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Proton range determination at relevant energies for proton therapy by detecting secondary gamma radiation: a proof-of-concept

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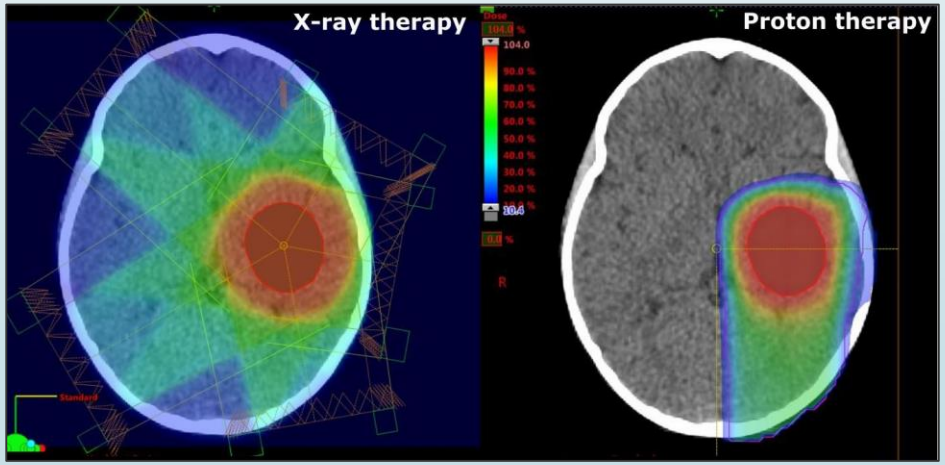
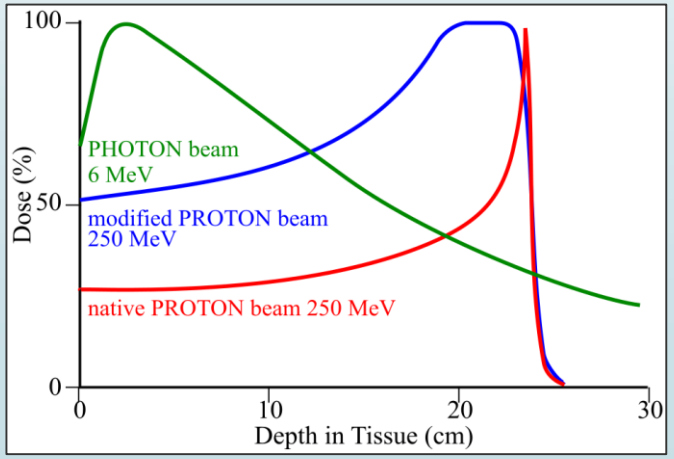
Introduction

- Proton therapy allows very located dose.
- Main problems:
  - **Planning:** X ray images ⟶ transformation from photon attenuation coefficients (HU) to proton relative stopping power is required.
  - **Treatment:** proton beam range verification (dose deposition) is needed.



M. Dell'Oro et al. *Cancers* 12(9), 2578 (2020)



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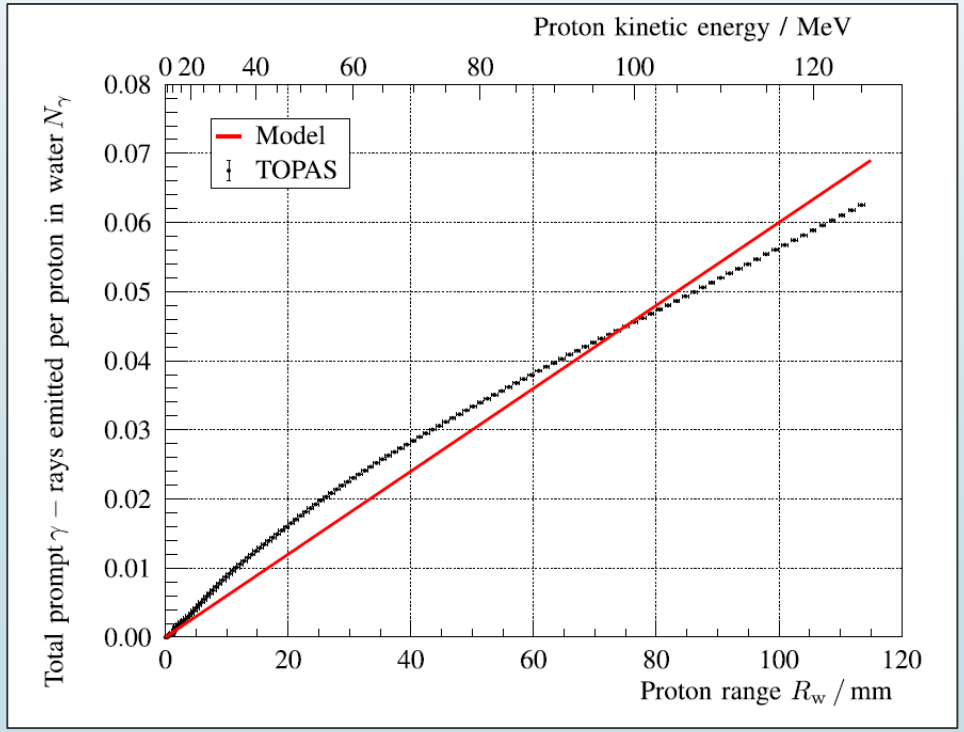
Motivation

- F. Hueso-González et al. (2020) suggests a **range verification method** based in the **measurement of secondary gamma radiation coaxially** respect to the proton beam.
- Model and simulation shows a **dependence between gamma radiation emitted and proton range**.
- **When the proton range is larger ⟶**
  - **higher production of gamma radiation**
  - **production is closer to the detector**



F. Hueso-González et al. *IEEE transactions on radiation and plasma medical sciences* 4 (2020), 170-183

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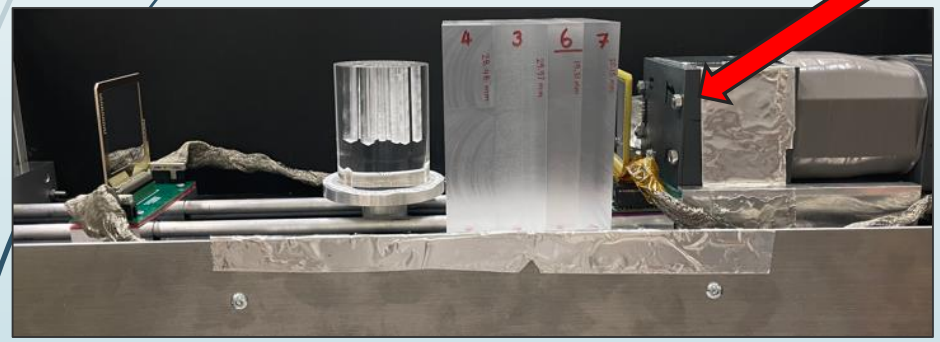
Experimental system

- ***Cyclotron Centre Bronowice*** **(CCB)** – Krakow, Poland
- IEM proton-scanner prototype: proton tomography and range verification.

CEPA4



Planning

Proton-CT scan

Treatment

Range verification

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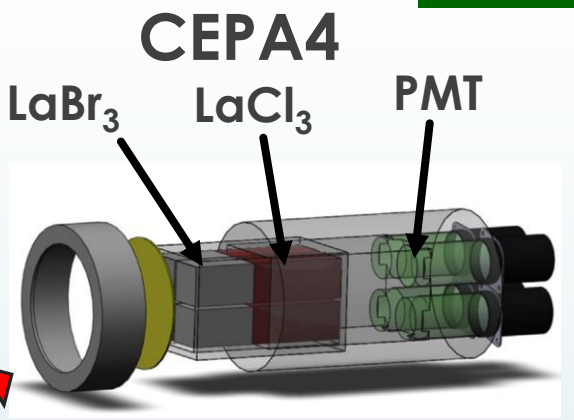
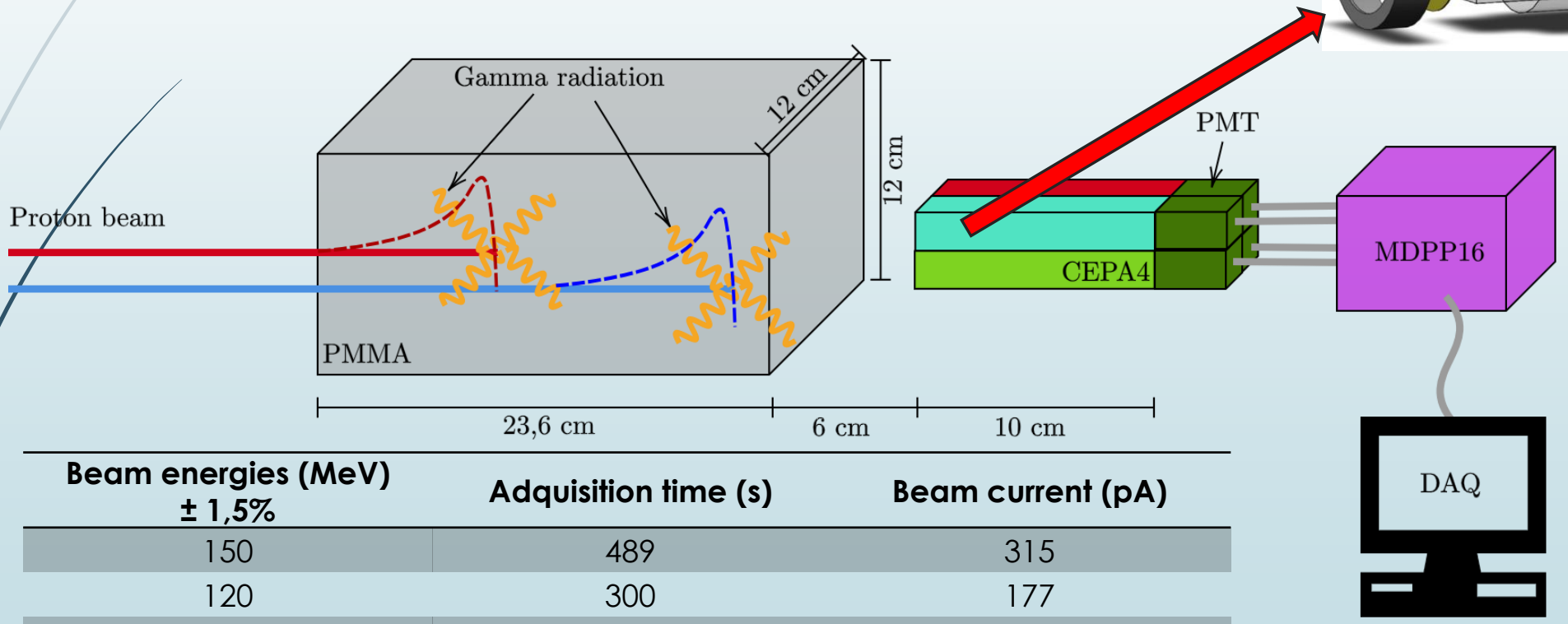
Experimental system

- **Set up is coaxial with proton beam**
- **CEPA4** = system of four phoswhich scintillators



E. Nácher et al.
NIM A 769
105-111 (2015)



Beam energies (MeV) ± 1,5%	Adquisition time (s)	Beam current (pA)
150	489	315
120	300	177
100	301	122
80	302	176

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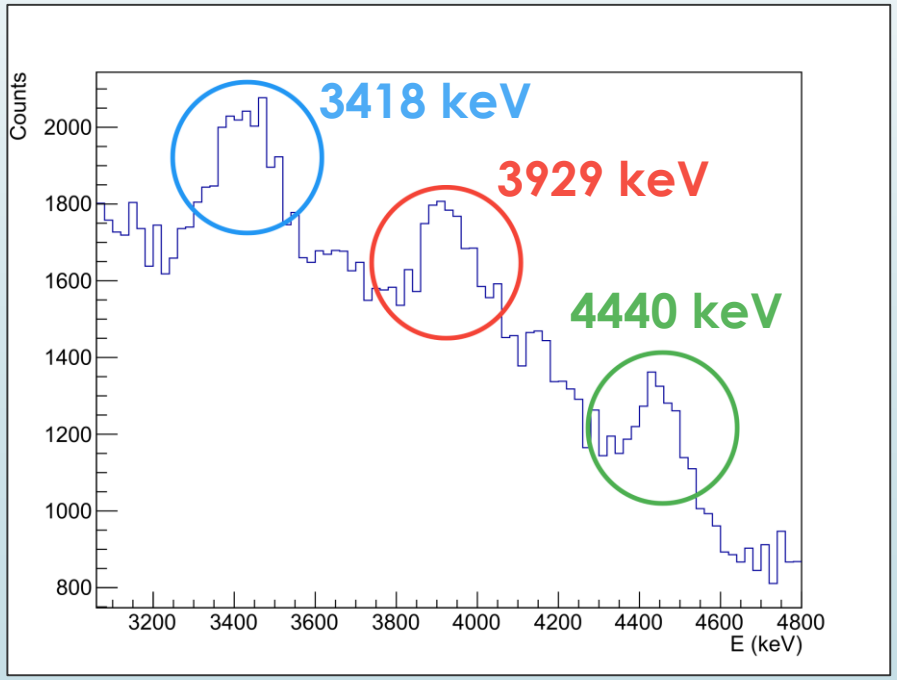
Experimental energy spectra: peak identification

- Range verification based in **gamma peaks identification:**
- **4440 keV** peak from $^{12}C(p,p')\ ^{12}C^*$ (*Full Energy Peak*) ⟶ **3929 keV** (*Single Escape Peak*) and **3418 keV** (*Double Escape Peak*)



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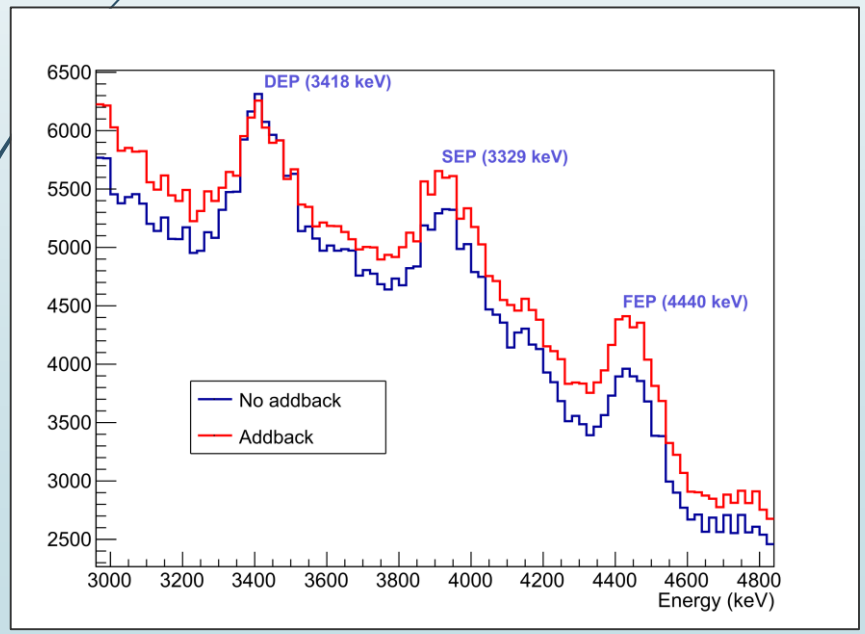
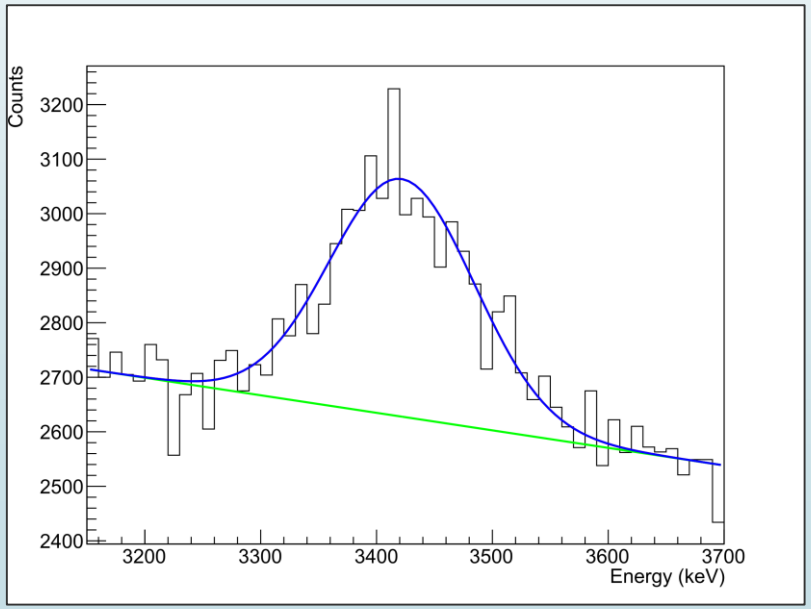
Analysis

- Analysis with total spectra added by **addback method**: for a same event, every energy fraction delivered in each crystal is added ⟶ better signal-to-noise ratio (higher peak-to-Compton)
- **Areas of gamma peaks** of interest are the **experimental measurement**: normalisation by adquisition time and beam current is needed ⟶ **normalised count rate**





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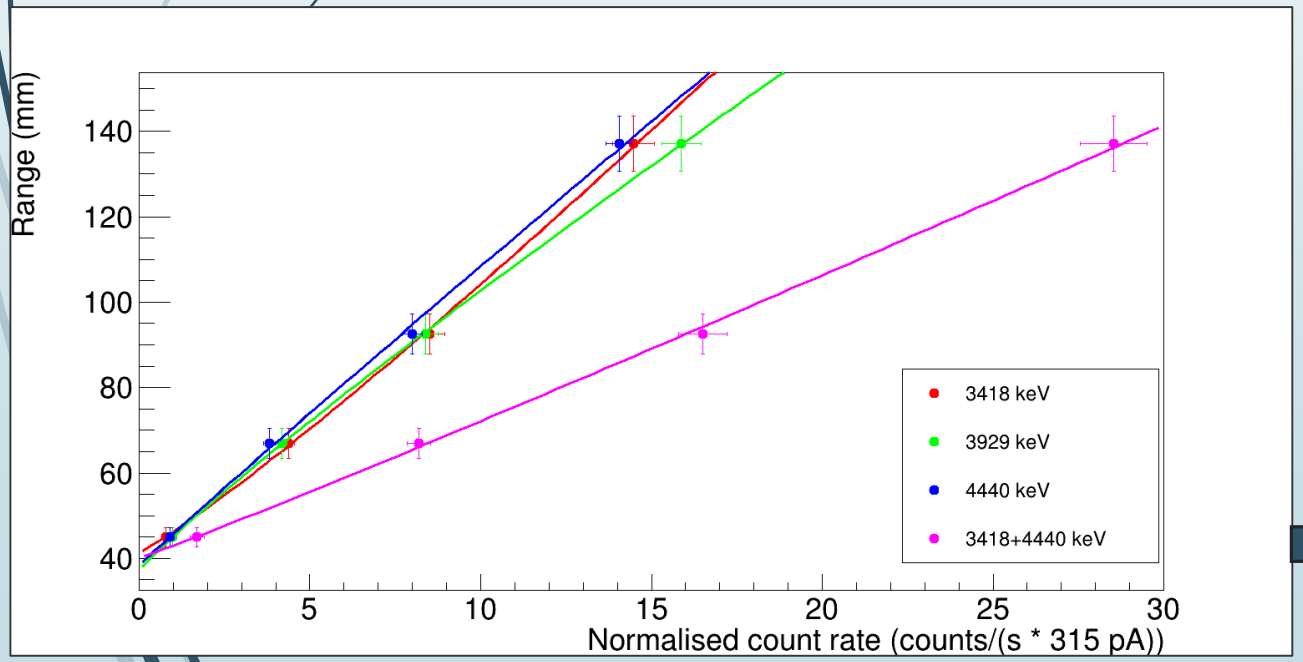
Results

- Range dependence on gamma radiation rate
  - **Proton beam range vs Normalised count rate plot**
  - **Power fit:** $R = c * A^b + n \longrightarrow$ exponent $b \sim 1$ **(linear)**
  - Possible **"contamination" of *SEP*** (3929 keV) at E_{beam} = **150 MeV** $\longrightarrow$ **^{14}N or ^{16}O**



Beam energies (MeV) ± 1,5%	Range* (mm)
150	45 ± 2
120	67 ± 3
100	93 ± 5
80	137 ± 7

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Transition	Fit exponent (b)
3418 keV	**1,13**
3929 keV	**0,9**
4440 keV	**0,96**
3418 + 4440 keV	**1,05**

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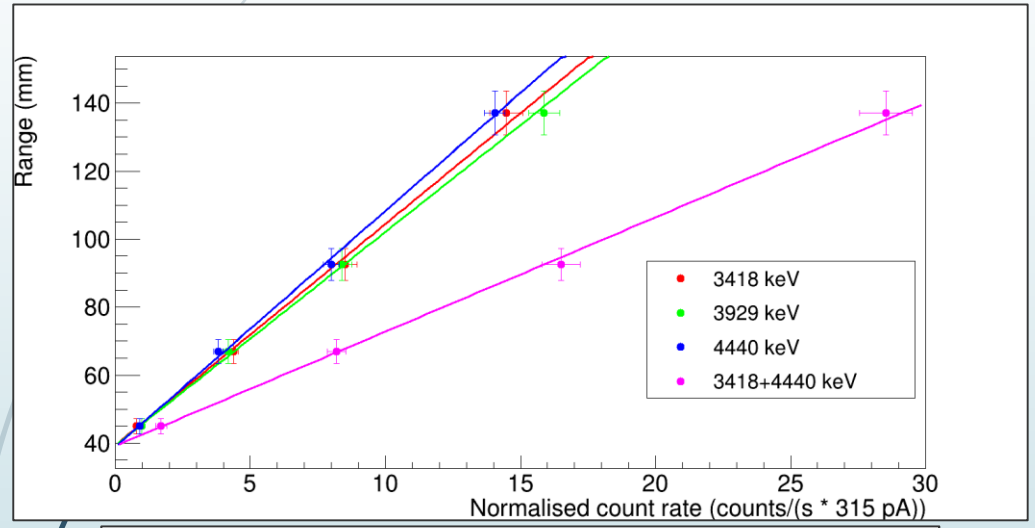
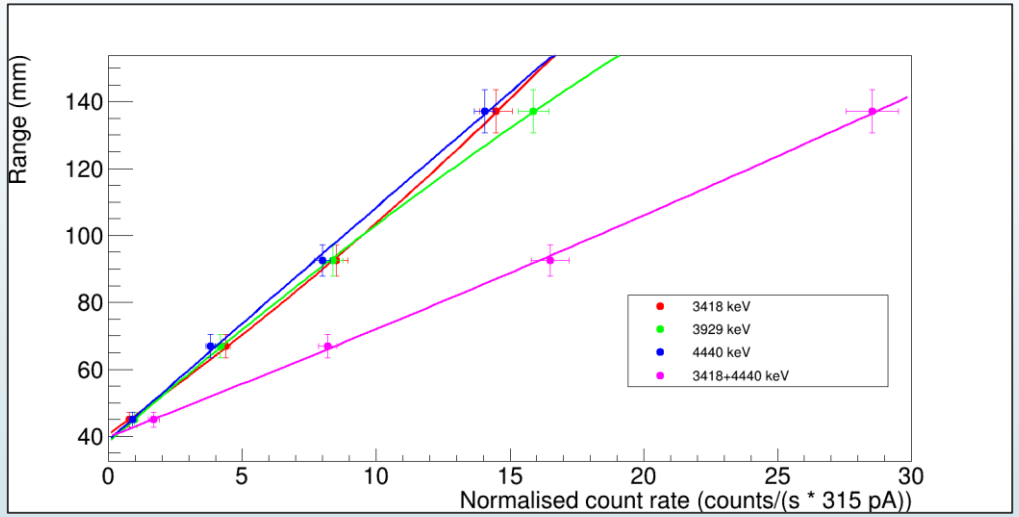
Results

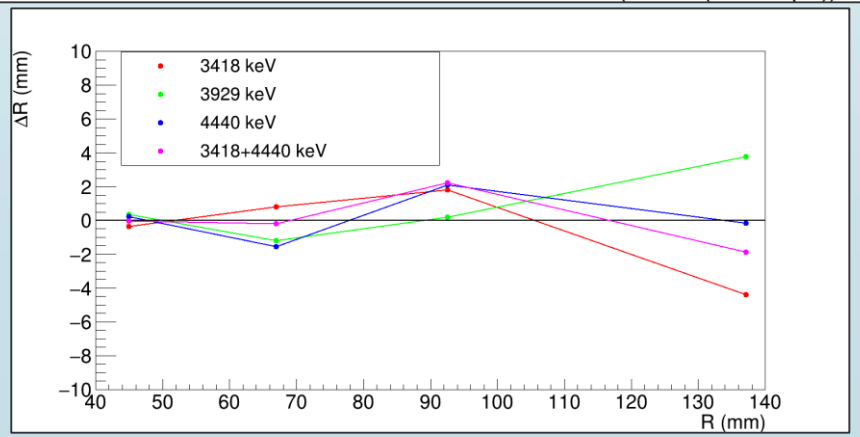
- Range dependence on gamma radiation rate

LINEAR FIT

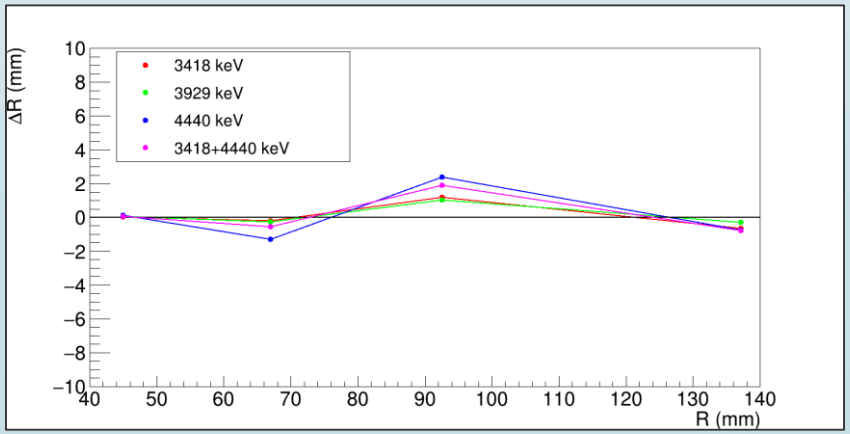


QUADRATIC FIT





Residuals



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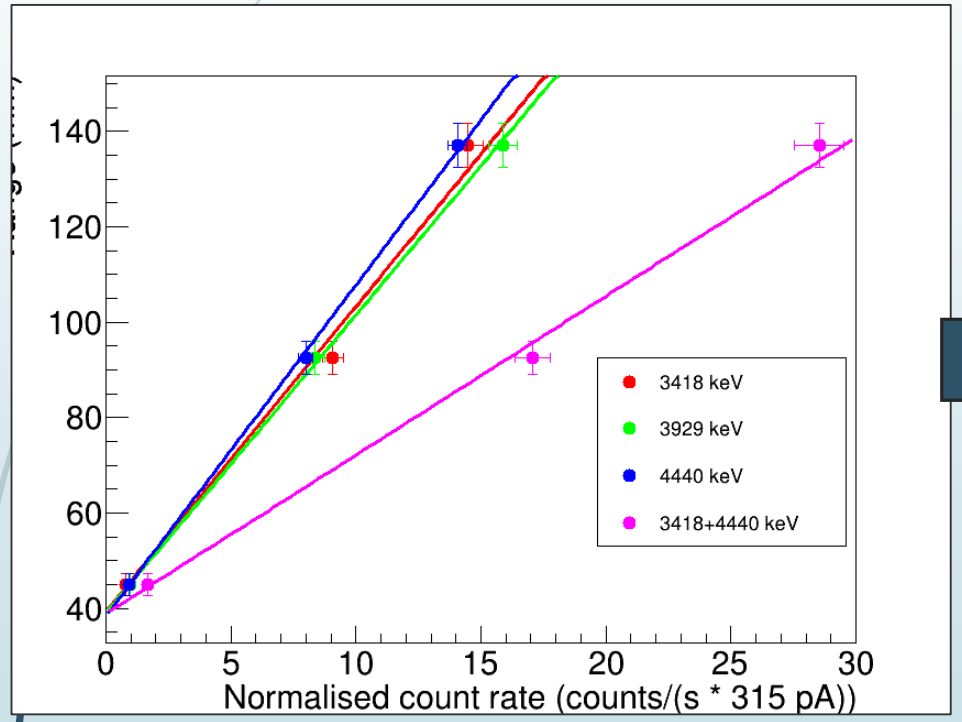
Results

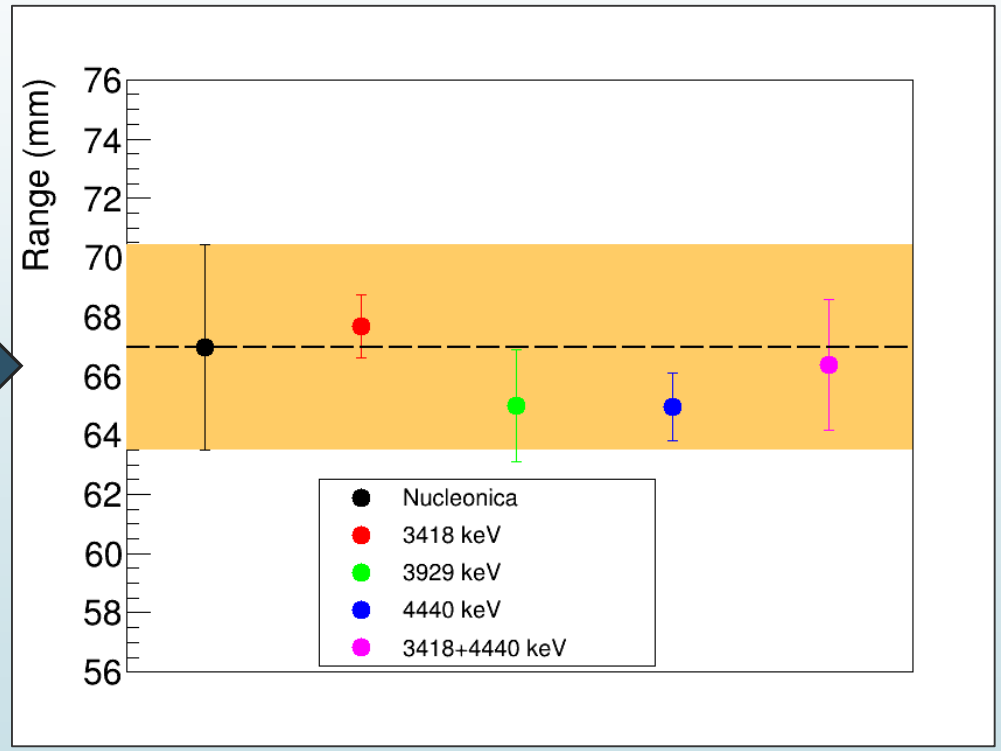
- Capability of range estimation

Example: **100 MeV (linear fit)**



Fit with only 3 of 4 beam energies

(80, 120 and 150 MeV)



Range estimation for E_{beam} = 100 MeV

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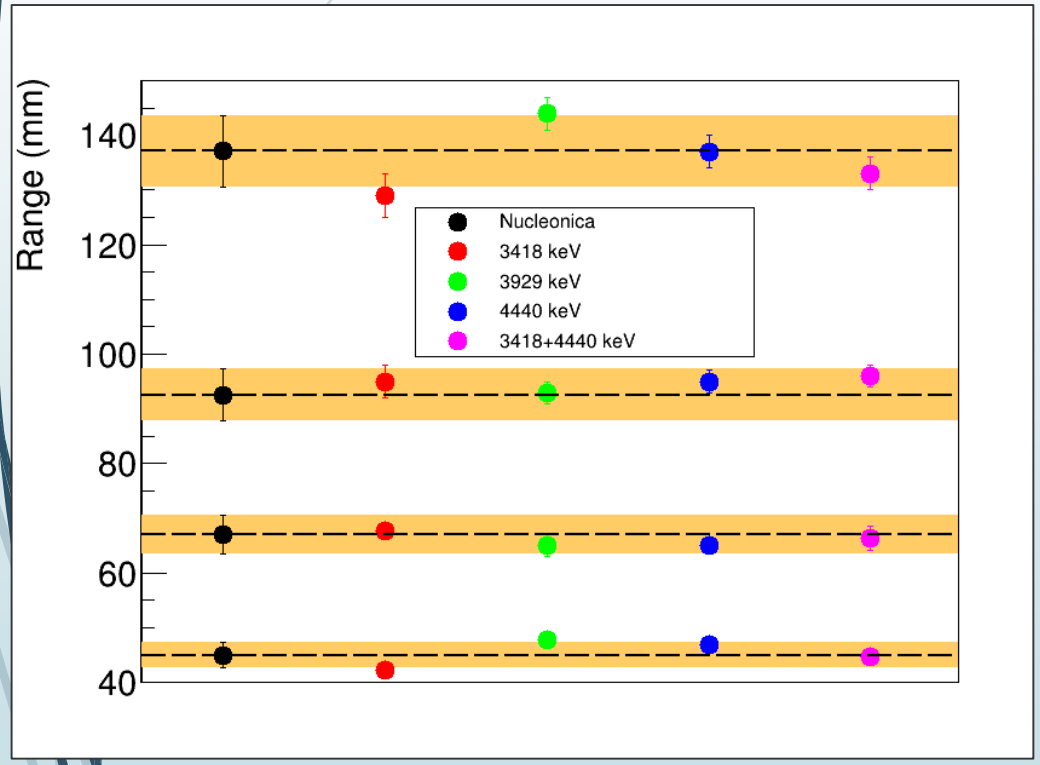
Results

- Capability of range estimation

LINEAR FIT



Beam energies

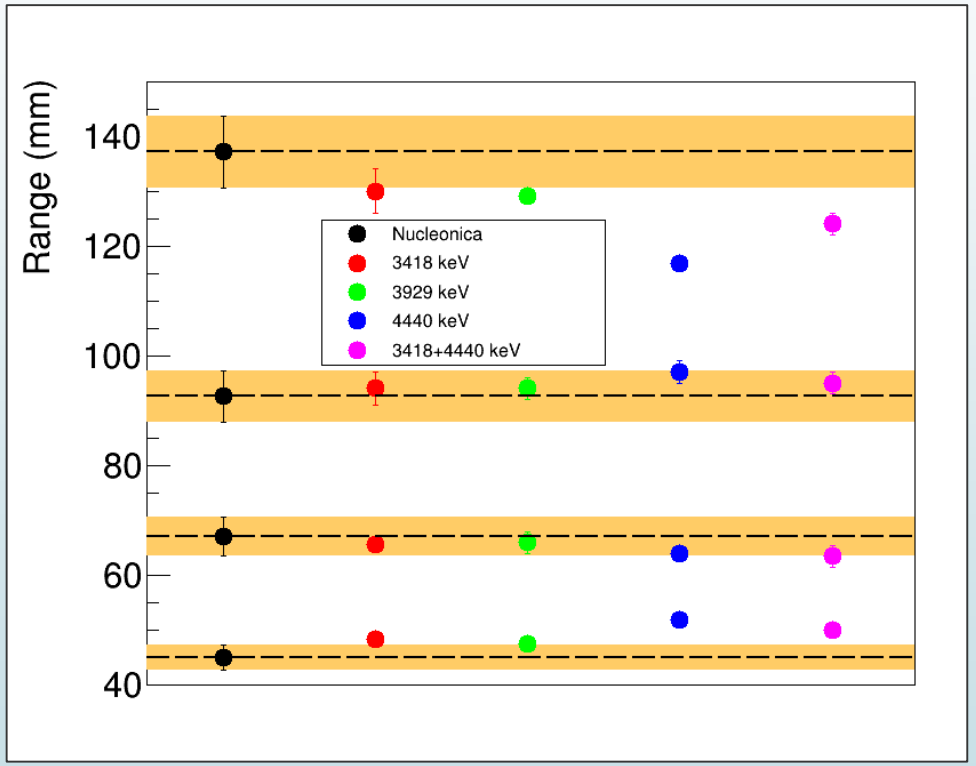
150 ± 2,25 MeV

120 ± 1,8 MeV

100 ± 1,5 MeV

80 ± 1,2 MeV

QUADRATIC FIT



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Results

- Capability of range estimation
  - **Linear fit** estimates proton range more accurately.
  - **4440 keV** peak curve has the **smallest deviation** from the tabulated range.
  - The **average** of the three curves corresponding to the peaks (3418, 3929 and 4440 keV) **improves the range estimation** (deviation **< 2 mm**)

Beam energies (MeV) ± 1,5%	Range* (mm)	Average		4440 keV	
		Estimated range (mm)	Deviation (mm)	Estimated range (mm)	Deviation (mm)
150	45 ± 2	46,0 ± 0,5	1,0	46,9 ± 0,6	1,9
120	67 ± 3	66,1 ± 0,7	-0,9	65,0 ± 1,1	-2,0
100	93 ± 5	94,3 ± 0,9	1,8	95 ± 2	2,9
80	137 ± 7	136,7 ± 1,1	-0,4	137 ± 3	-0,4
		Average relative deviation	1,50%		2,70%

*nucleonica.com

Conclusions and outlooks

- The developed **experimental setup** allows to **detect the variation of received gamma radiation intensity as a function of proton beam energy** and to **identify emissions from PMMA**.
- The **range verification method based** on F. Hueso-Gonzalez (2020) paper is **sensitive to proton beam range.**
- The **linear dependence** of the range on the normalised rate returns **estimations with a smaller deviation** than the quadratic dependence.
- The **average of estimations** of the three studied peaks (3418, 3929 and 4440 keV) **has a deviation < 2 mm.**
- This study demonstrates the **suitability** of the experimental system to the **proton range verification objective**.
- **New experiment in 2025**: higher energy range, longer acquisition time, new detectors and comparison of methods (protons, neutrons...).

Thanks for your attention

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