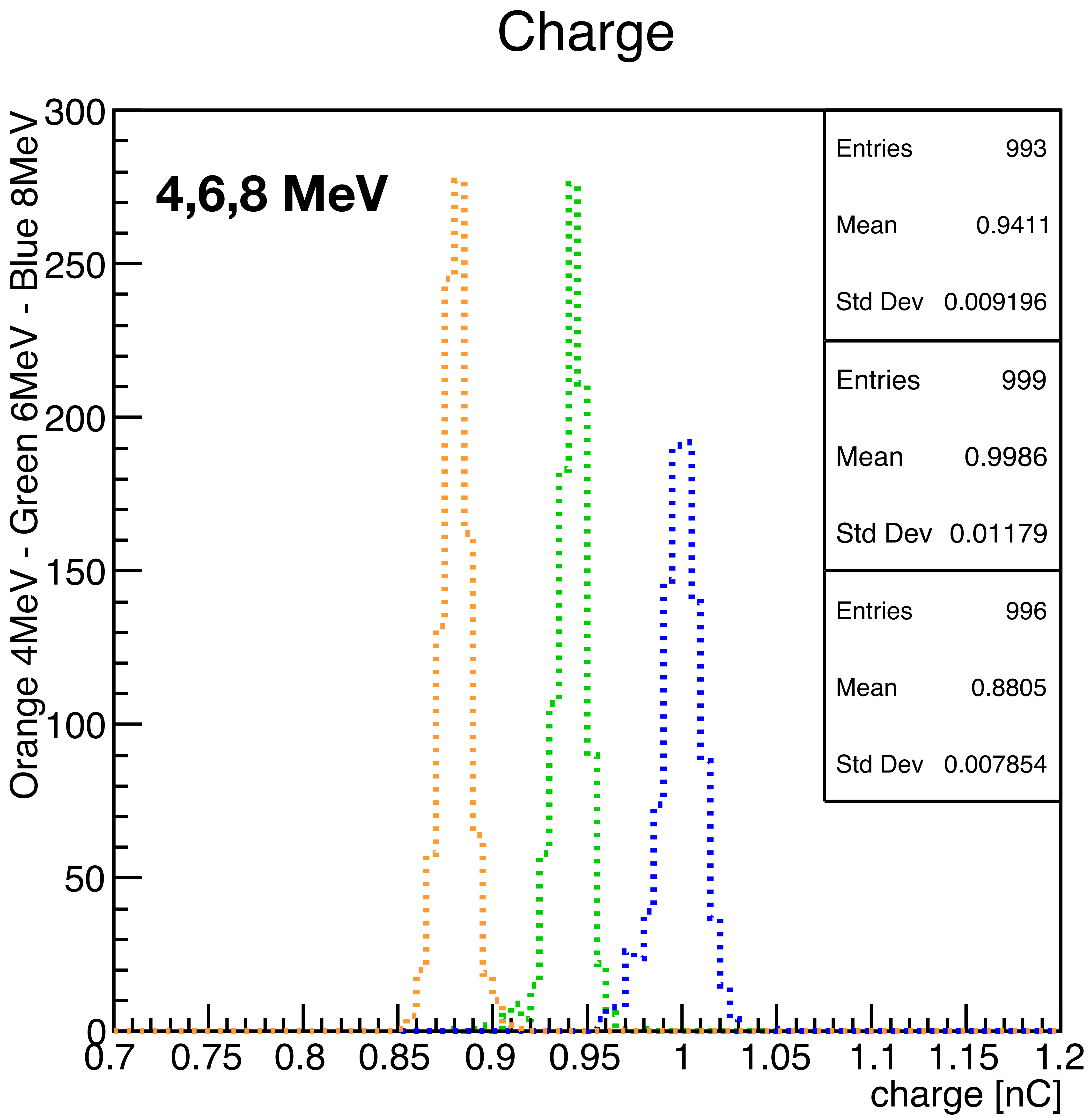
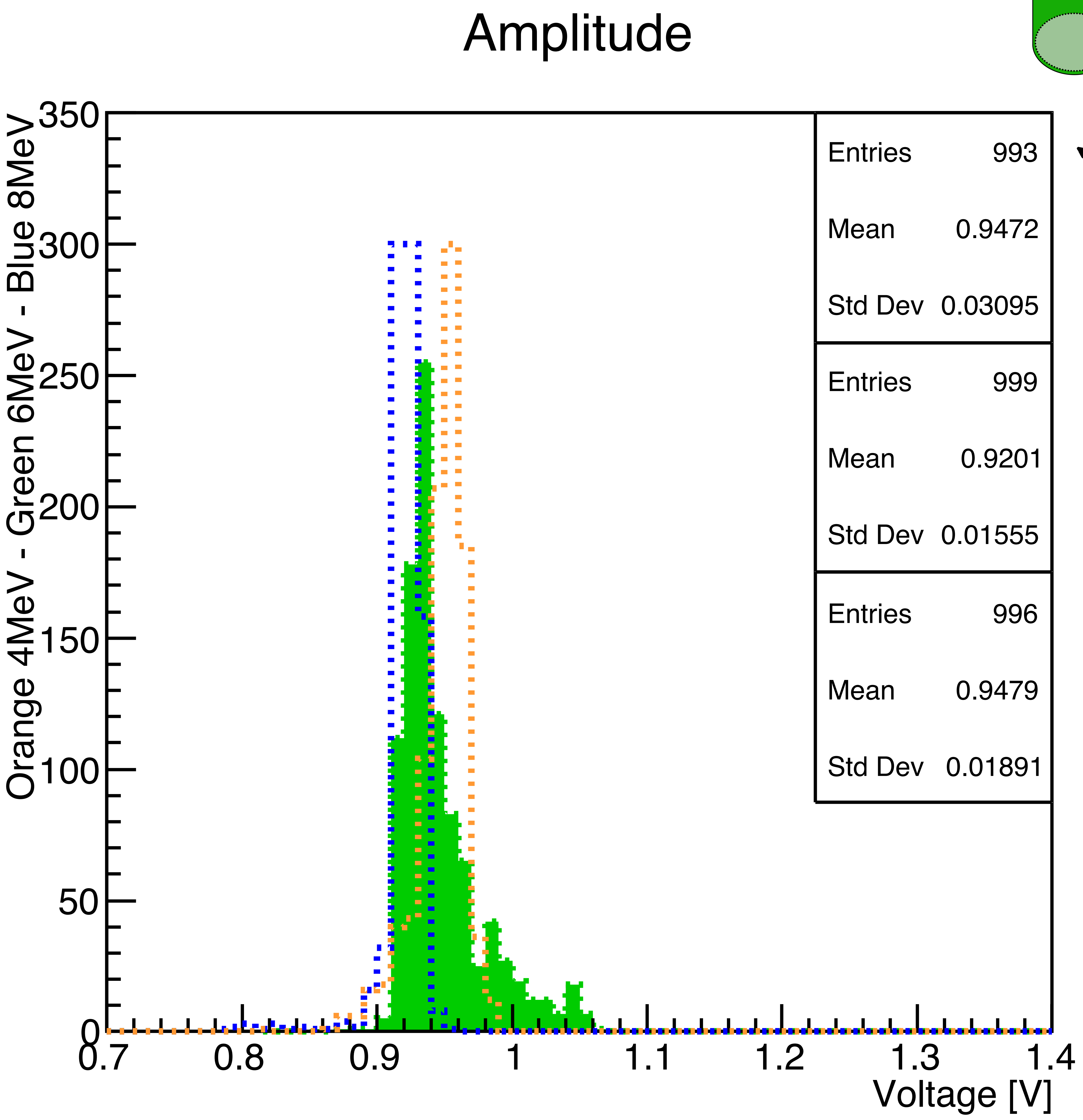
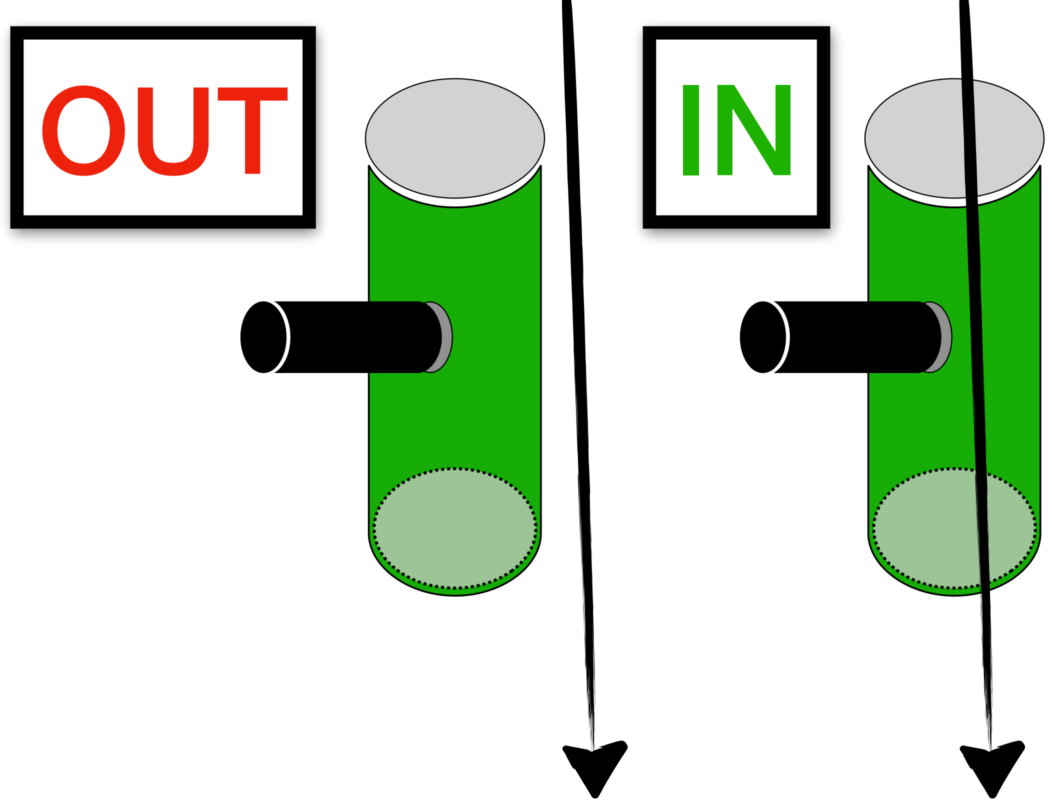






Preliminary Conclusion with PERISCOPIO



- ☑ We do see the beam IN and OUT difference in the detector.
- ☐ We observe some 'dependency' in the detector response as a function of the beam, probably we are mainly sensitive to the secondary products.
- ☐ It can be everything :)
- ☐ We are too close with the PMT.
- ☐ The "applicatore" produces background

Expected photons

According to the detector we decide to implement.. SIT LIAC machine

Per elettroni da "13" MeV ci aspettiamo:
- 4 ph. al m di fluorescenza (@4π)
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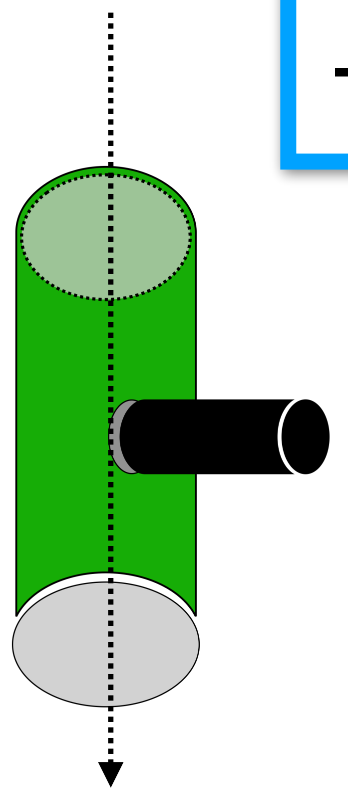
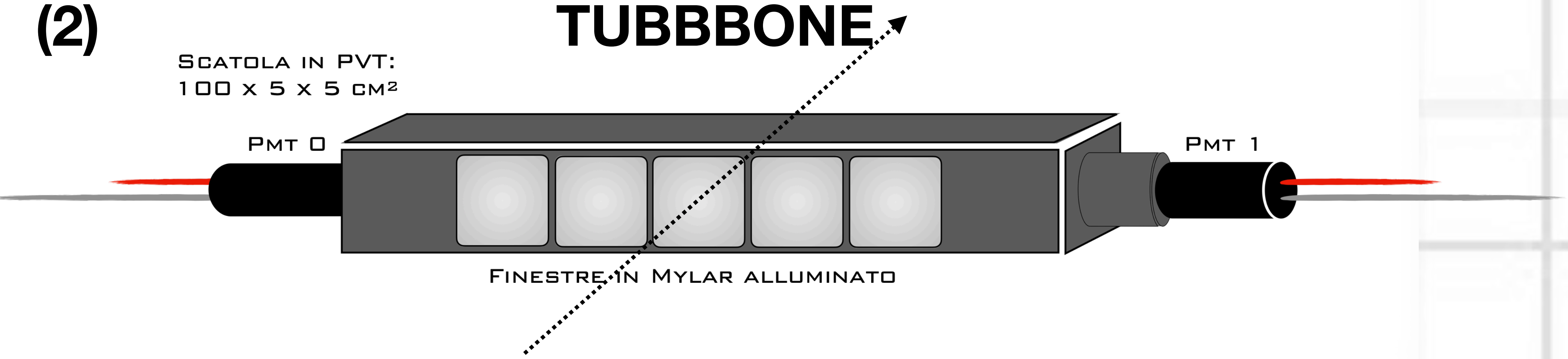
(1) **PERISCOPIO**



(2) **TUBBBONE**



(1):
- 0.04 ph x 10 cm x 0.1 x 10^10 (elet./pulse) ~ 4 10^8 ph
- ~ 8 10^7 ph.el

➡ **PMT troppo dentro l'alone del fascio**

* riflessione on/off

(2):
- 0.04 ph/cm x 5 cm x 0.005 (sottostima/sovrastima geometria*) x 10^10 (elet./pulse) ~ 1 10^7 ph
- ~ 2 10^6 ph.el

➡ **L'applicatore produce troppo fondo che arriva ai PMT!**

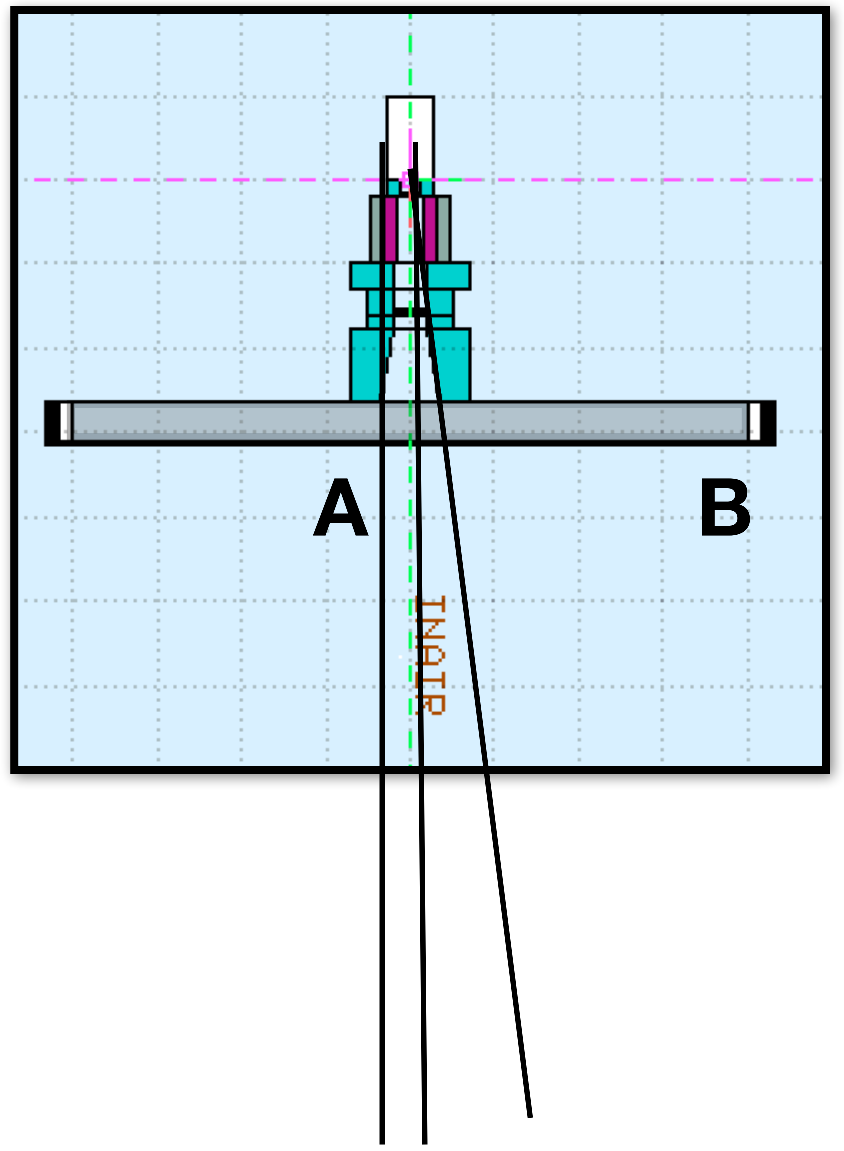
➡ **Senza applicatore siamo in grado di vedere l'IN/OUT beam**

MC FLUKA SIMULATION

By Gaia, Antonio (and Battistoni for support)

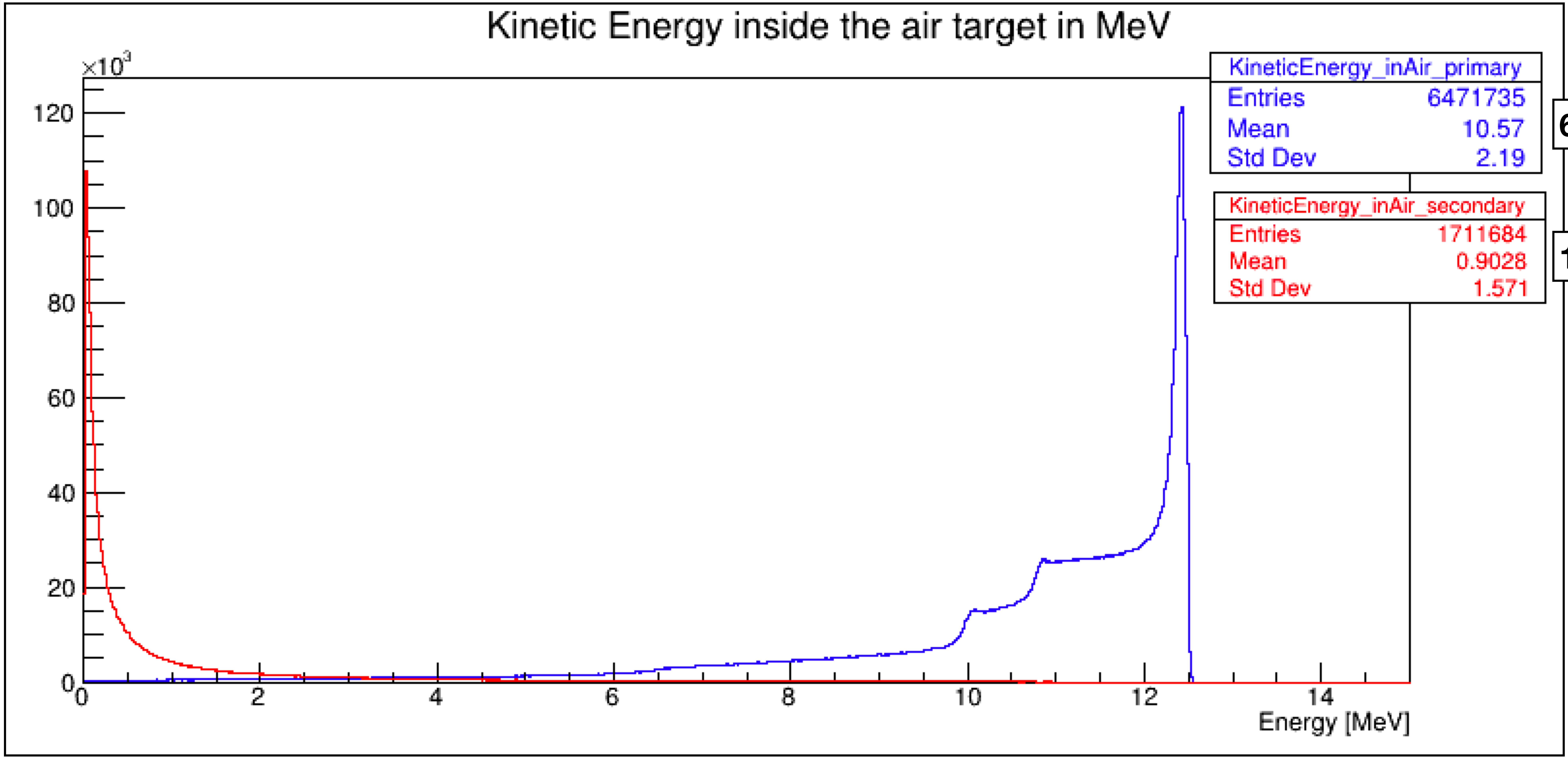
MC FLUKA SIMULATION

By Gaia, Antonio (and Battistoni for support)



- # Electrons: 10^7
- Energy: 13 MeV

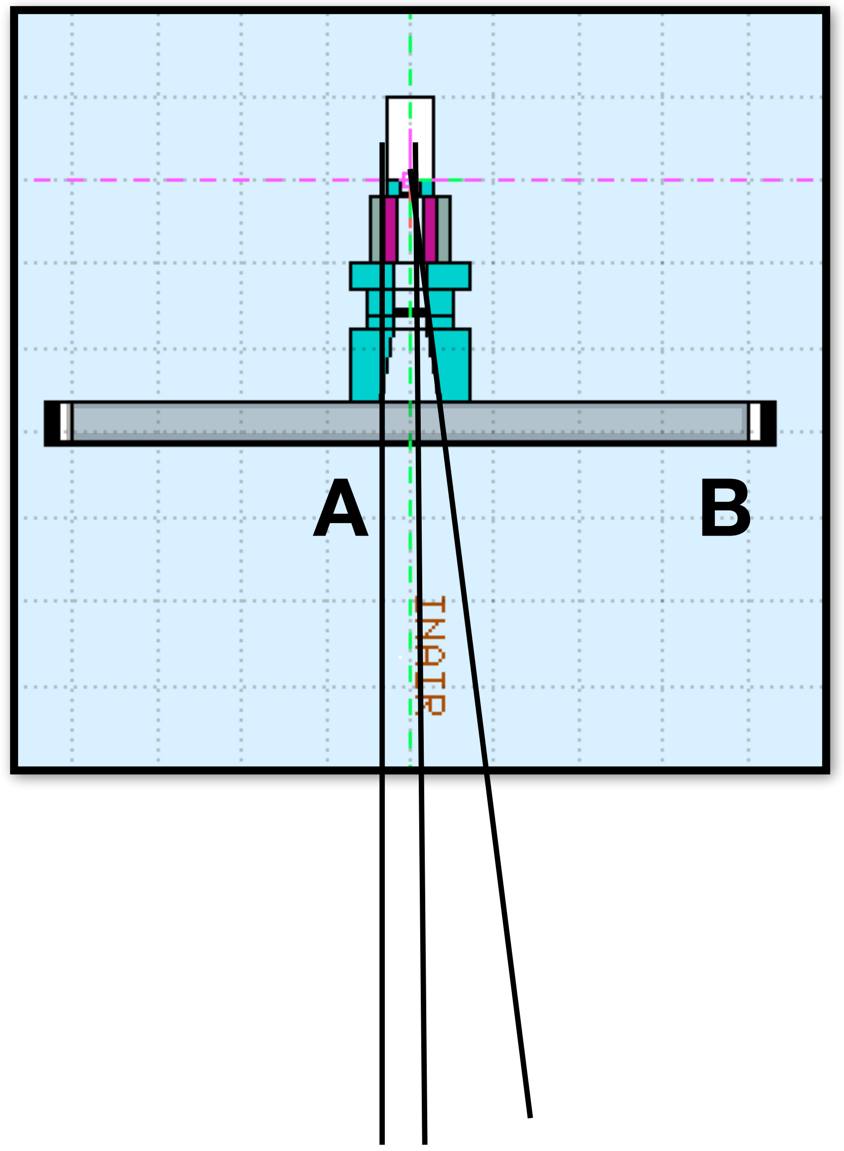
just for time-consuming reasons..



6.4E6

1.7E6

MC FLUKA SIMULATION



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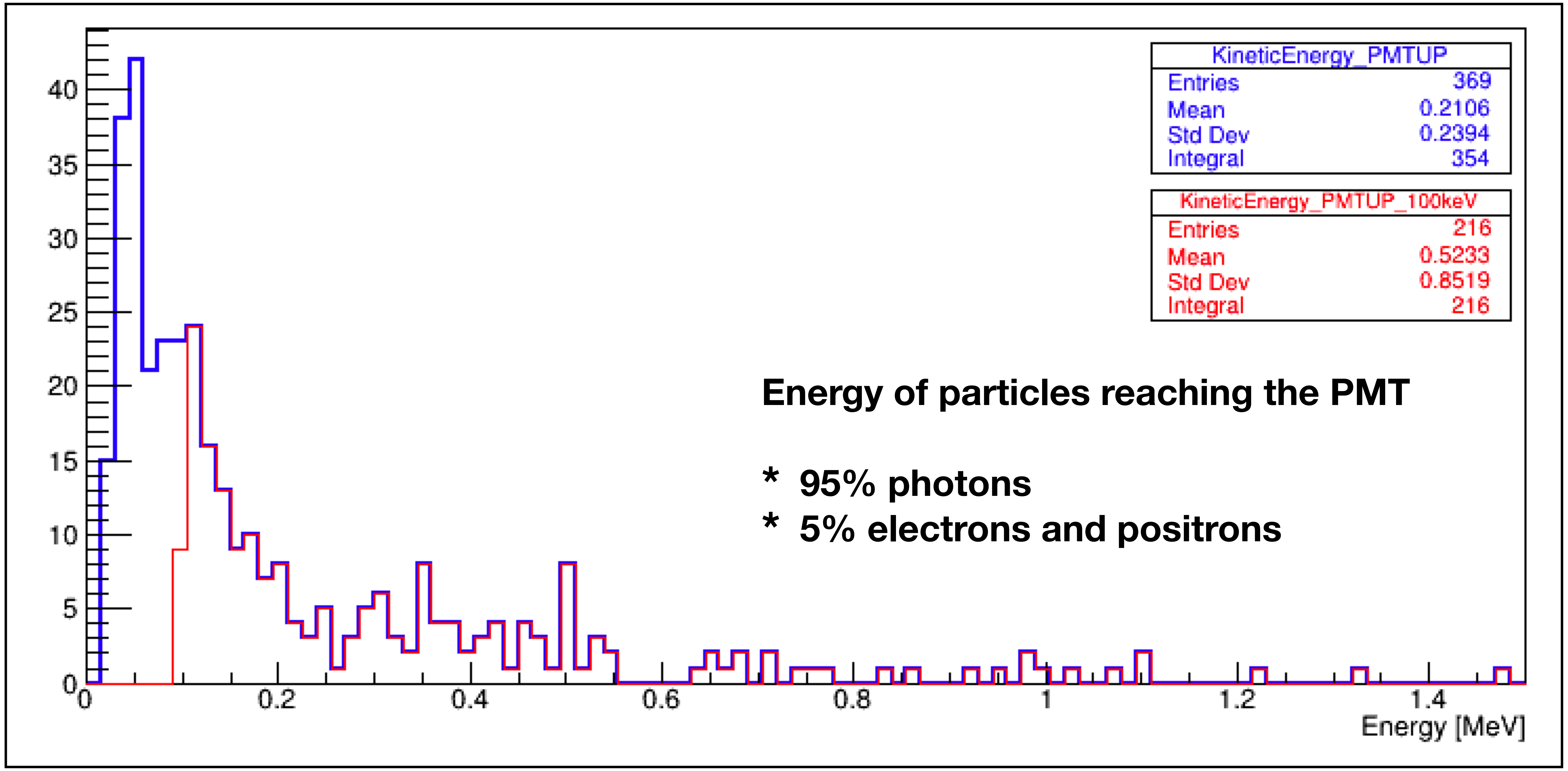
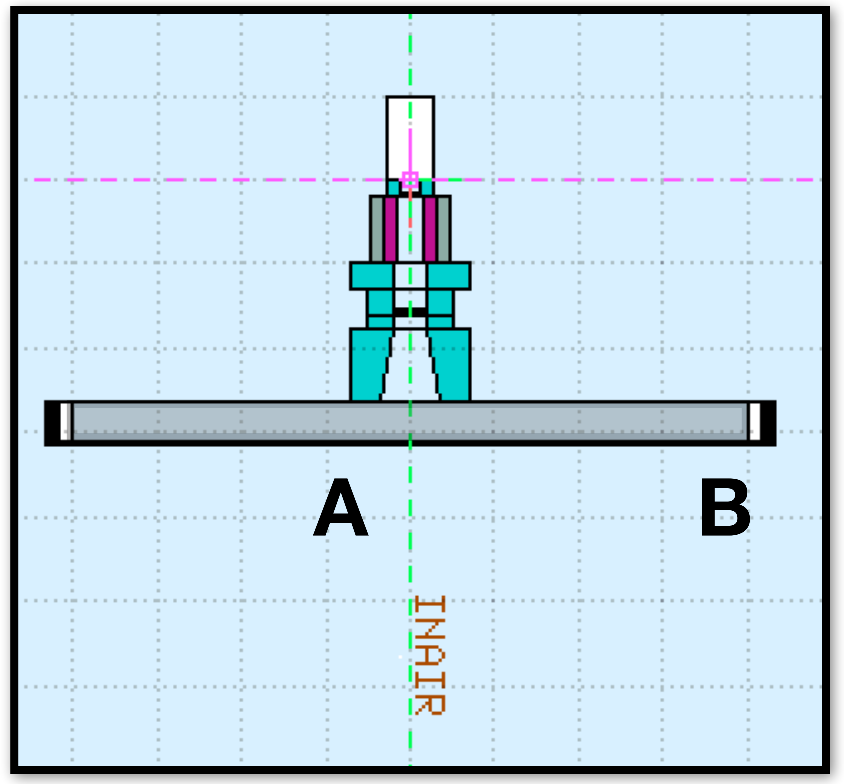


MC FLUKA SIMULATION: Optic photons card activation



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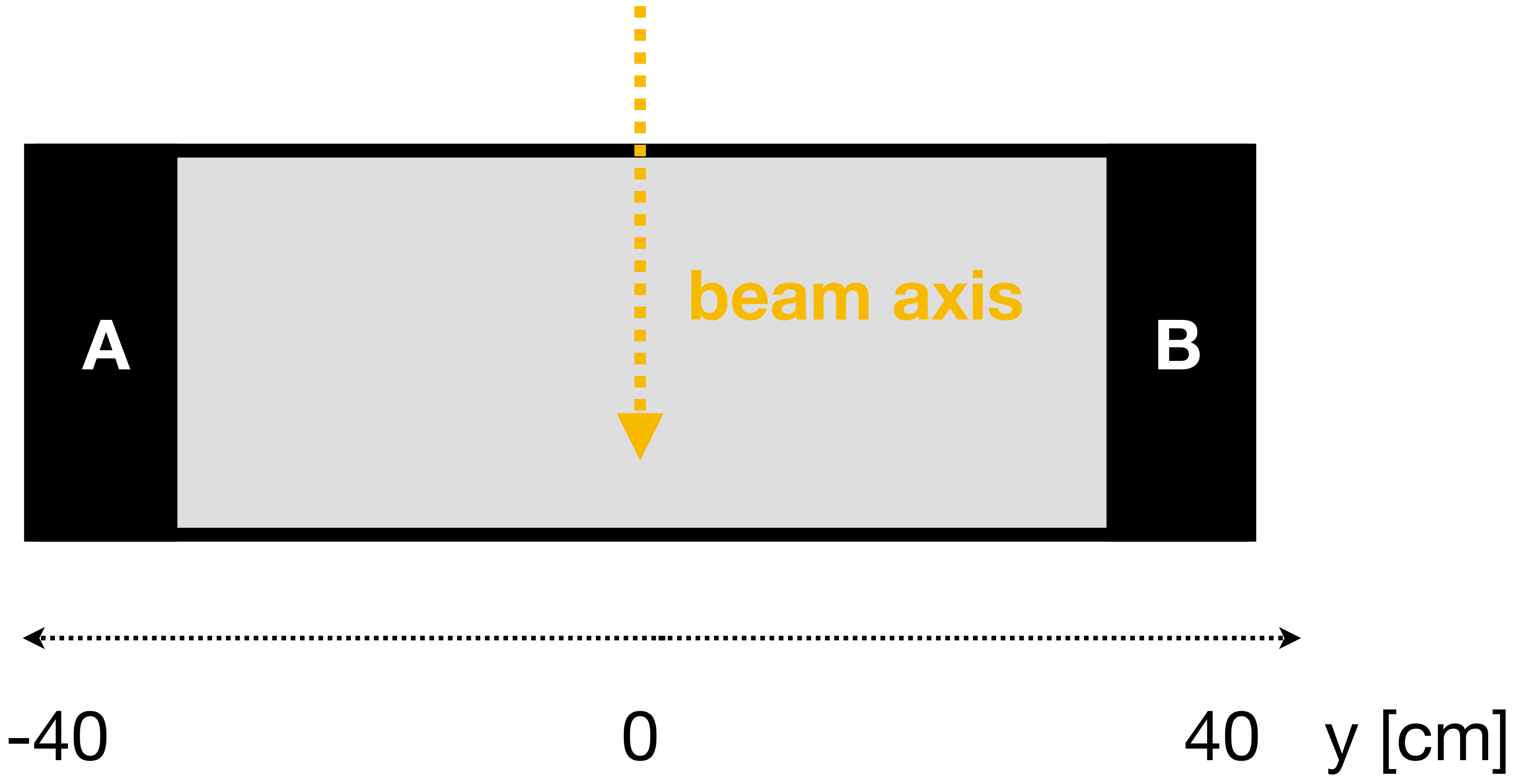
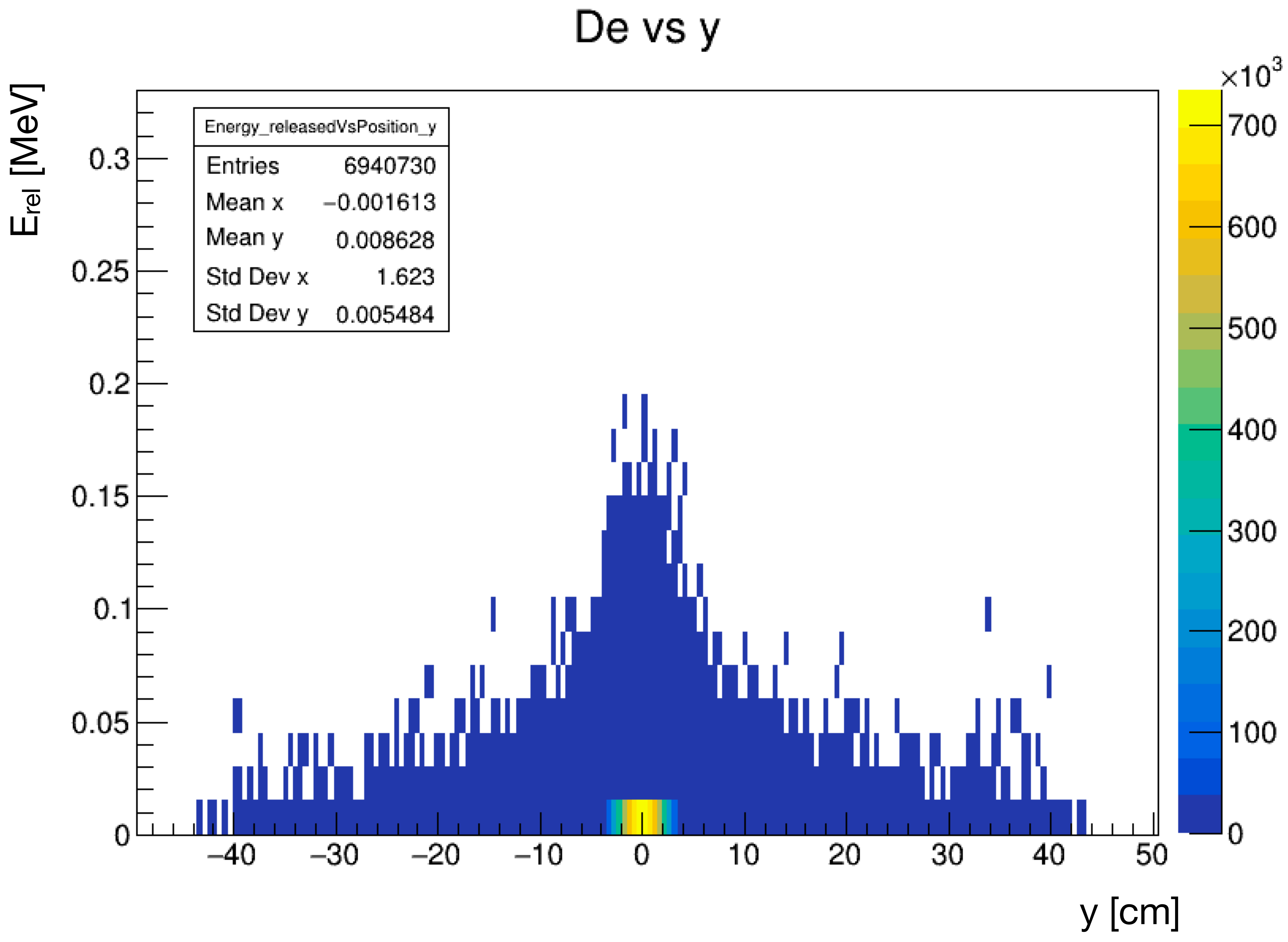
- Energy: 13 MeV

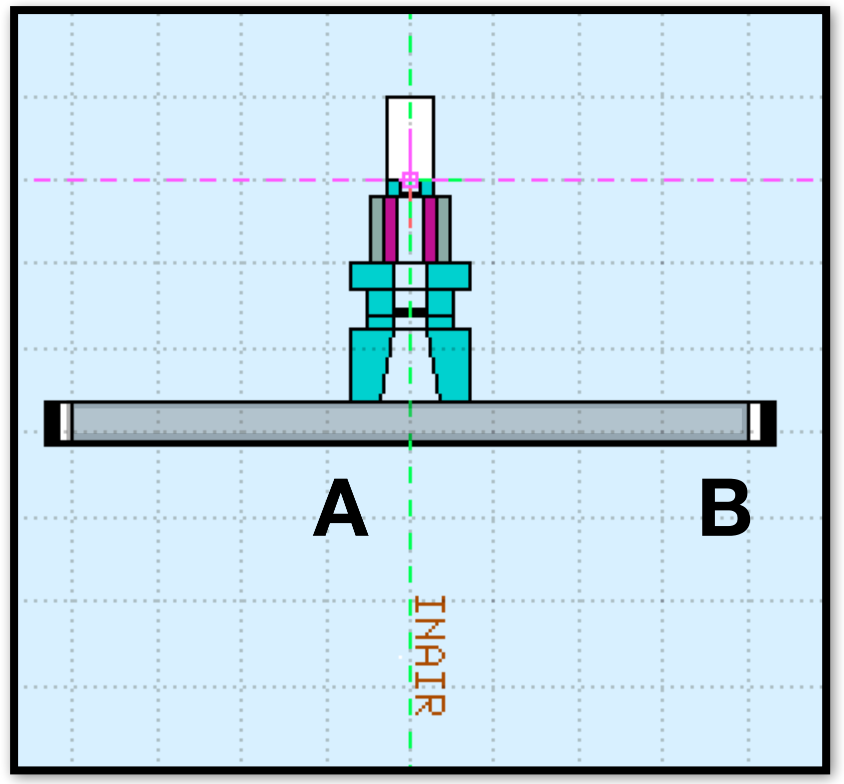


The wallets are reflective at 90% (Teflon sheet from Thorelabs)

Released energy in the Air target



MC FLUKA SIMULATION: Optic photons card activation



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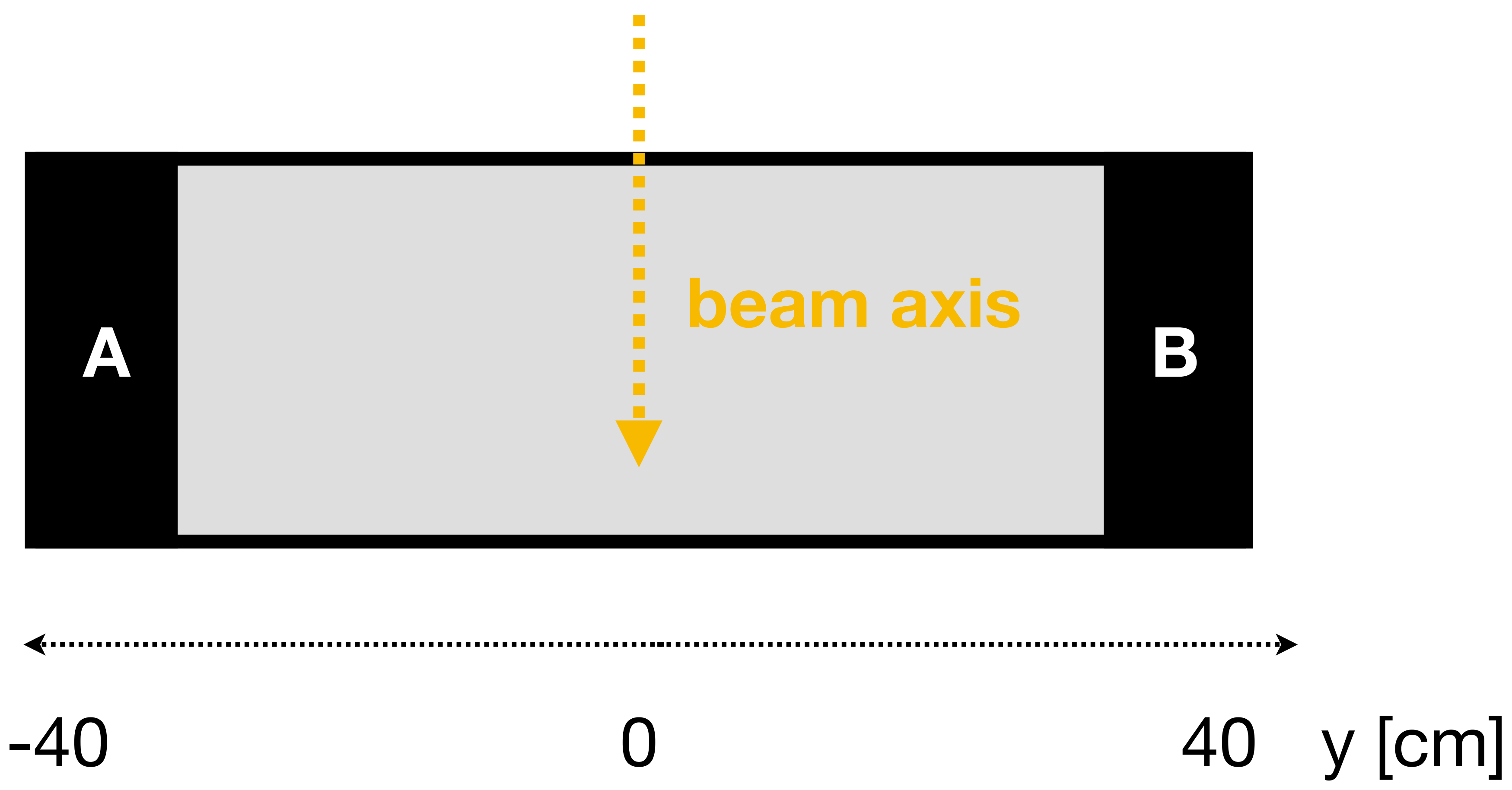
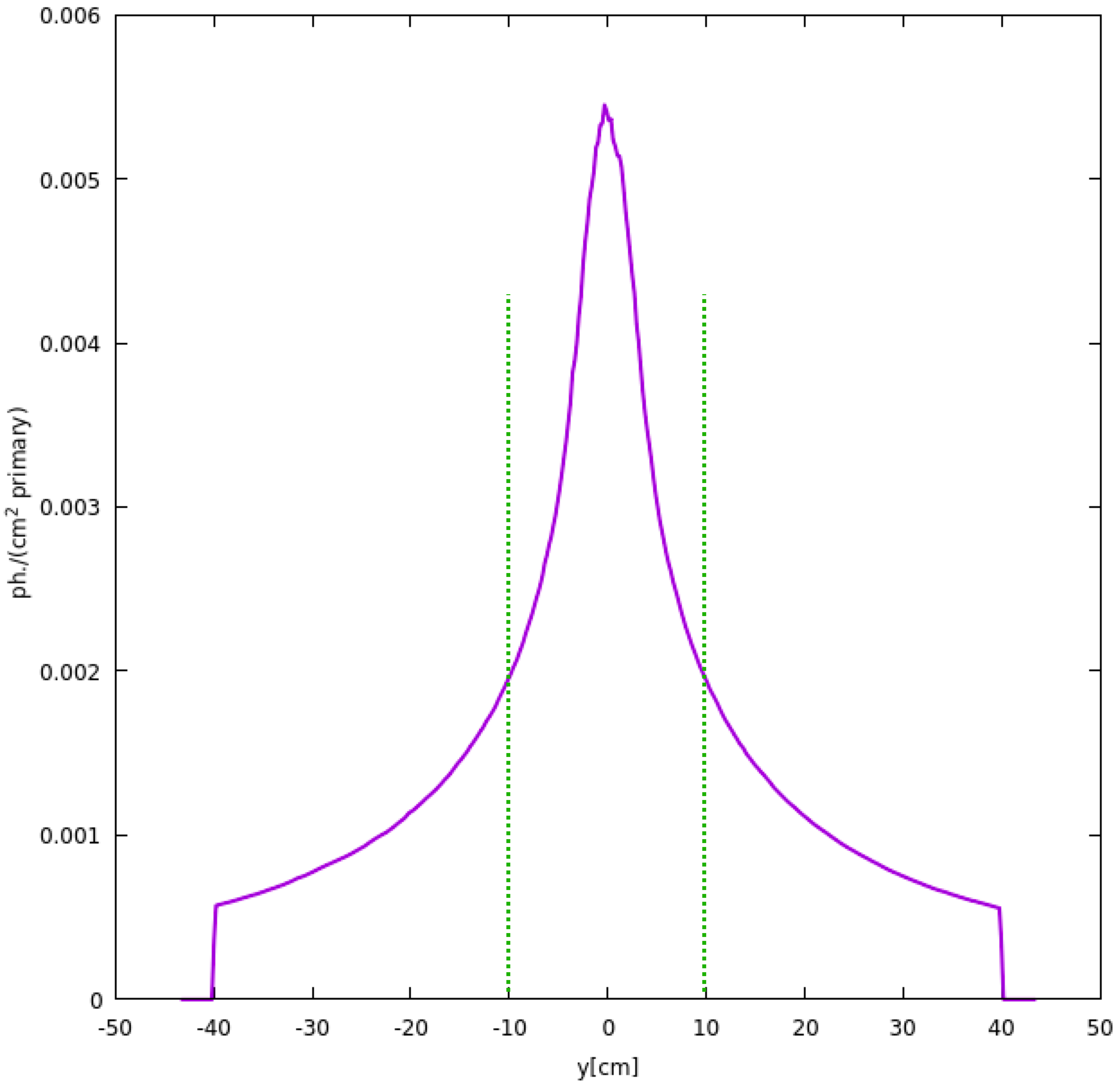


The wallets are reflective at 90%
(Teflon sheet from Thorelabs)

Optical Photons Fluence - FLUKA generated [# ph./(cm² primary)]



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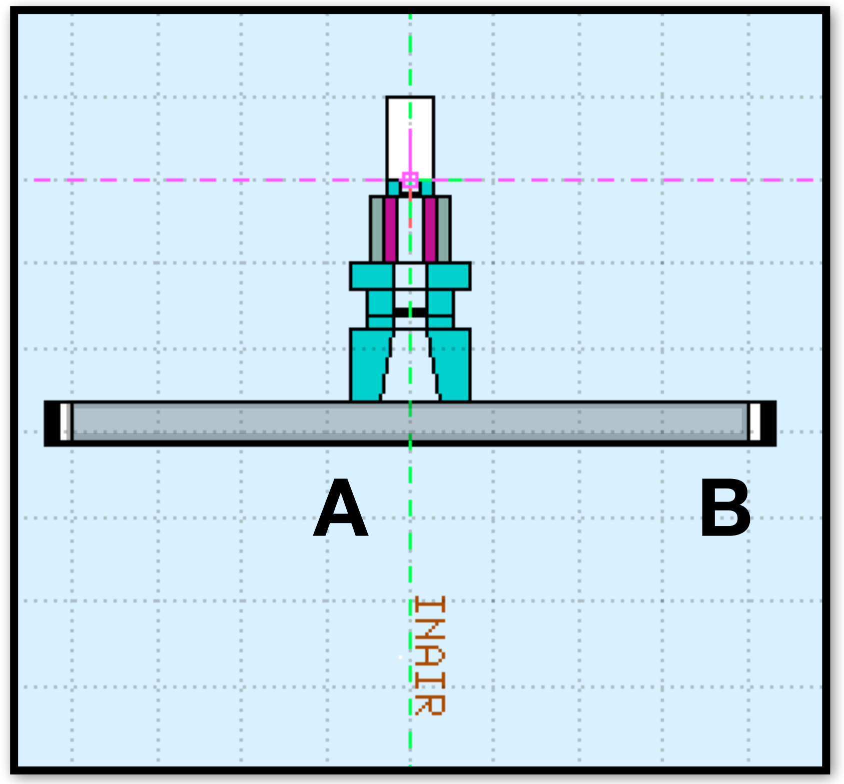
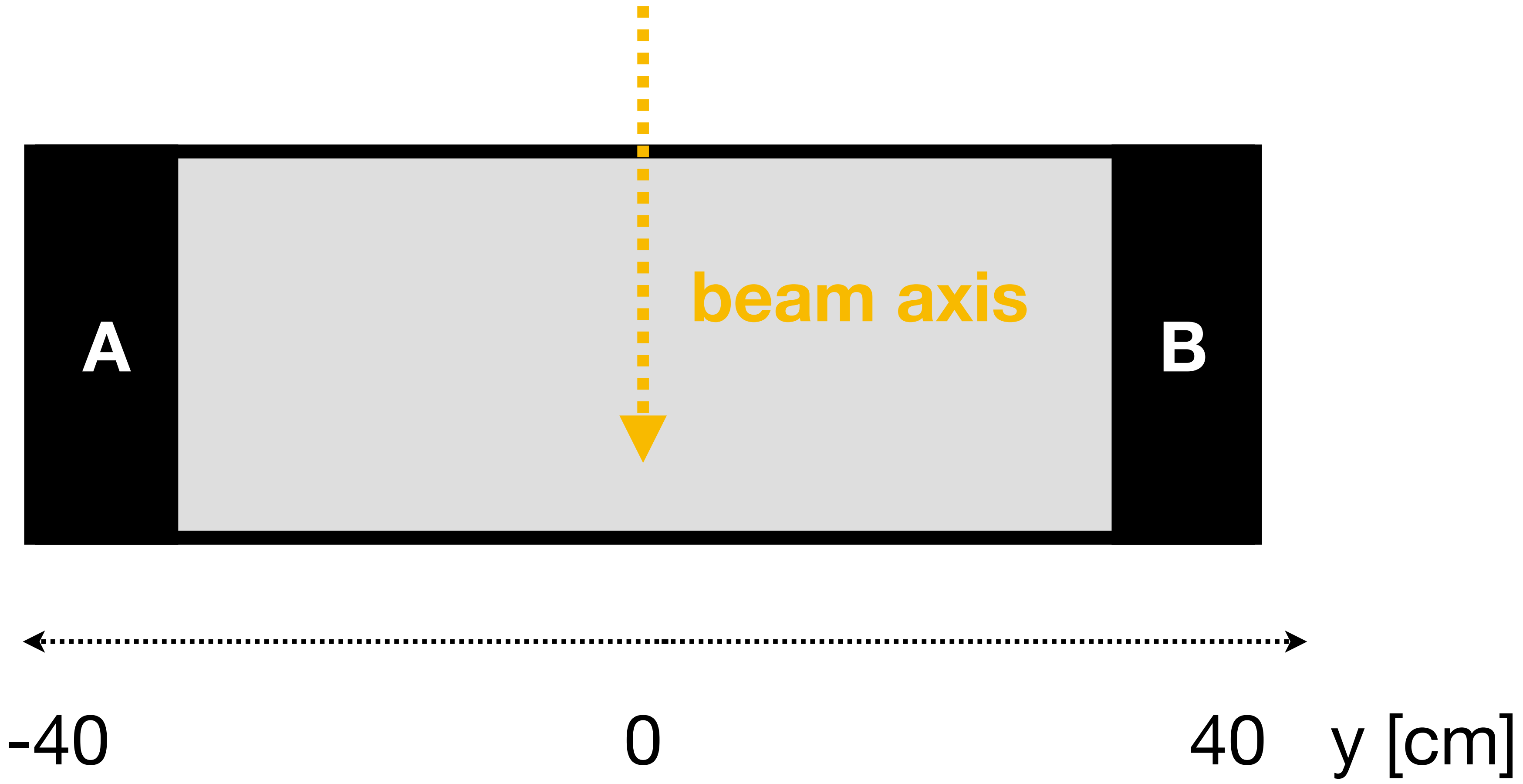
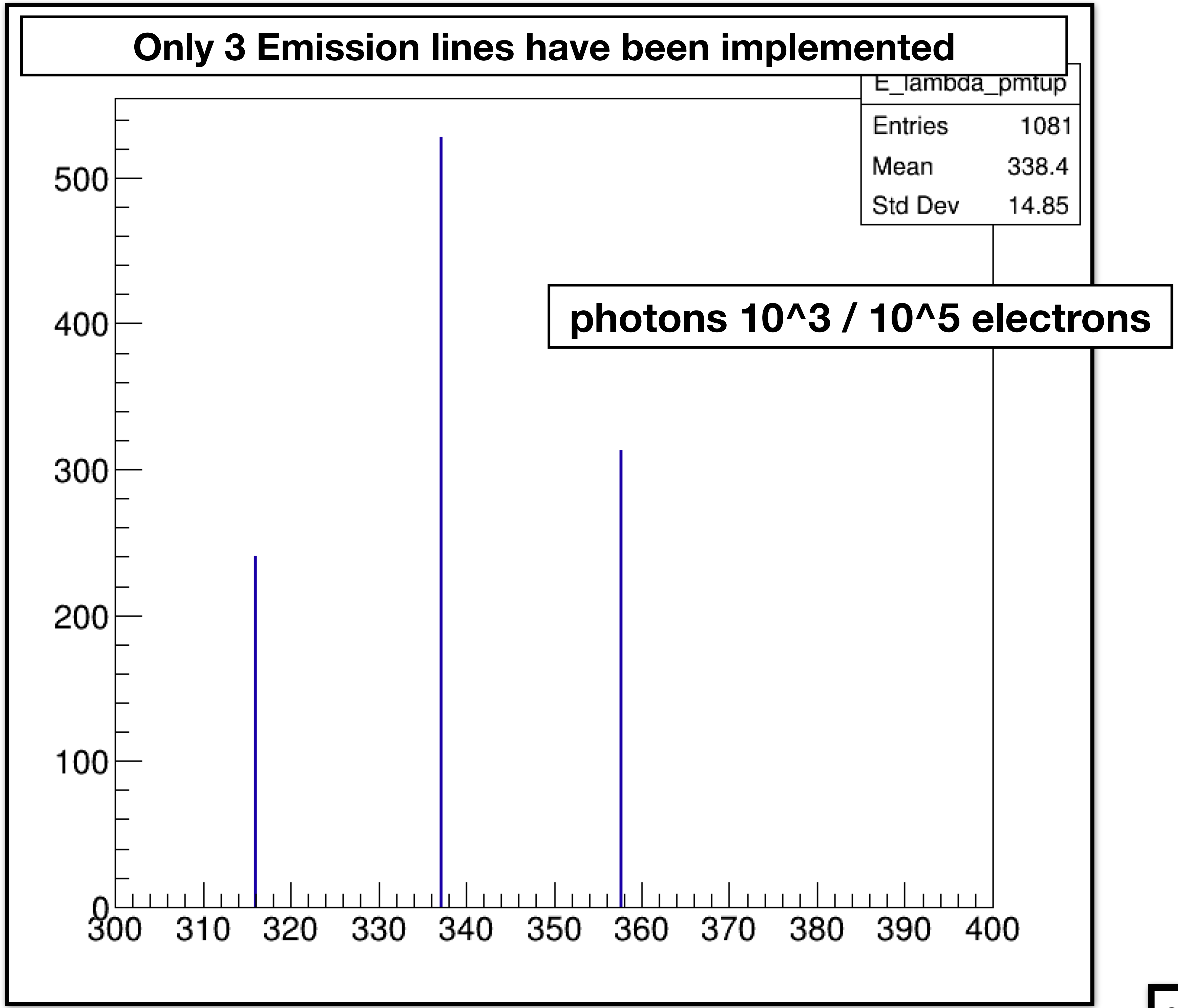


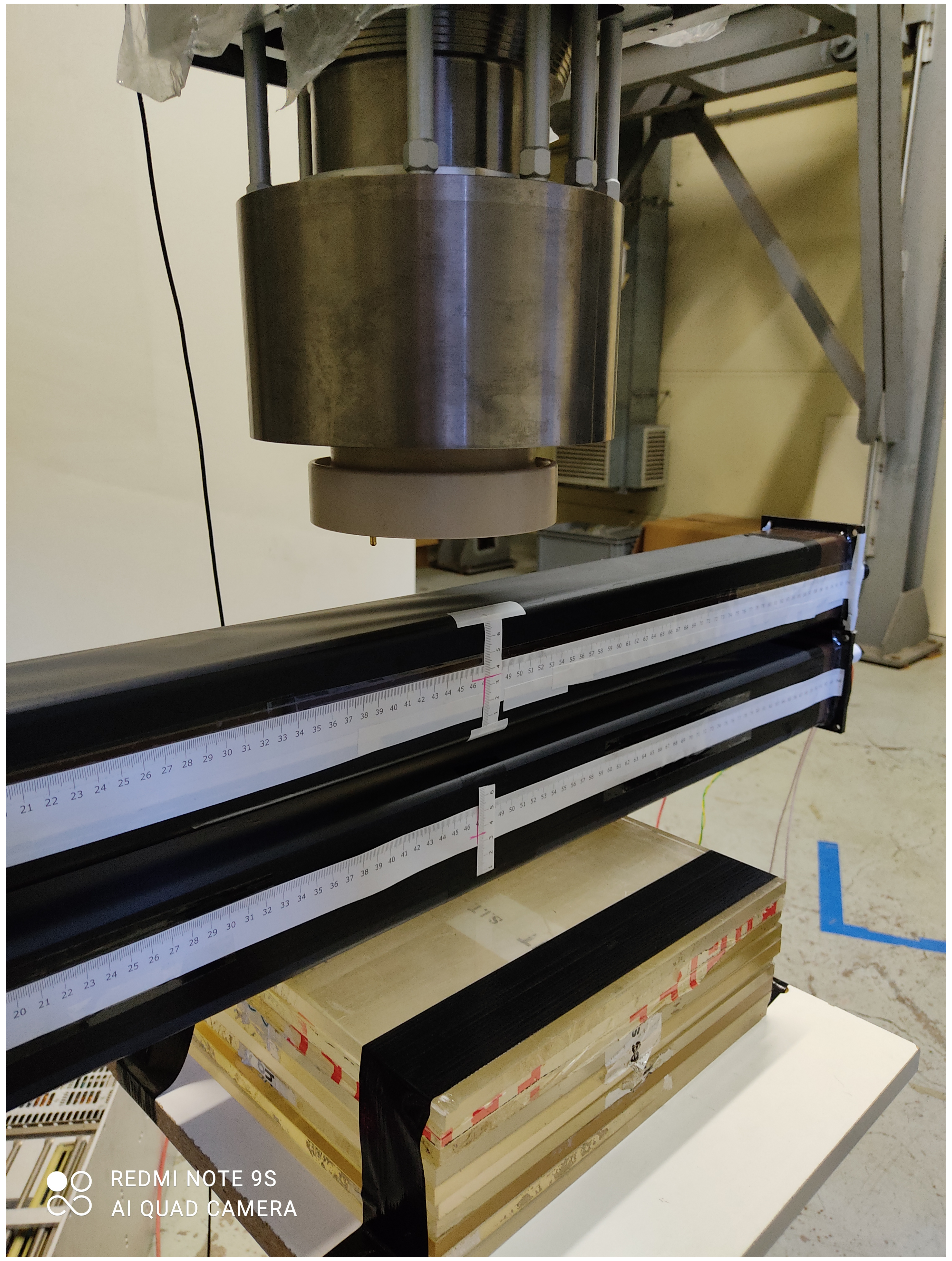


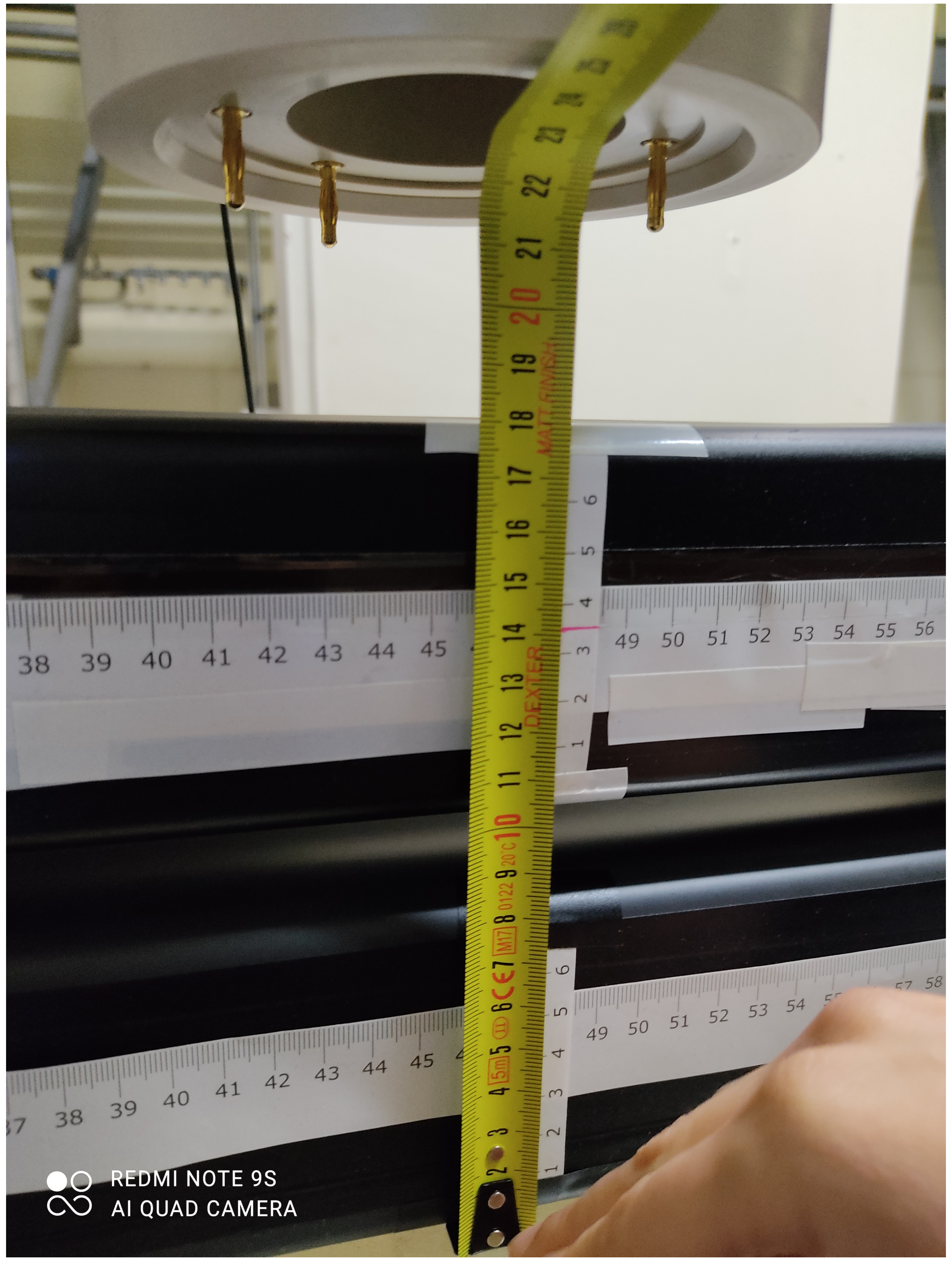


The wallets are reflective at 90% (Teflon sheet from Thorelabs). Black configuration decreases the number of photons of a factor 100.

Tubone@SIT: 22.3.2021

- The LIAC HWL shoots 10^{10} electrons with energy 6 MeV in a pulse 4μs long at a frequency of 10Hz.
- The first run was performed with the beam shooting straight at the center of the dosemeters (ref. up, abs. down).



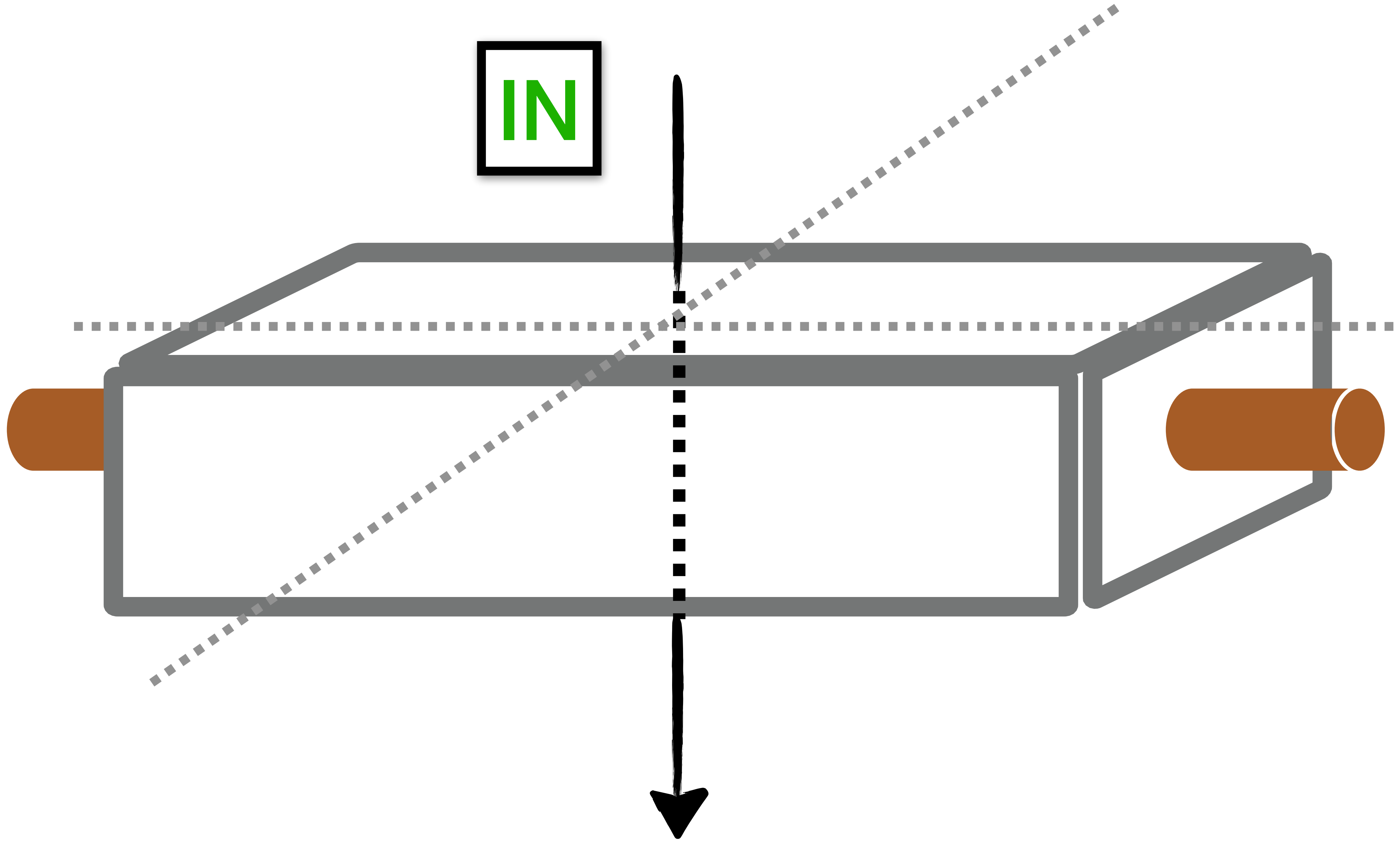


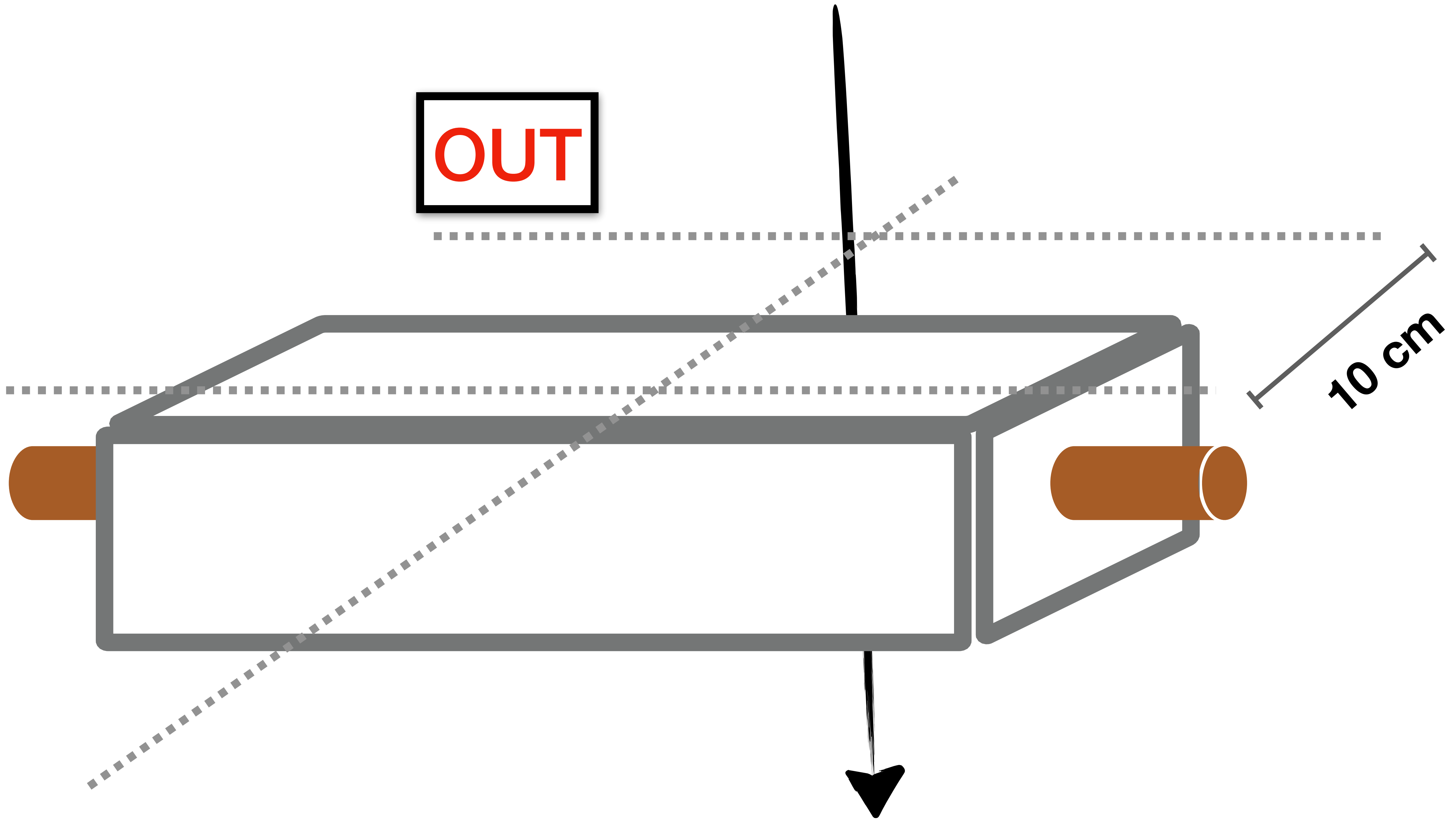
Tubone@SIT: 22.3.2021

- **1st question**: can we observe in-beam/off-beam difference?

  - **From sim.:** (with 10^{10} el./pulse)

MC FLUKA	IN BEAM	OFF BEAM	RATIO
#opt.phot.	1,05E+08	1,6E+05	$\sim 1.5 \ 10^{-3}$





Tubone@SIT: 22.3.2021

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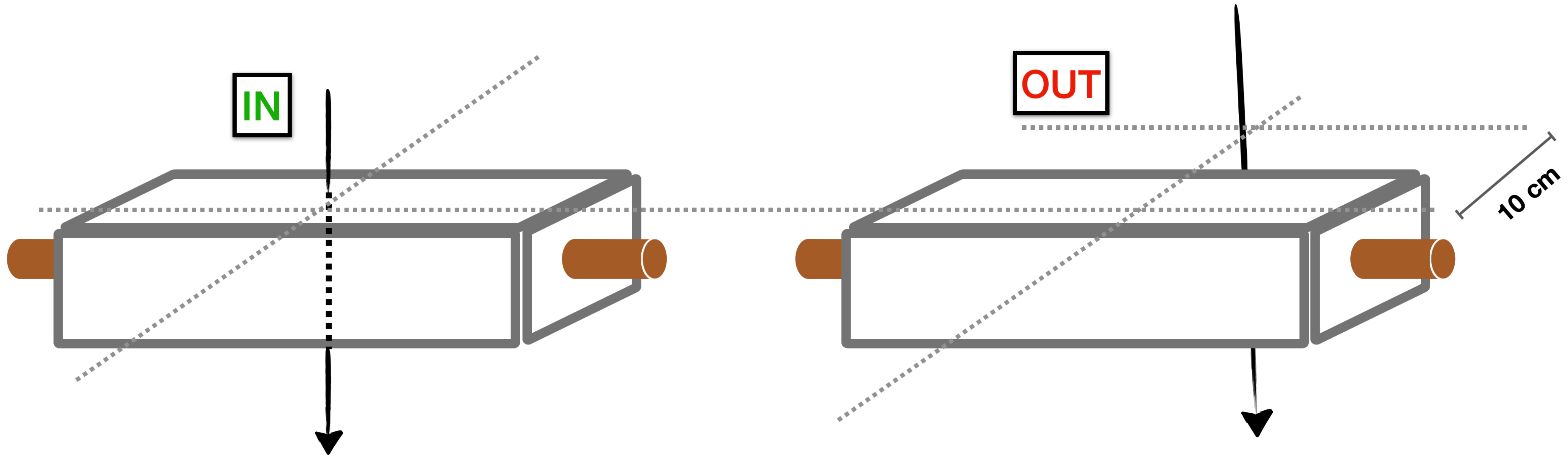

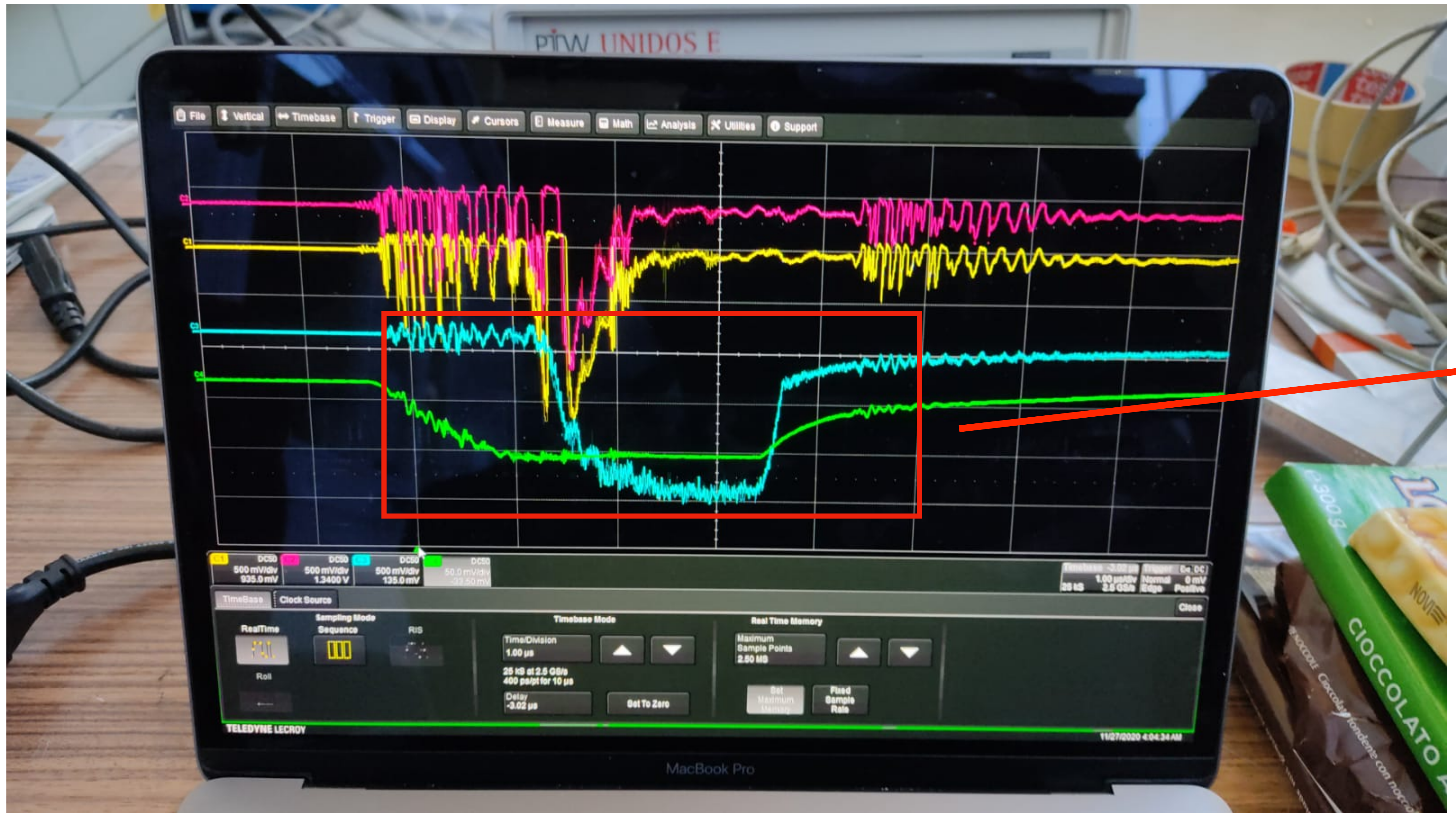

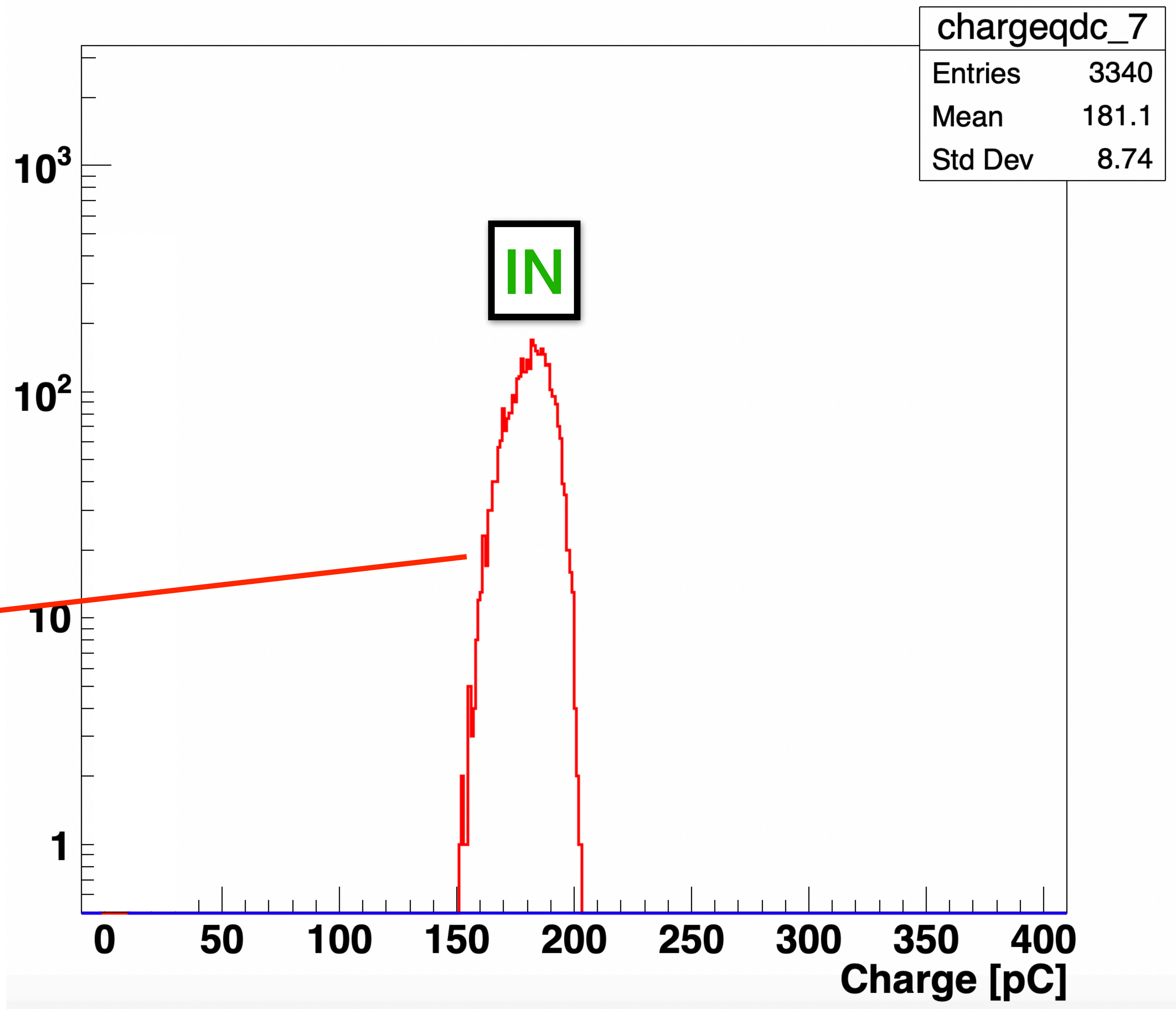

Tubone@SIT: 22.3.2021

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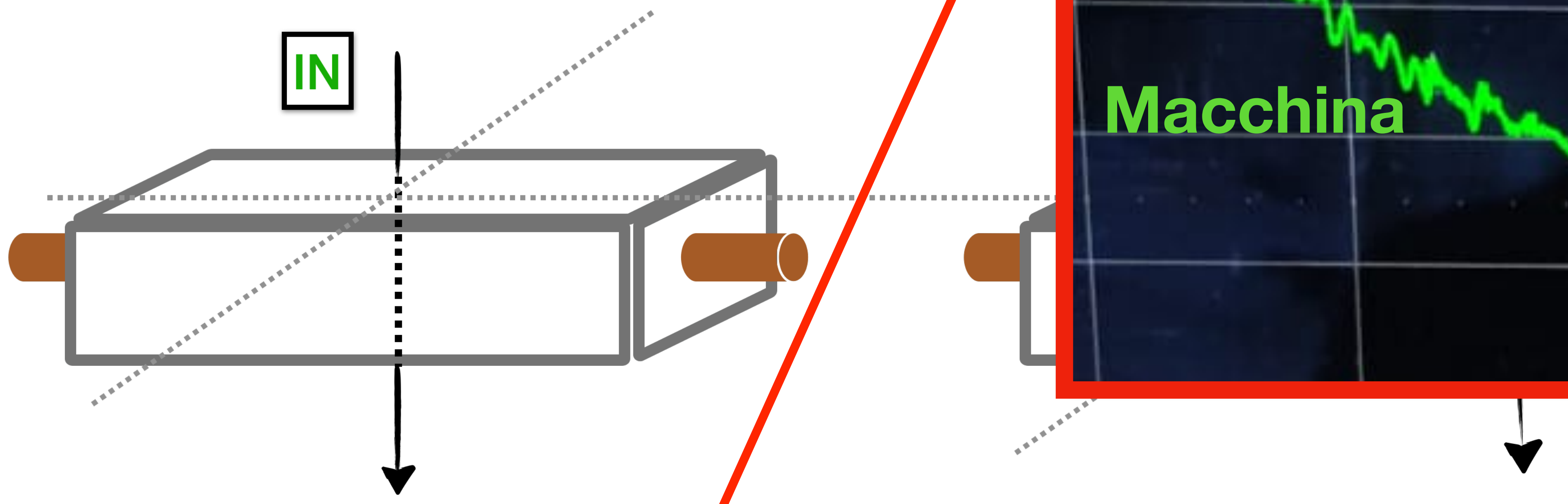

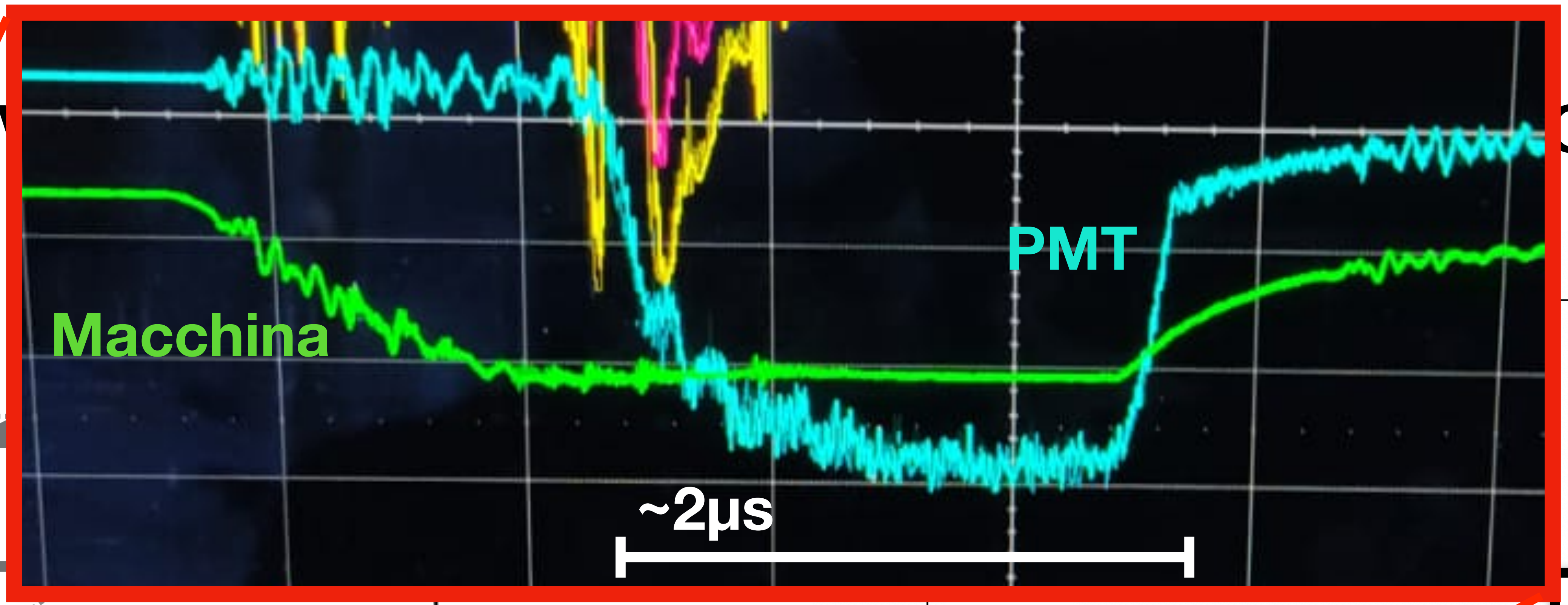

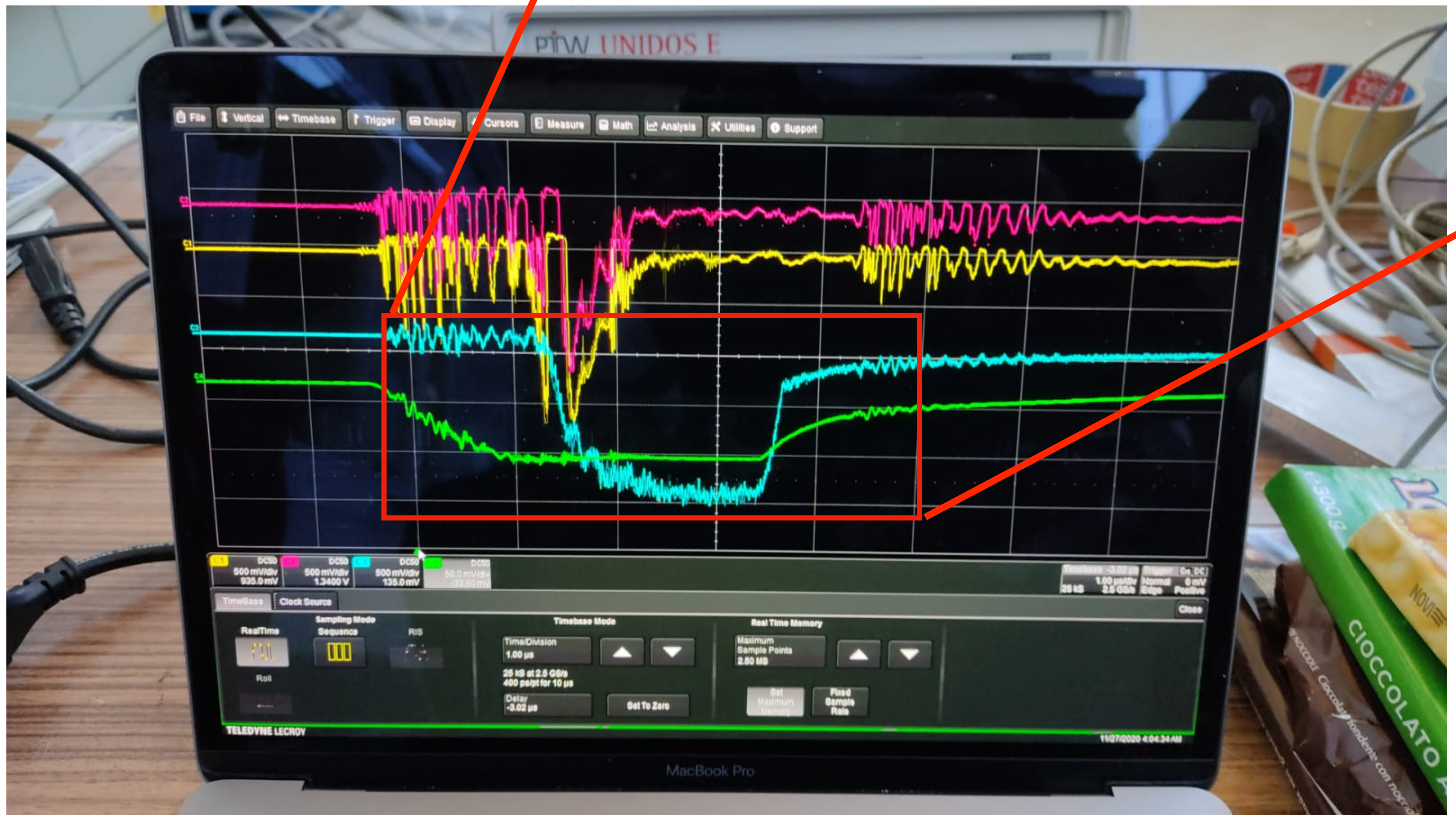

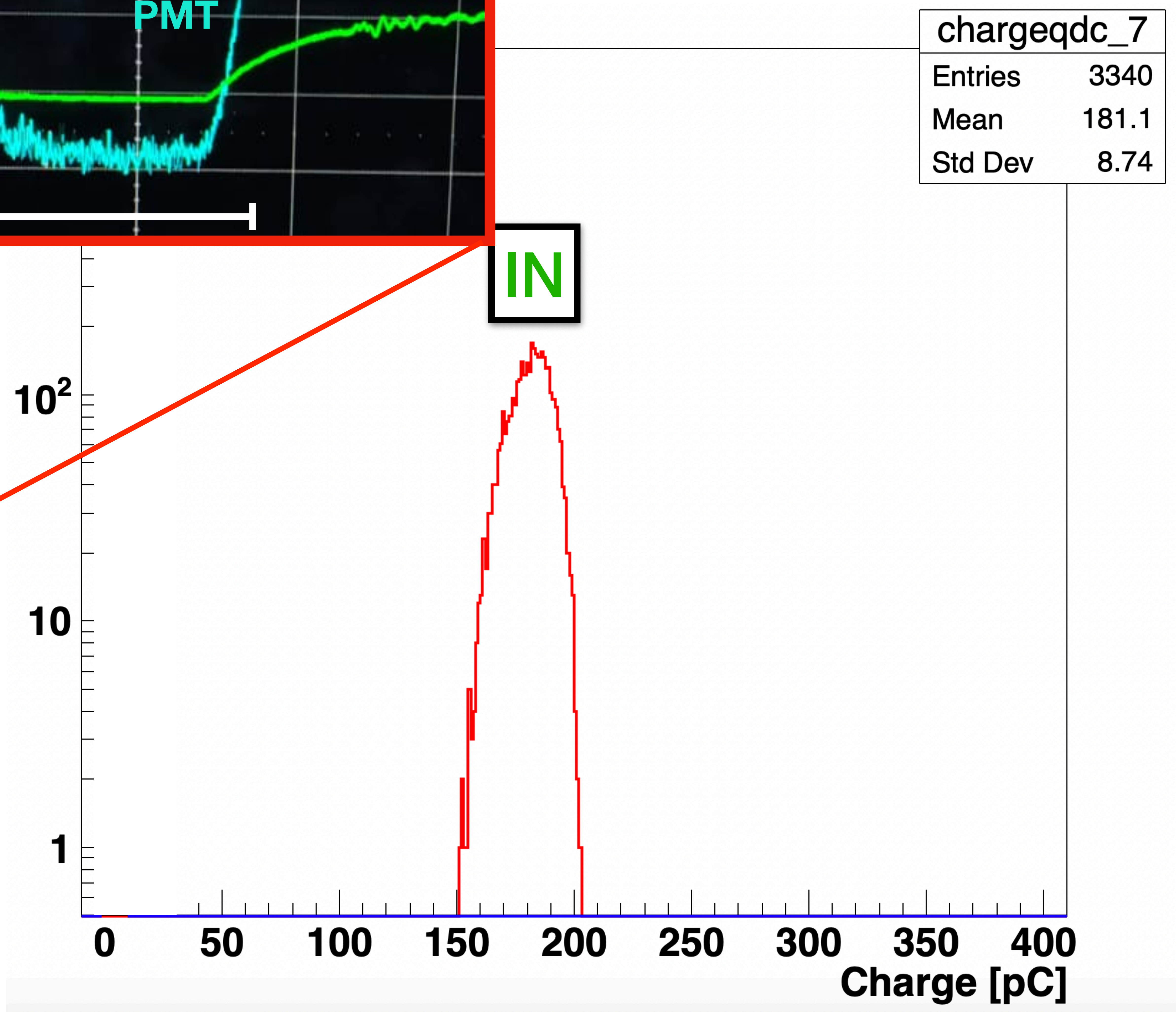

Tubone@SIT: 22.3.2021

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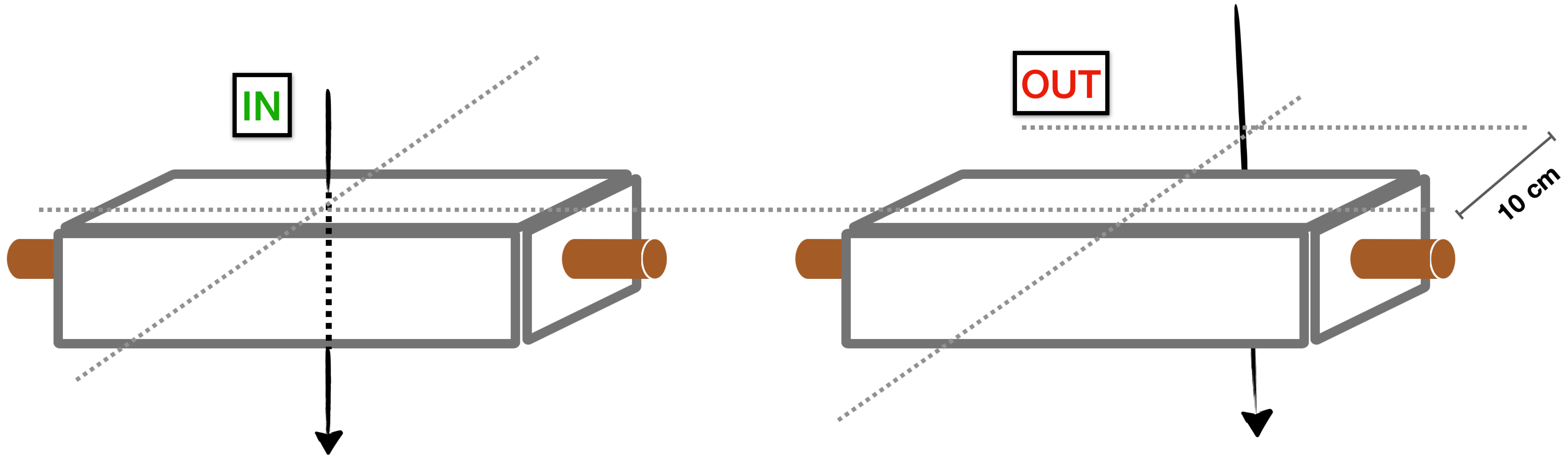
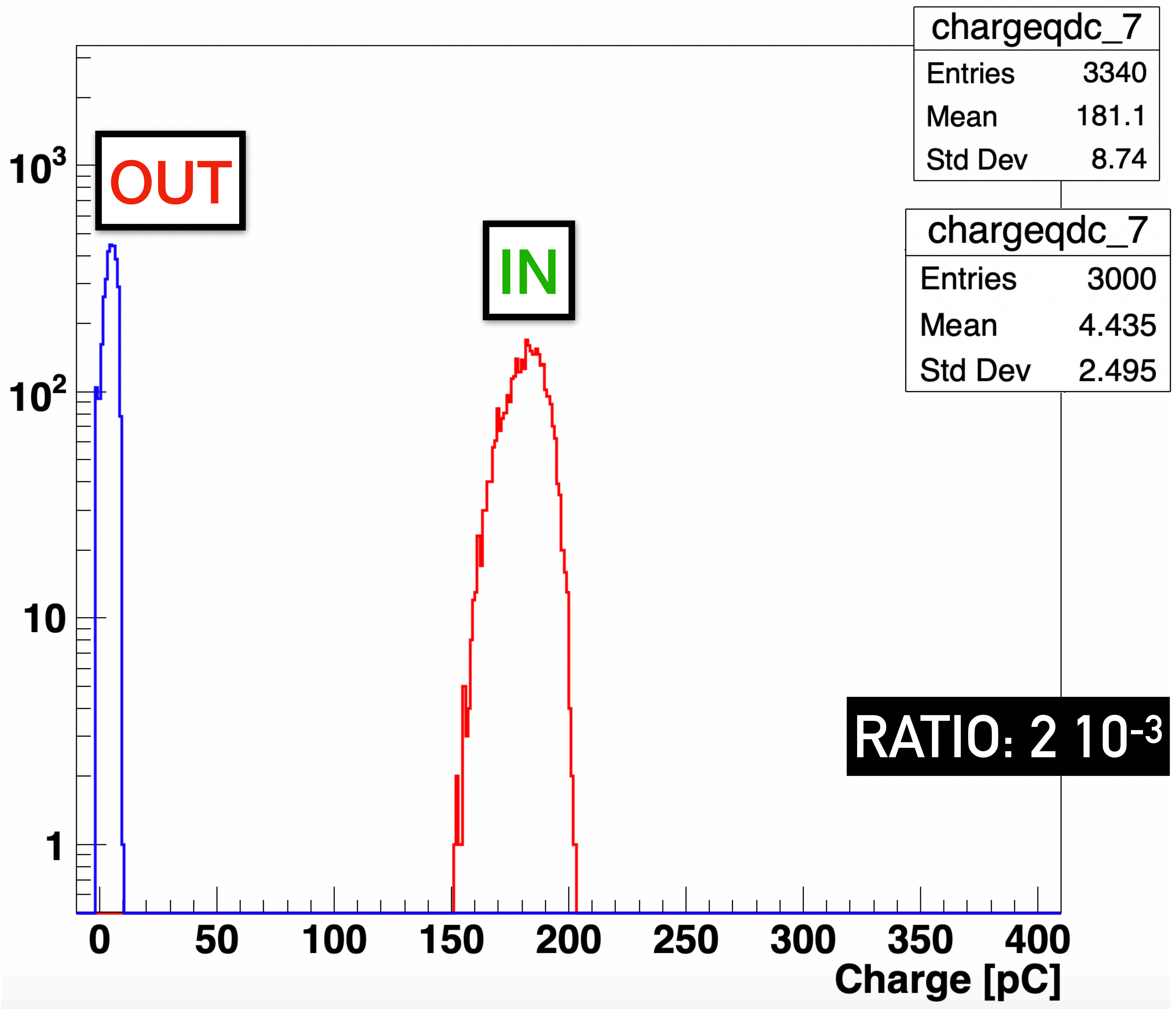


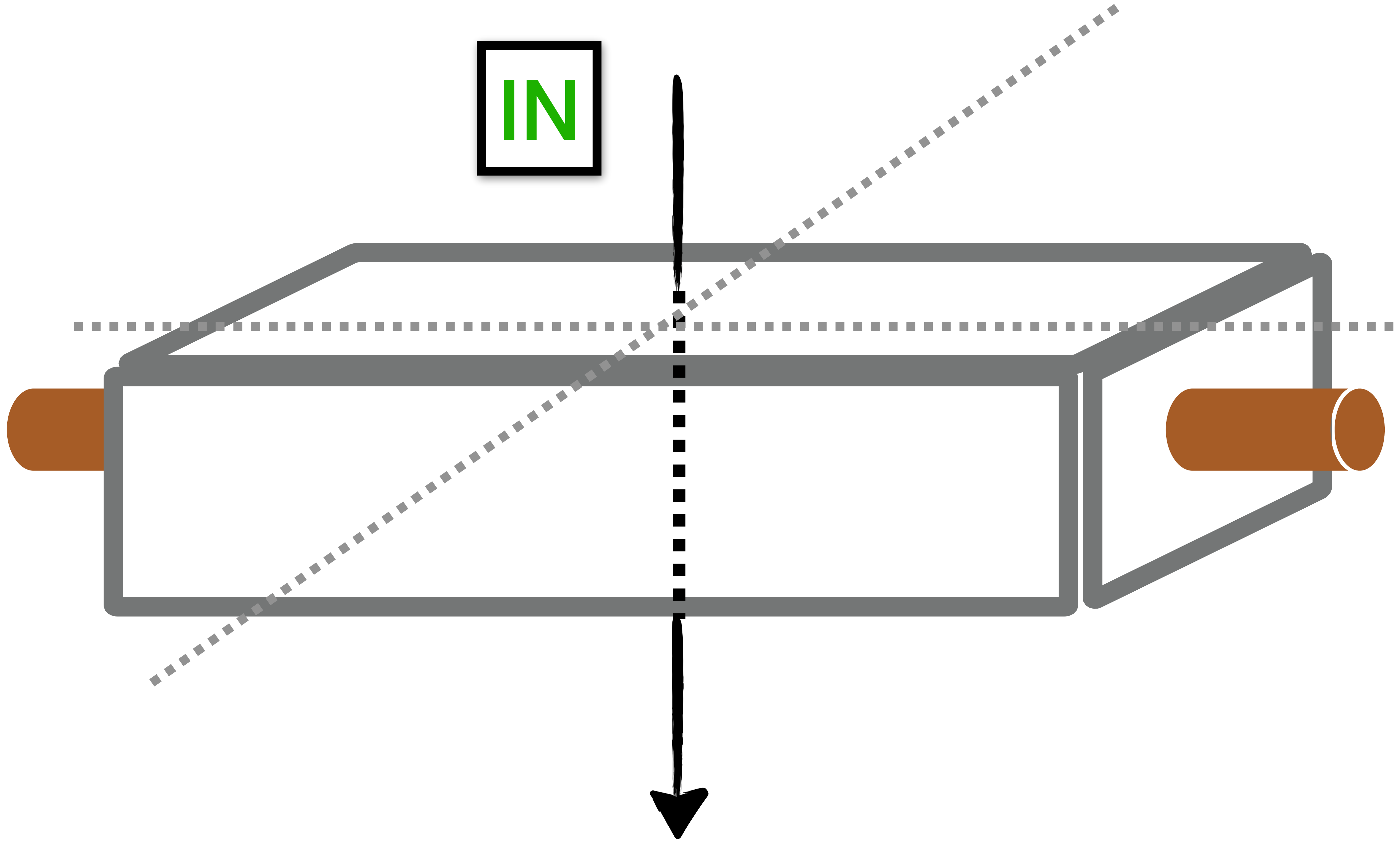


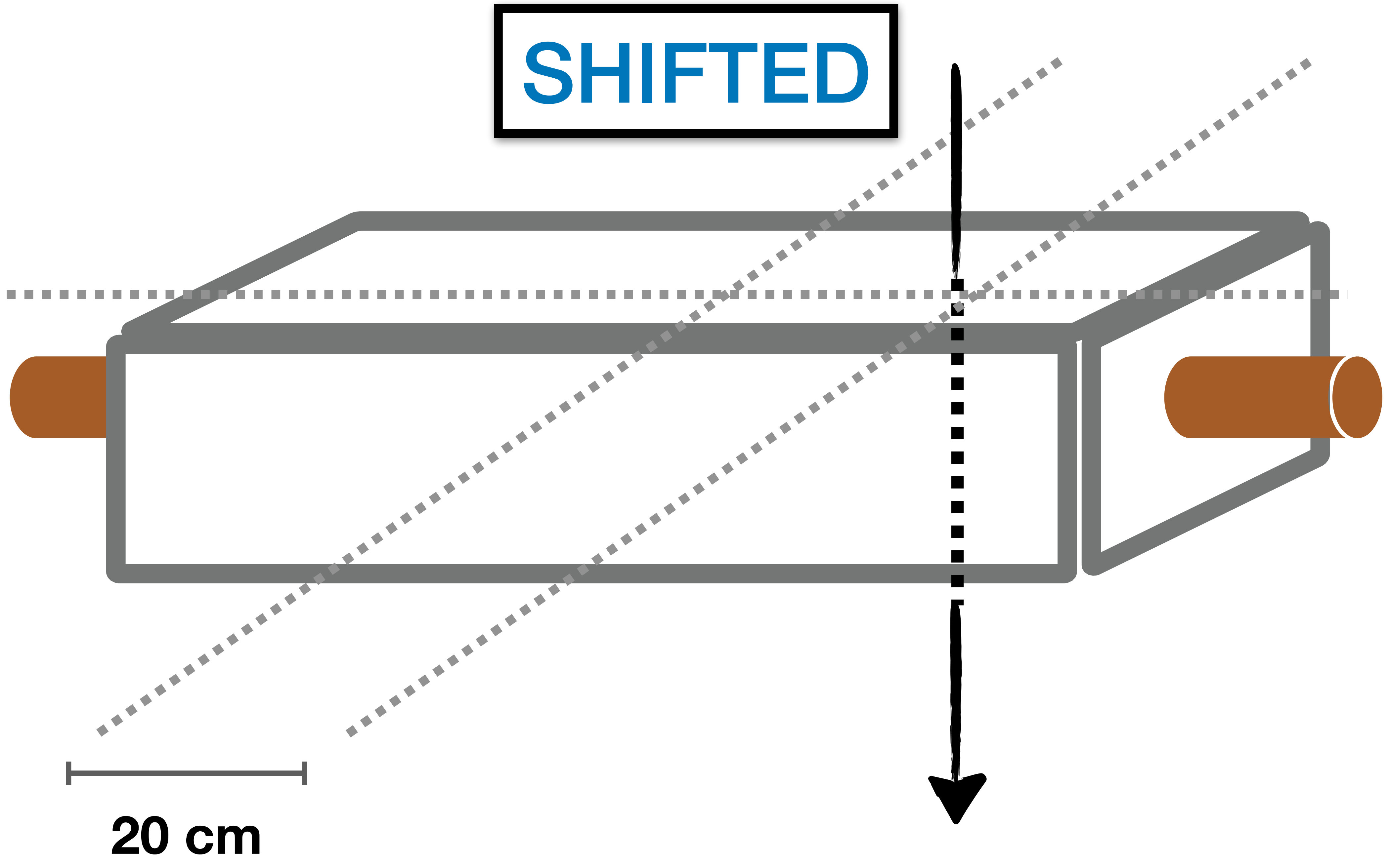
Tubone@SIT: 22.3.2021

- **2rd question:** What if one of the PMTs is **farther** from the aperture?

  - **From sim.:** (with 10^{10} el./pulse)

MC FLUKA	IN BEAM	SHIFTED BEAM	RATIO
#opt.phot.	1,05E+08	7,06E+07	~2





Tubone@SIT: 22.3.2021

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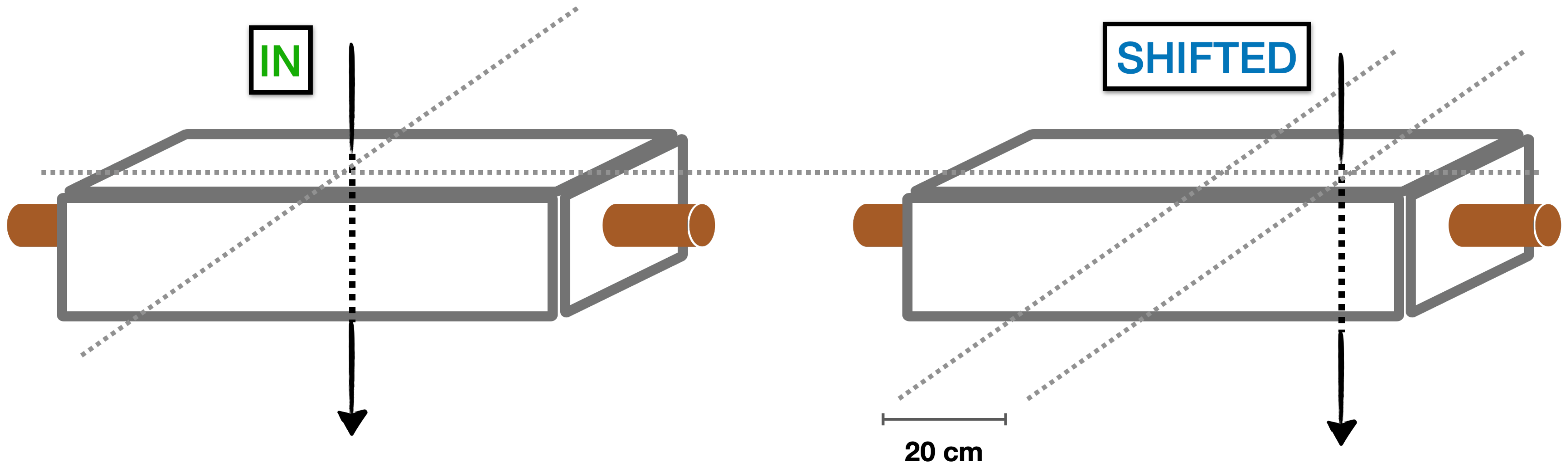
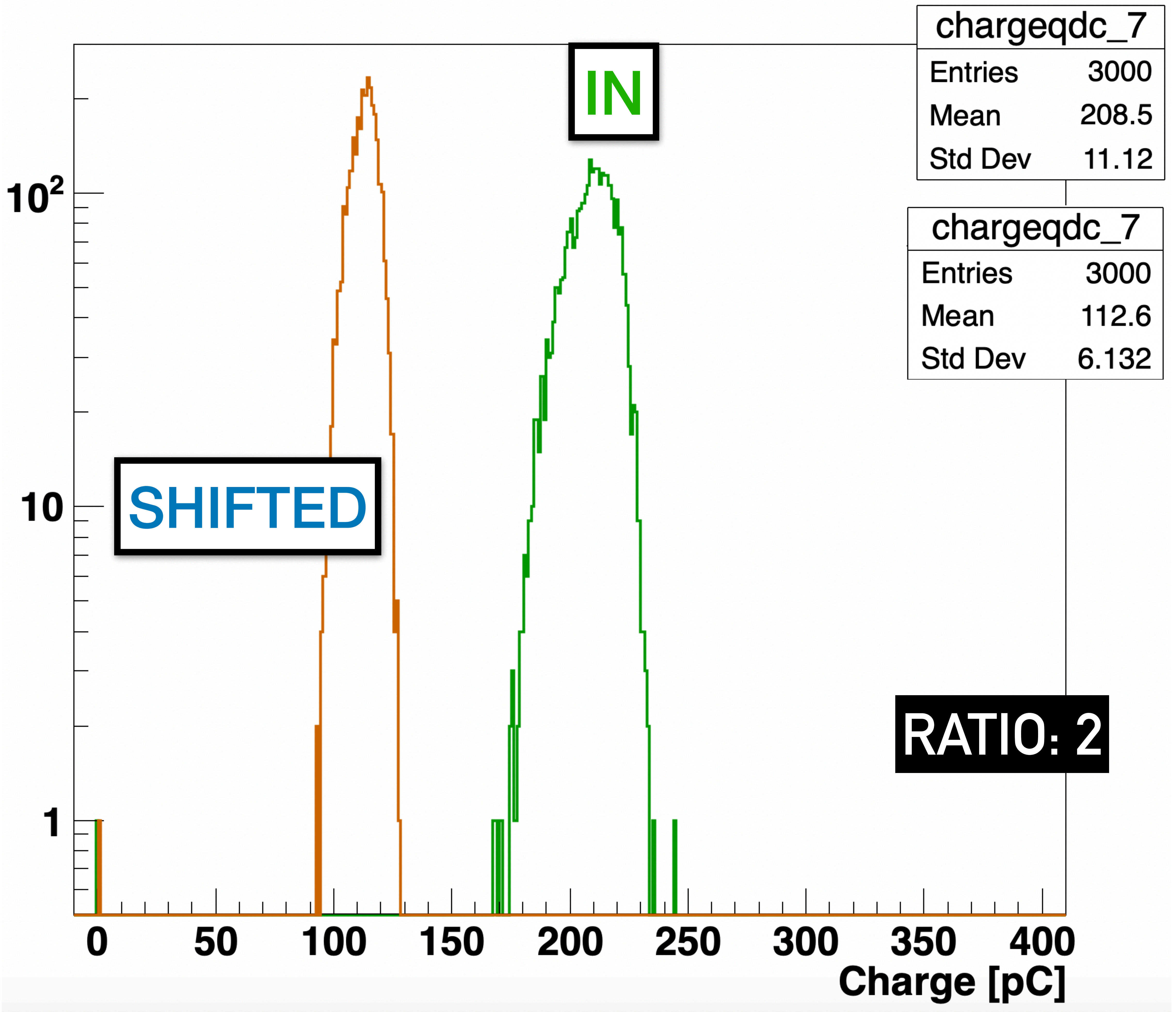


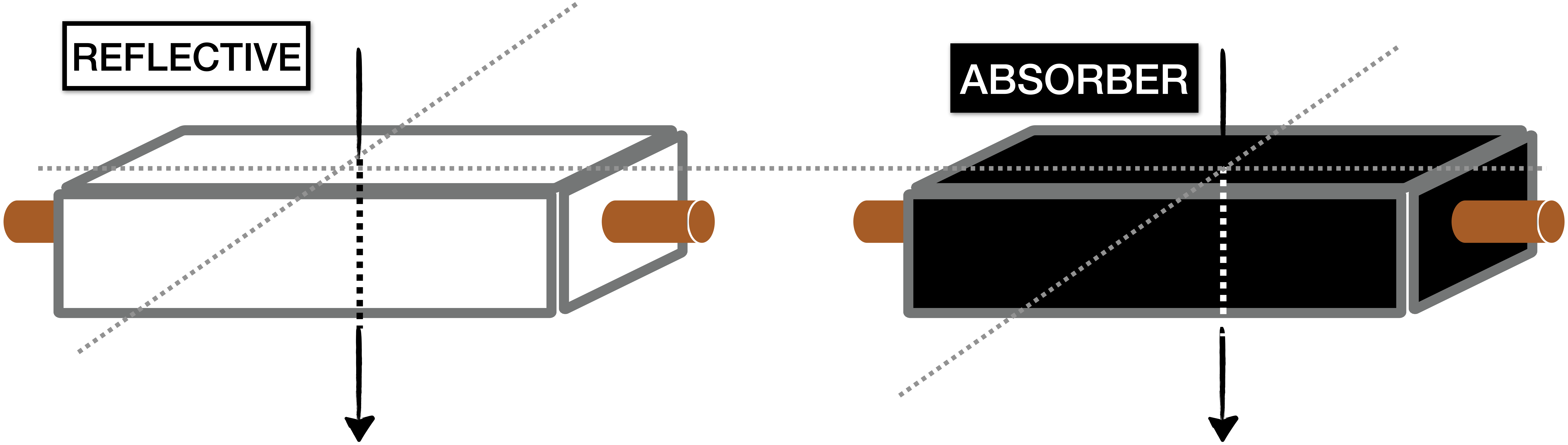


Tubone@SIT: 22.3.2021

- **3rd question:** What difference do **reflective** and **absorber** make?

  - From sim.: (with 10^{10} el./pulse)

MC FLUKA	REFLECTIVE	ABSORBER	RATIO
#opt.phot.	1,05E+08	1,05E+06	$\sim 10^{-2}$



Tubone@SIT: 22.3.2021

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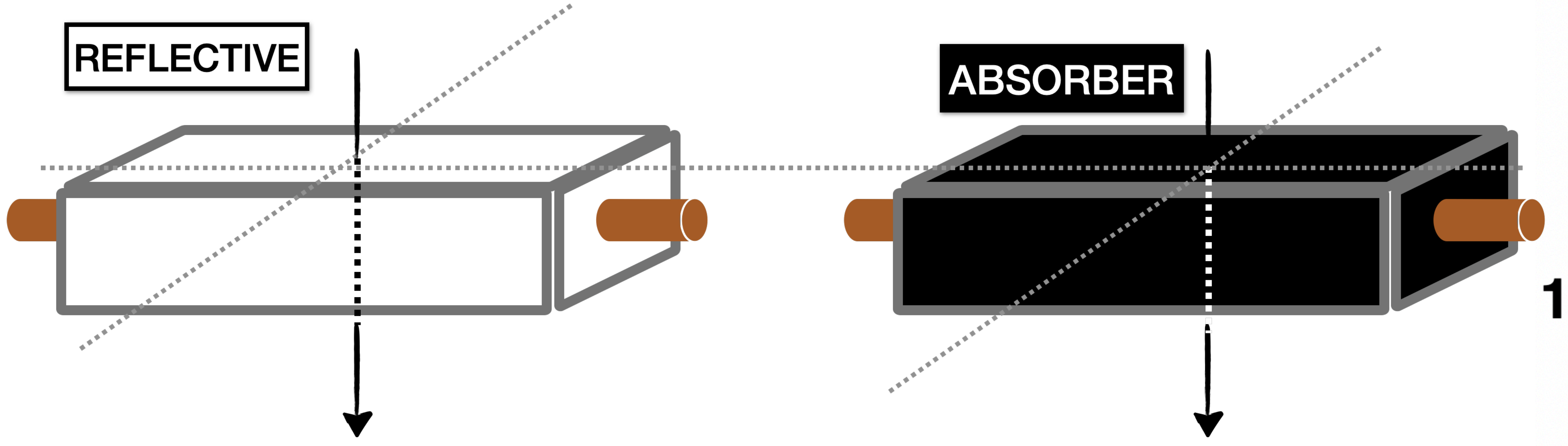
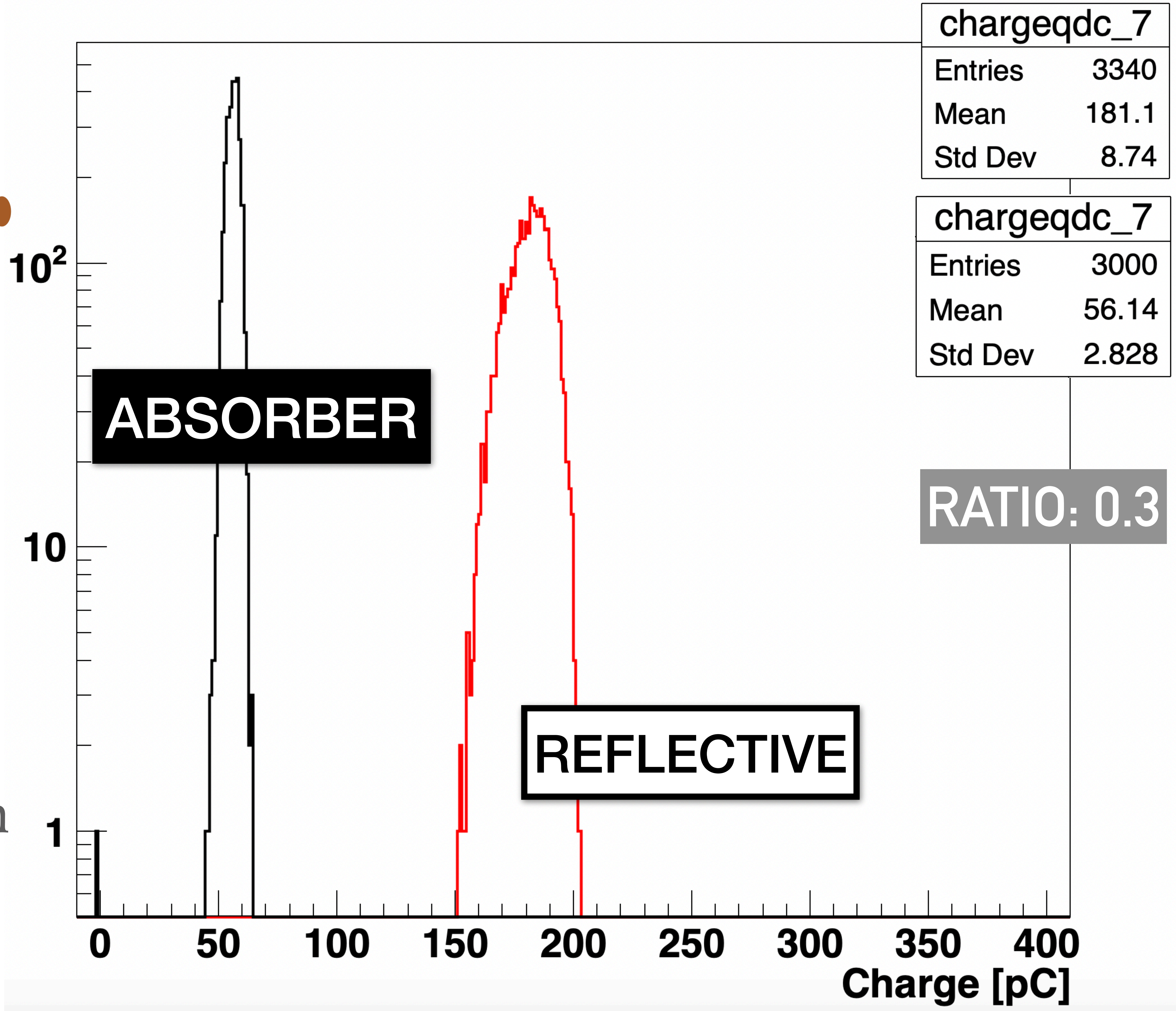


➤ **Note (1):** In the simulation, the walls of the detector are all perfectly absorbing (reflectivity 0%).

➤ **Note (2):** In real word only two faces of the detector are reflective, so the reduction is not the one expected of a factor 100.



Tubone@SIT: 22.3.2021

DETECTOR	IN-BEAM [pC]	OFF-BEAM (10 cm) [pC]	OFF-BEAM/ IN-BEAM	SHIFTED (58 cm) [pC]	SHIFTED (33 cm) [pC]
REFLECTIVE TOP	180	4	$2\ 10^{-2}$	/	/
ABSORBER TOP	56	0.8	$1.5\ 10^{-2}$	30	/
REFLECTIVE BOTTOM	208	16	$7\ 10^{-2}$	113	SATURATE

- We can see the IN beam from the OFF beam
- The response of the detector is sensitive to position and geometry
- The study reflectivity/absorption with MC and data is coherent with expectancy.. probably a not-reflective detector is a better choise .
- Filters study => to do..

Preliminary Conclusion with TUBONE

DETECTOR	IN-BEAM [pC]	OFF-BEAM (10 cm) [pC]	OFF-BEAM/ IN-BEAM	SHIFTED (58 cm) [pC]	SHIFTED (33 cm) [pC]
REFLECTIVE TOP	180	4	$2\ 10^{-2}$	/	/
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- ☑ We can see the IN beam from the OFF beam
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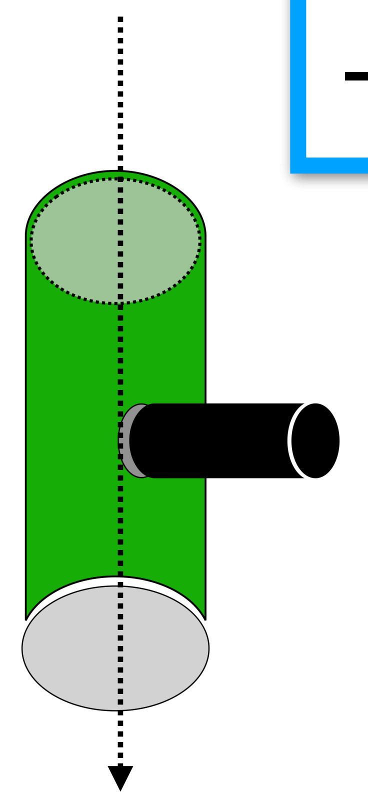
Expected photons

According to the detector we decide to implement.. SIT LIAC machine

Per elettroni da “13” MeV ci aspettiamo:
- 4 ph. al m di fluorescenza (@4π)
- Cherenkov sotto soglia

(1) 

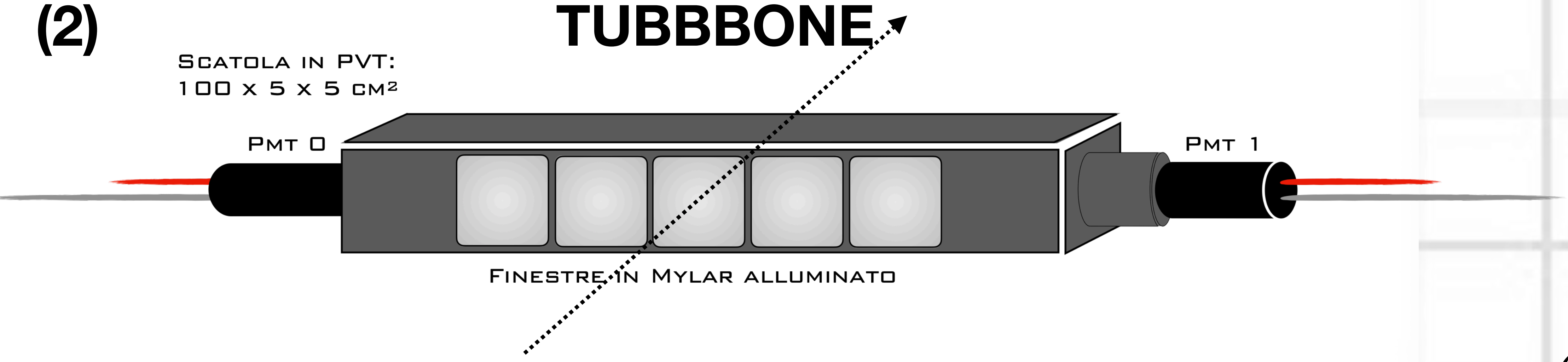
PERISCOPIO

PMT: H10580

(1):
- 0.04 ph x 10 cm x 0.1 x 10^10 (elet./pulse) ~ 4 10^8 ph
- ~ 8 10^7 ph.el

➡ **PMT troppo dentro l’alone del fascio**

(2) TUBBBONE



* riflessione on/off

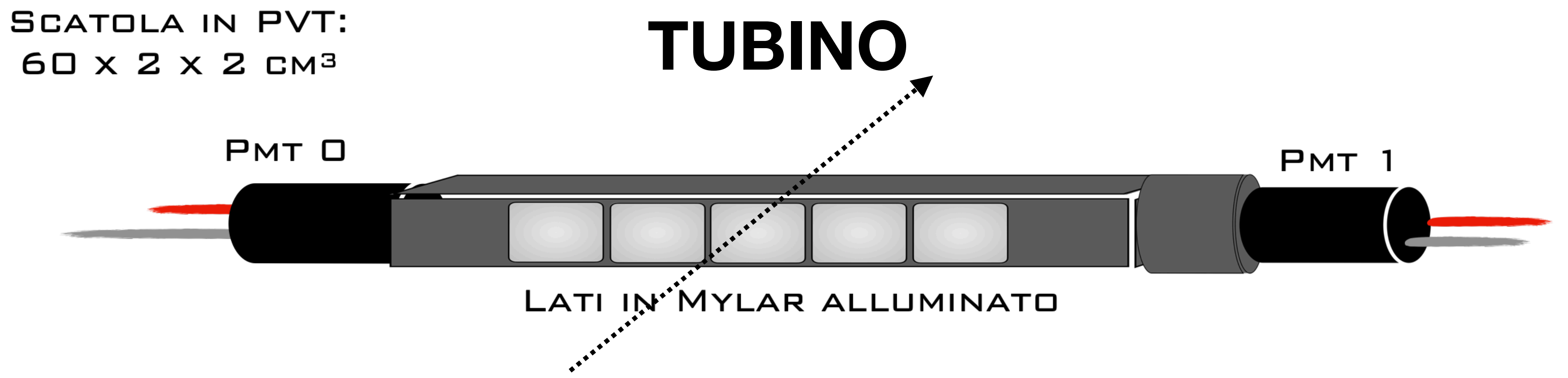
(2):
- 0.04 ph/cm x 5 cm x 0.005 (sottostima/sovrastima geometria*) x 10^10 (elet./pulse) ~ 1 10^7 ph
- ~ 2 10^6 ph.el

PMT: XP1911

➡ **L’applicatore produce troppo fondo che arriva ai PMT**

➡ **Senza applicatore siamo stati in grado di vedere l’IN/OUT beam**

(3) TUBINO



(3):
- 0.04 ph/cm x 2 cm x 0.003 x 10^12* (elet./pulse) ~ 2 10^8 ph
- ~ 5 10^7 ph.el

➡**Senza applicatore**

PMT: H6524

*FLASH machine in 100 times more intense

Tubino@SIT: 05.07.2021 (dal futuro con < 3)

- We plan to take the FLASH beam..
- The inside is not reflective. Less saturation effects, less geometry dependence.

Tubino@SIT: 05.07.2021 (dal futuro con < 3)

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- For the moment we just equalised the PMT response..
- “New”.. less noice and more stable
- Test with UV Filters..

Figure 2: Typical Gain Characteristics

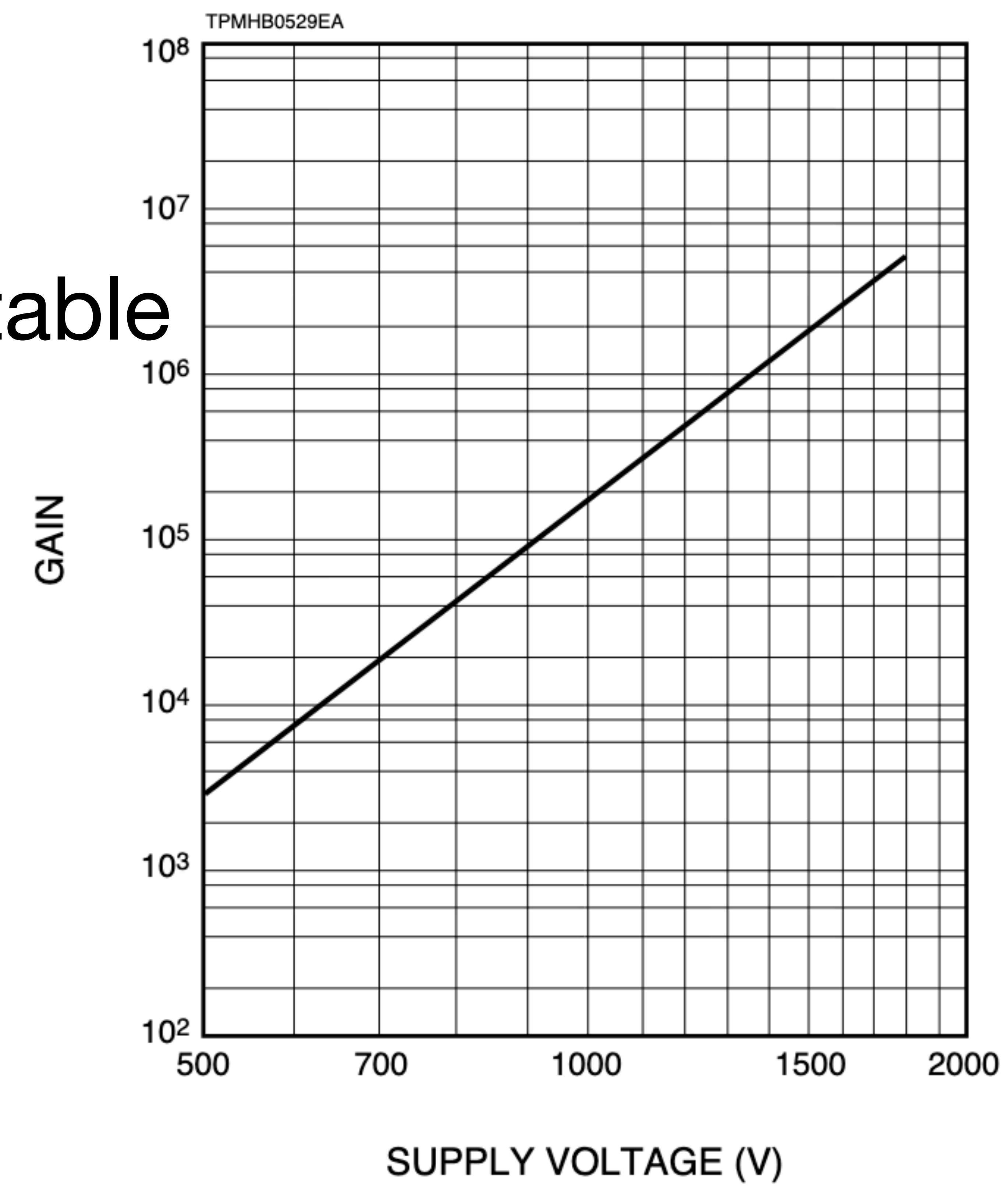
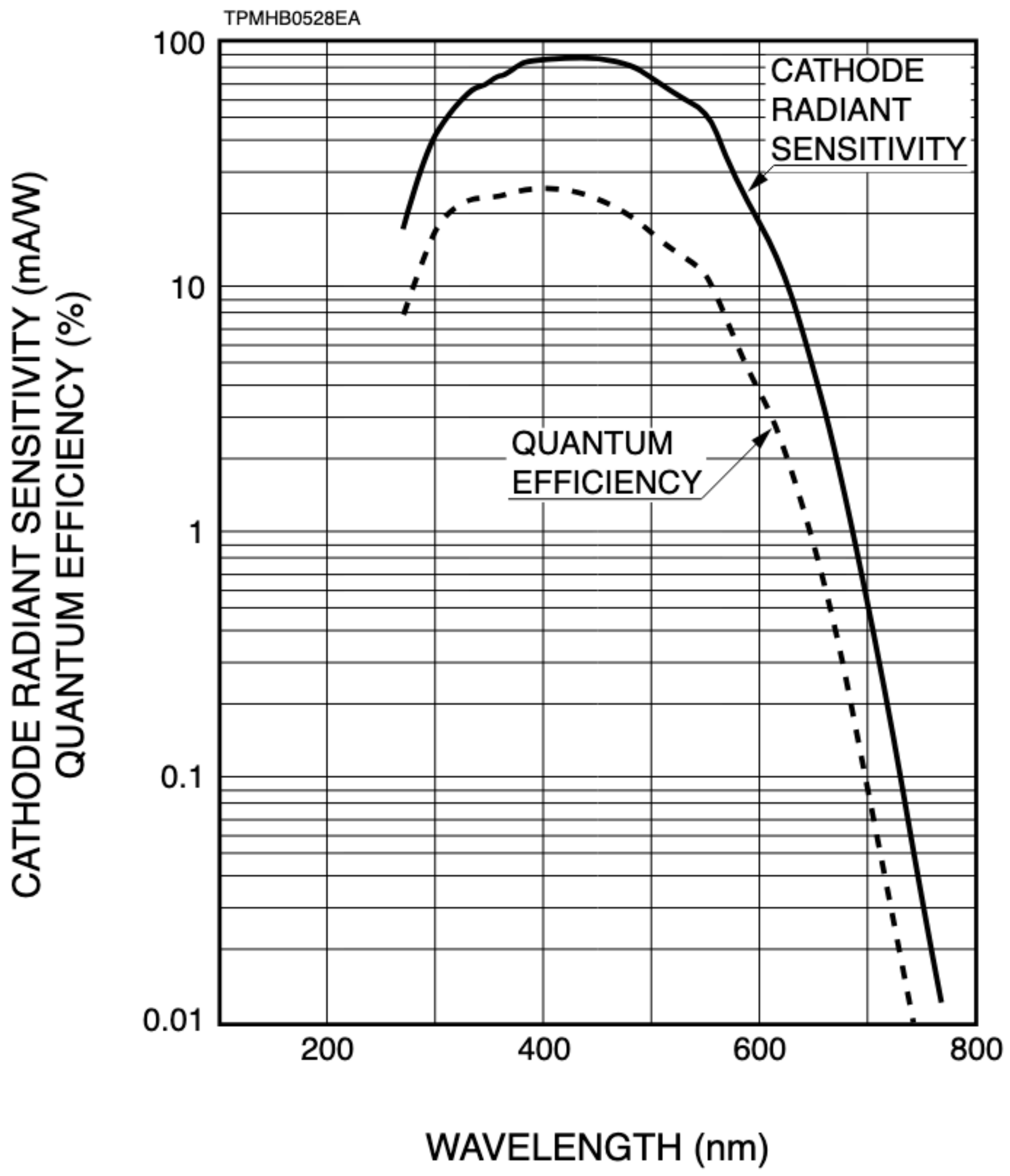


Figure 1: Typical Spectral Response



Tubino@SIT: 05.07.2021 (dal futuro con < 3)

- We plan to take the FLASH beam..
- The inside is not reflective. Less saturation effects, less geometry dependence.
- For the moment we just equalised the PMT response..
- “New”.. less noice and more stable
- Test with UV Filters..
- We plan to change the current of the beam and see if we can follow the

<u>Matteo Pacitti:</u>

A parità di lunghezza dell'impulso possiamo variare la corrente di fascio da 73 mA fino a 130 mA. Considerando un impulso rettangolare di durata 4 us, quindi approssimando leggermente, andiamo da 1.8 x 10^{12} elettroni a 2.9 x 10^{12} elettroni.

Future prospective..

- I definitely find very ‘romantic’ that an empty detector can produce light..
- It is certainly true that this light can be correlated with the electron beam (on/off, shift, …)
- We have to make the step further and go from a very ‘qualitative measure’ a a raw ‘quantitative measure’.. and than decide what to do..
- The new geometry should help.. but it is not the best choice ever..
    - => charge average study
    - => wavelength study
    - => geometry optimisation
- **<u>We still need to prove that we can correlate with the number of electrons.. !!</u>**