Range monitoring in proton and carbon therapy with the TIARA detector

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[2] *CPPM and Aix-Marseille University, Marseille, France*
[3] *Centre Antoine Lacassagne, Nice, France*
[4] *CNAO, Pavia, Italy*

June 18th 2025, GdR DI2I, Lyon, France

Context – Hadron therapy

Advantages of hadron therapy

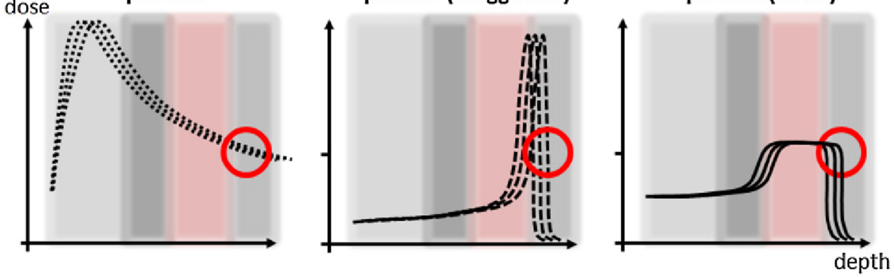
Characteristic *depth-dose deposition profile* (Bragg peak)

→ Less dose deposition in upstream healthy tissue compared to conventional X-ray therapy
→ High ballistic precision

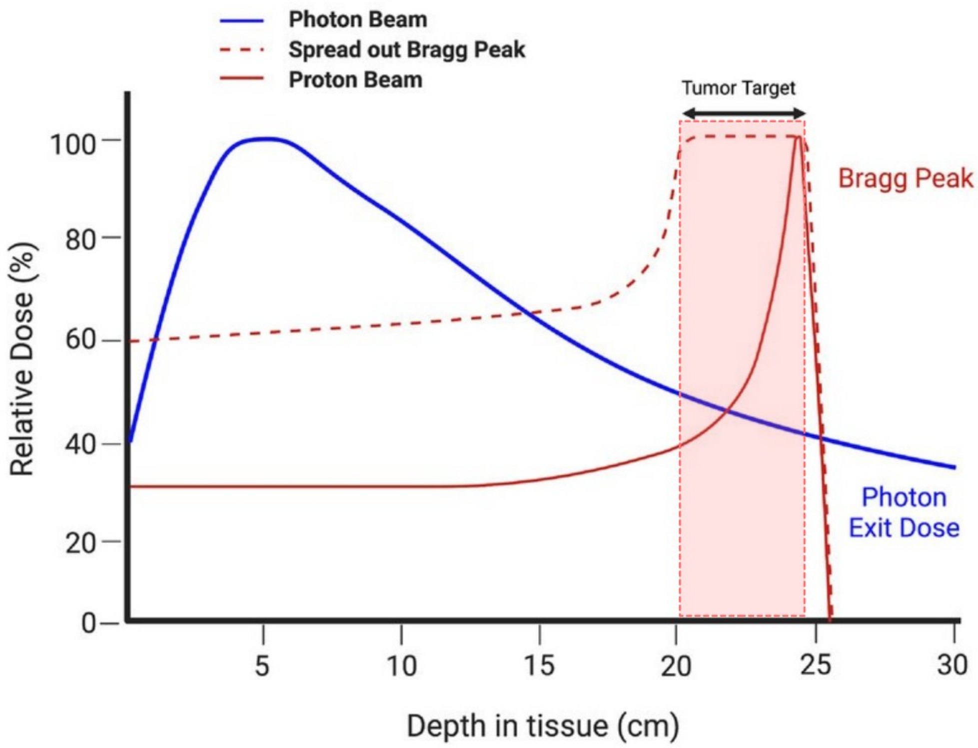
Current limitations

Uncertainties / anatomical changes in patient tissue composition

→ Increased safety margins hinder the potential of hadron therapy



Knopf, A. C., & Lomax, A. (2013). In vivo proton range verification : A review. Physics in Medicine & Biology, 58 (15), 131-160



Mohamed, Nader & Lee, Anna & Lee, Nahyun. (2021). Proton beam radiation therapy treatment for head and neck cancer. Precision Radiation Oncology. 6. 10.1002/pro6.1135.

Context – Prompt Gamma (PG) rays

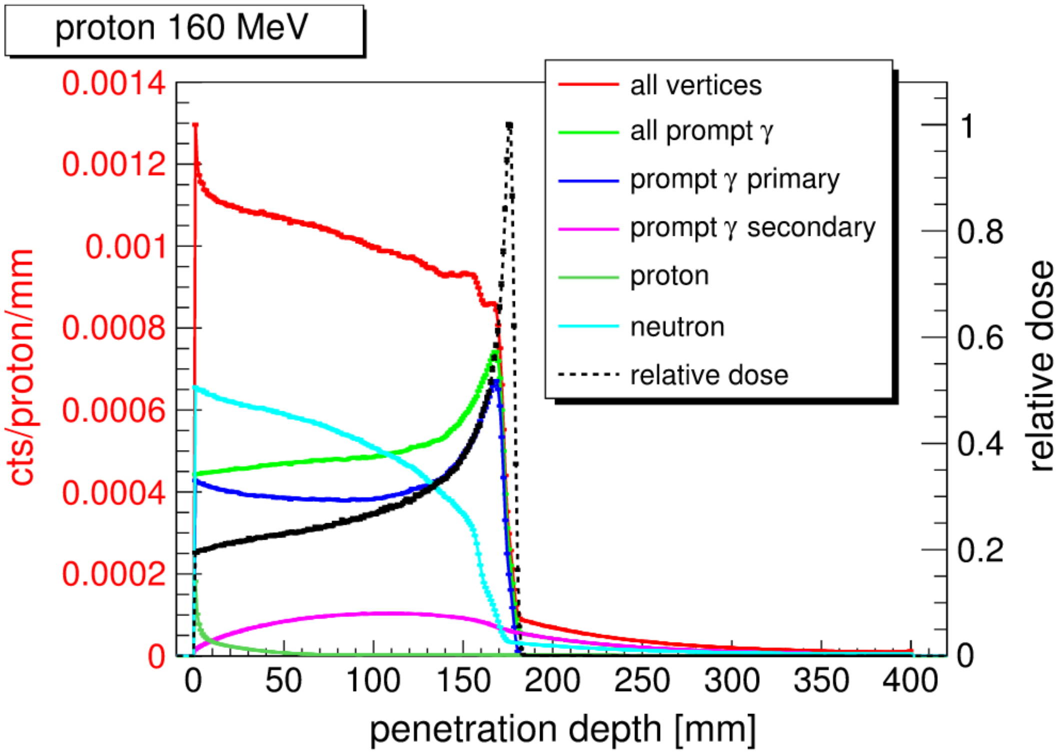
Range monitoring of hadron therapy by secondary particle detection

Prompt Gamma (PG) rays are good candidates

→ **Byproduct of nuclear reactions between the beam and the target nuclei**

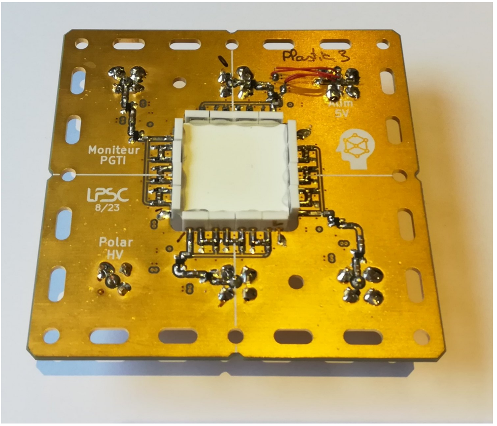
→ **Emitted within 1 ps**

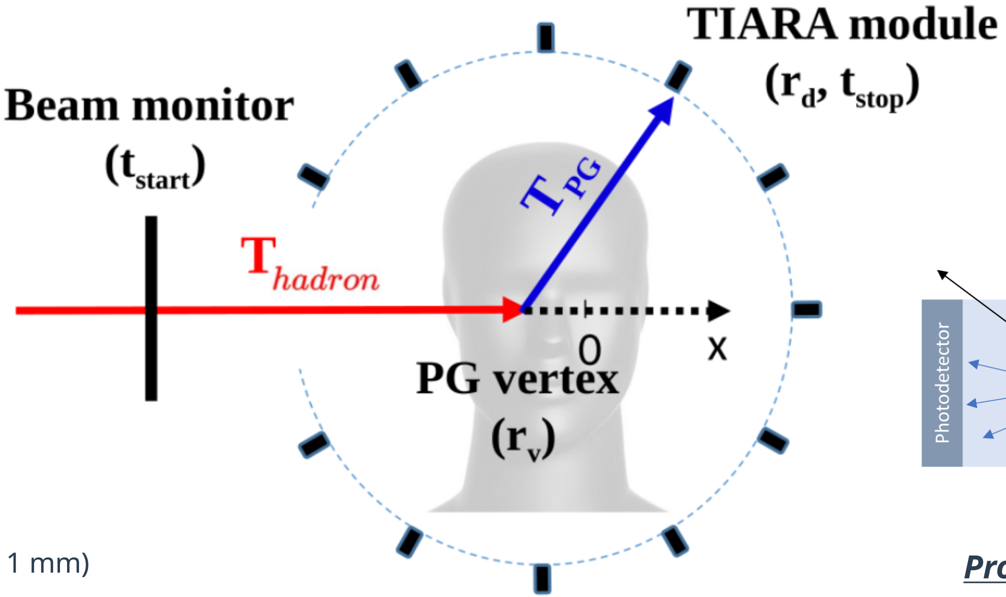
→ **Prompt Gamma emission probability strongly correlated to dose**

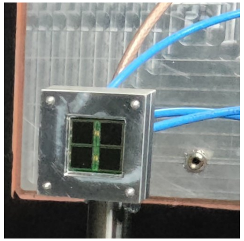


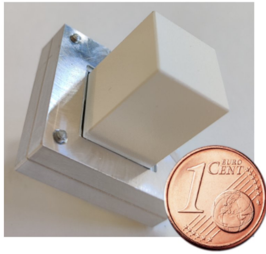
J. Krimmer et al. Prompt-gamma monitoring in hadrontherapy: A review. Nucl. Instrum. Methods Phys. Res. A, 2018, 878, pp.58-73. 10.1016/j.nima.2017.07.063

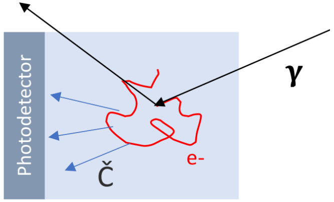
Context – Time Imaging ARrAy (TIARA)

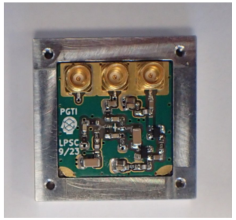












Beam monitor

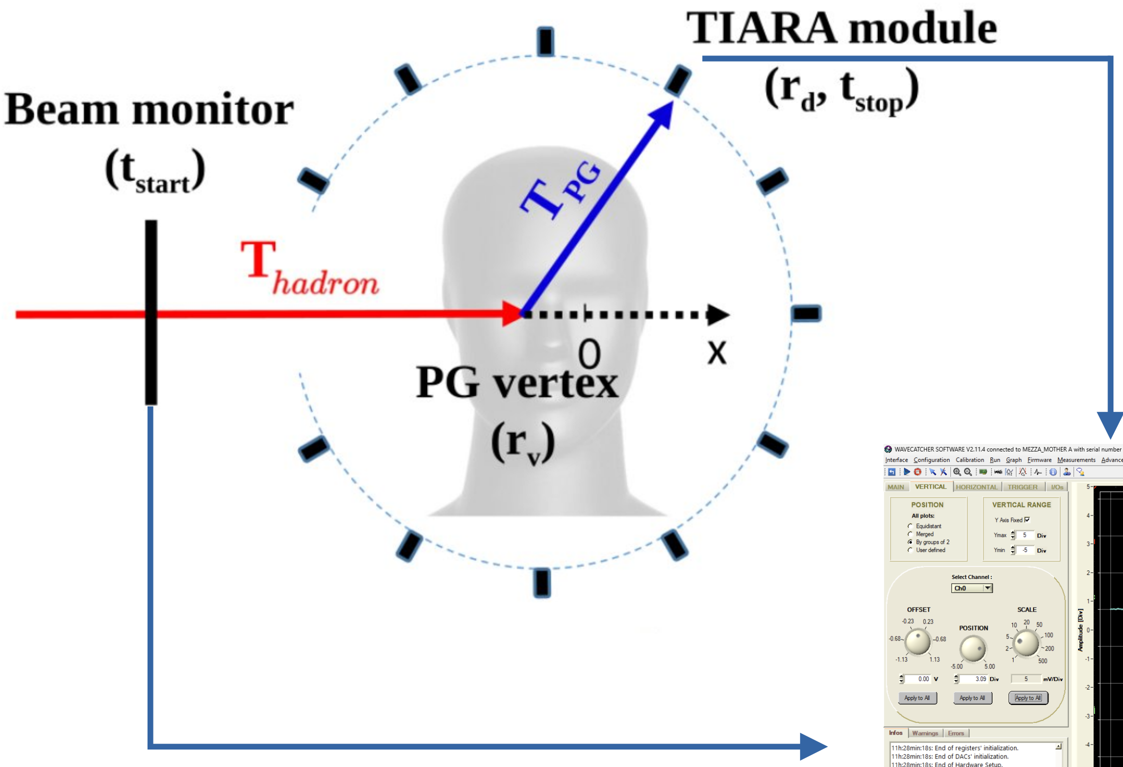
Fast EJ-204 **plastic scintillator** (25 x 25 x 1 mm)
4 SiPMs per side read out in parallel
Front-end amplifier
DTR = 51 ps σ for 63 MeV proton

$$TOF = T_{hadron}(r_v, v) + \frac{1}{c}||r_d - r_v||$$

Prompt gamma (PG) modules

1.5 x 1.5 x 2 cm^3 **PbF_2 Cerenkov crystal**
2 x 2 SiPM array read out in parallel
Front-end amplifier
DTR = 85 ps σ

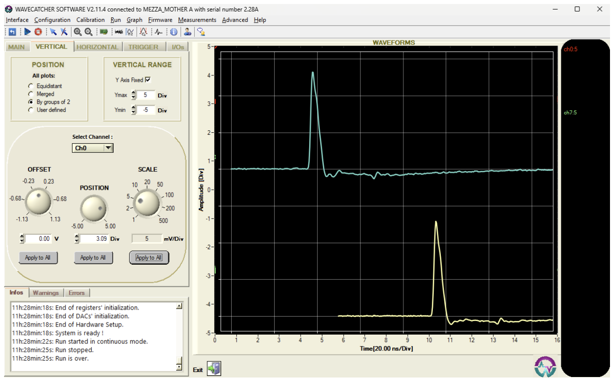
Context – Time Imaging ARrAy (TIARA)



Data acquisition system

Wavecatcher / *SAMPIC* TDCs developed by IJCLab Orsay, France

Work in progress : In house digital TDC on FPGA board at LPSC, Grenoble, France



Detection of anatomical variations with the TIARA system for proton beams

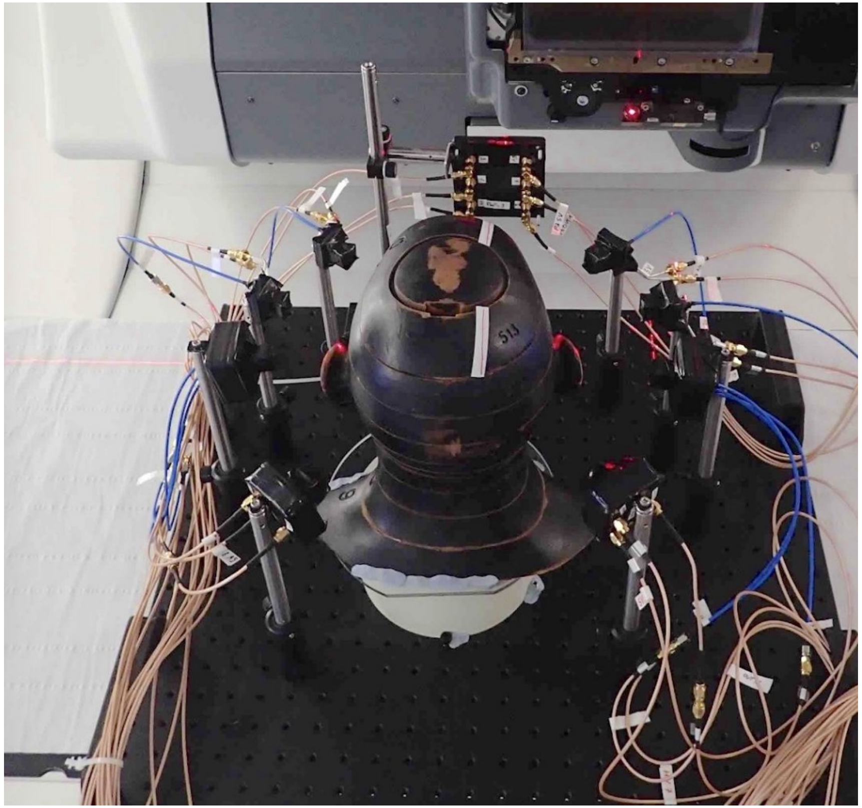
PGTI
PROMPT GAMMA TIME IMAGING

<u>March 2024 campaign at the Proteus One at CAL (Centre Antoine Lacassagne), Nice, France</u>

First test of an **8 PG module prototype**

Irradiation of a RANDO head phantom with 100 MeV protons at **Single Proton Regime (SPR, 10^7 protons/s)**

→ Full sinus (ultrasound gel)
→ Empty sinus



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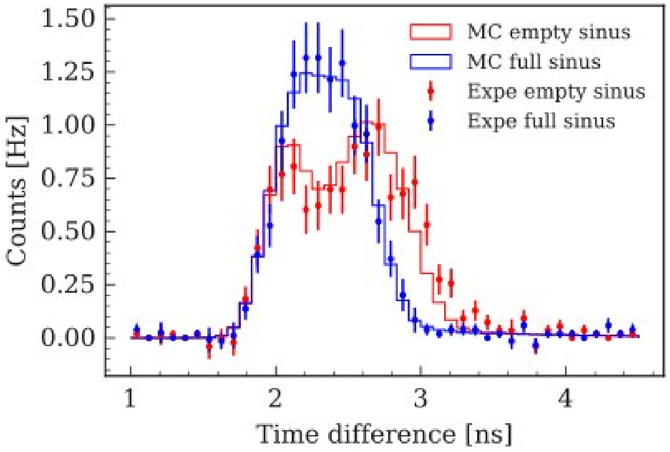

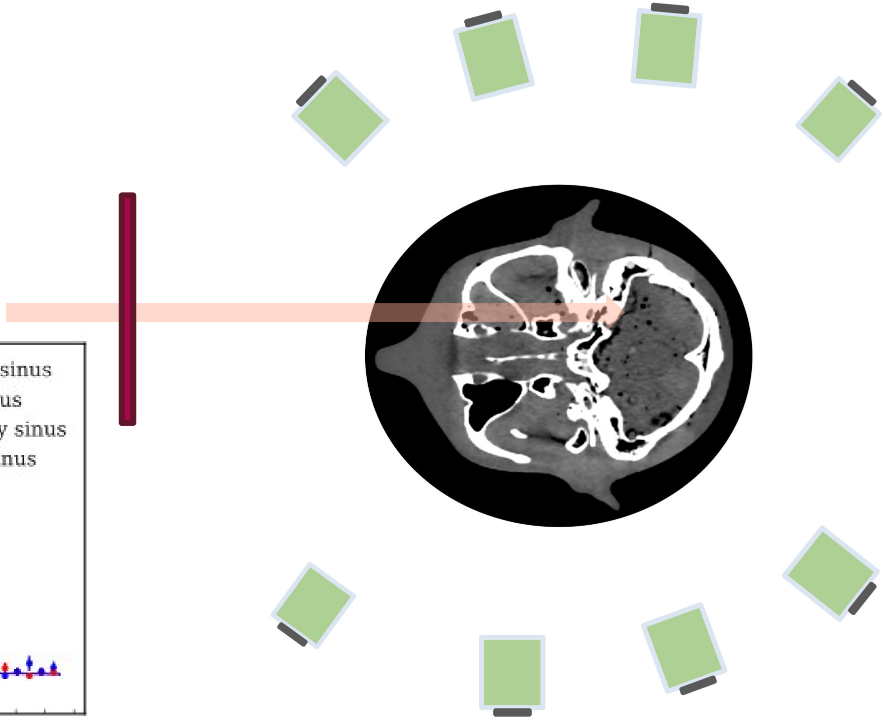

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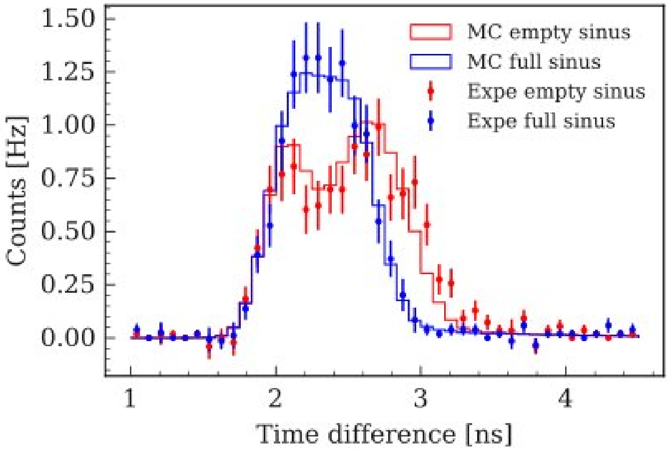

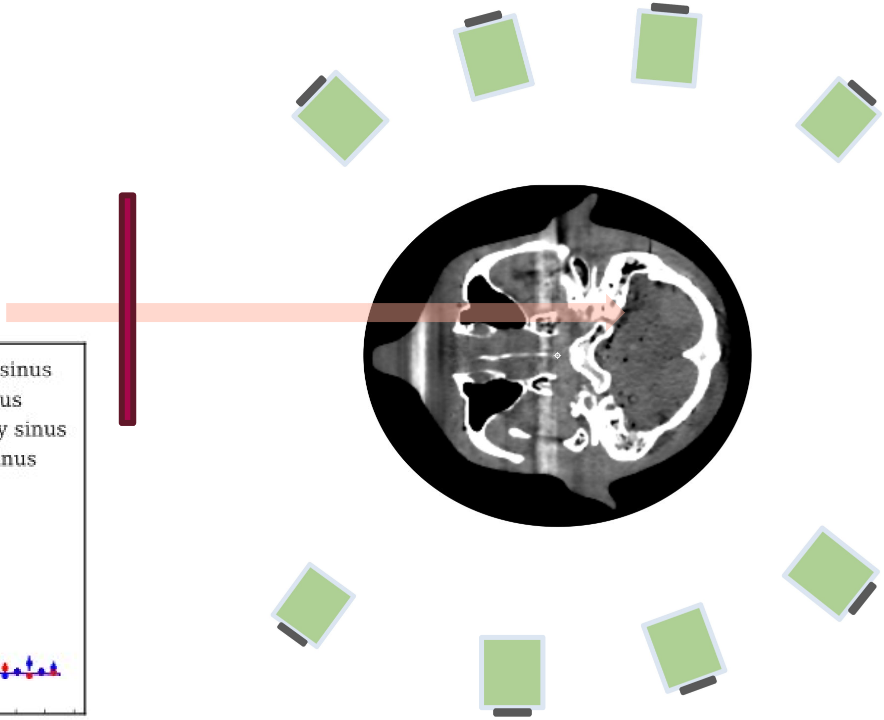

The TIARA system with carbon ion beams at CNAO, Pavia, Italy

Challenges linked to carbon ions

Fragmentation tail of secondary particles (mostly protons)
→ **Source of background for the TIARA system**

Higher LET than protons
→ **Requires modifications of the beam monitor**

Time structure of CNAO synchrotron
→ **Data analysis not quite as simple**

CNAO (National Center for Oncological Hadrontherapy) synchrotron in Pavia, Italy

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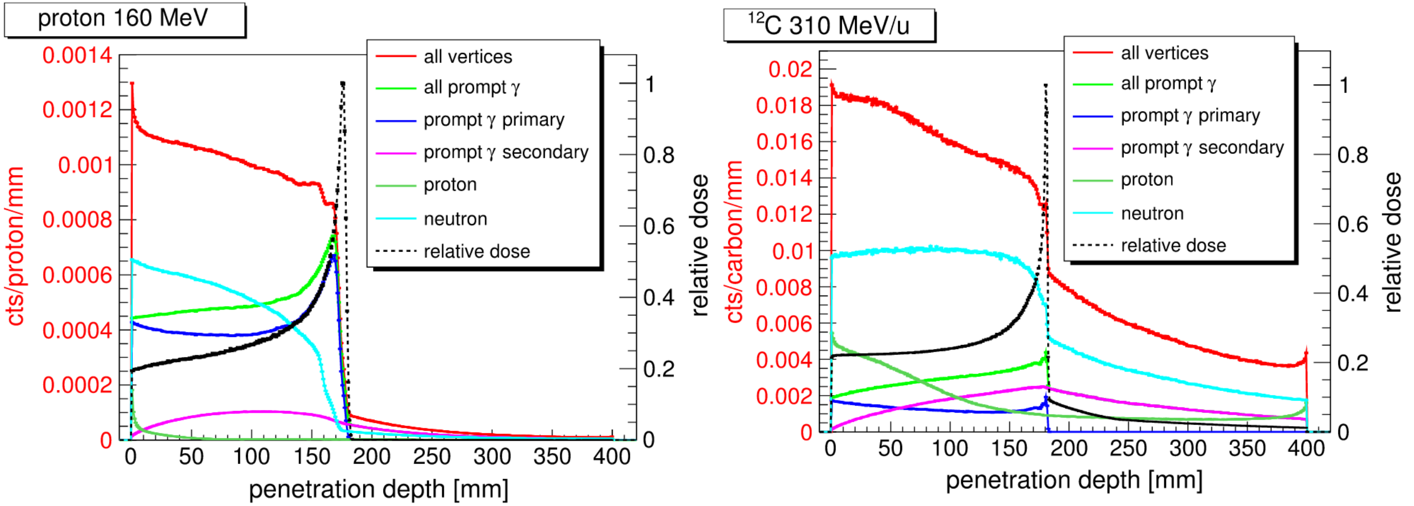

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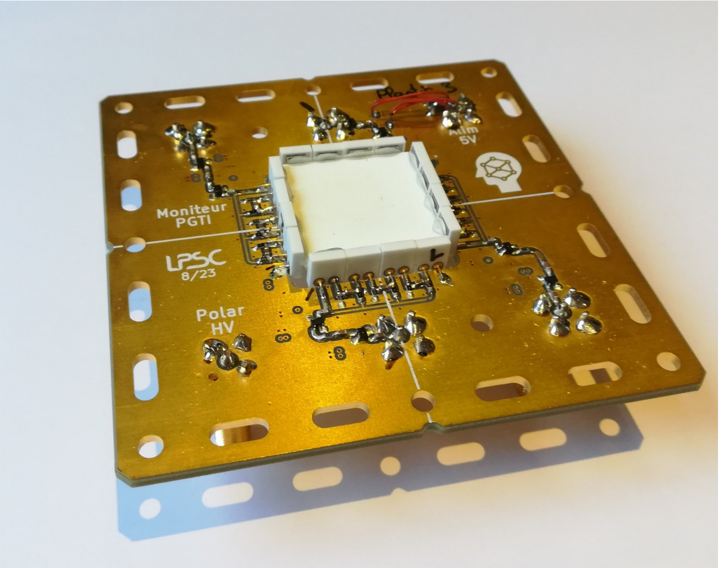
<u>Higher LET than protons</u>
<u>→ Requires modifications of the beam monitor</u>

- ***Reduced amplifier gain***
- ***Reduced thickness of plastic scintillator (1 mm → 0.5 mm)***

Time structure of CNAO synchrotron
→ **Data analysis not quite as simple**



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PROMPT GAMMA TIME IMAGING

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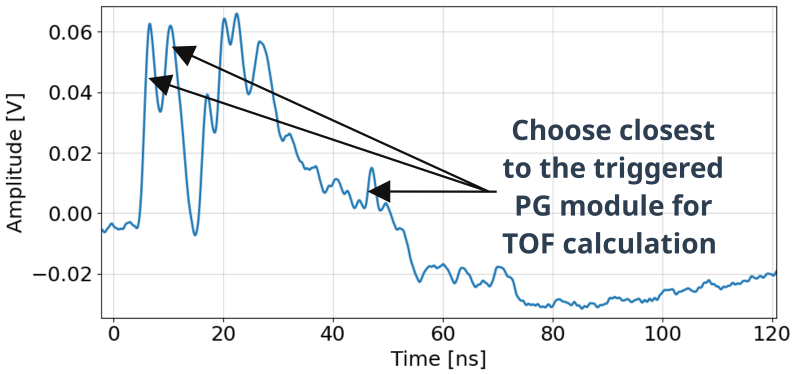
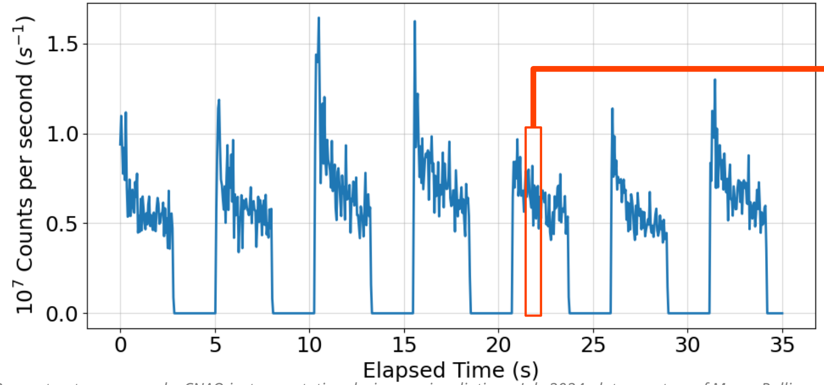
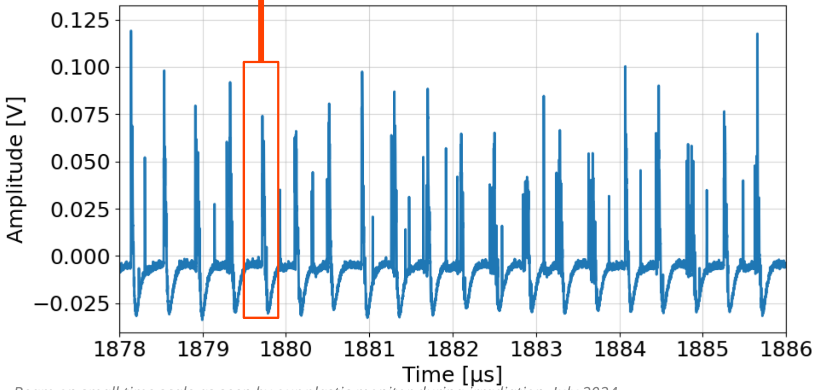




Beam structure as seen by CNAO instrumentation during our irradiations, July 2024, data courtesy of Marco Pullia



Beam on small time scale as seen by our plastic monitor during irradiation, July 2024

The TIATA system with carbon ion beams at CNAO, Pavia, Italy

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PROMPT GAMMA TIME IMAGING

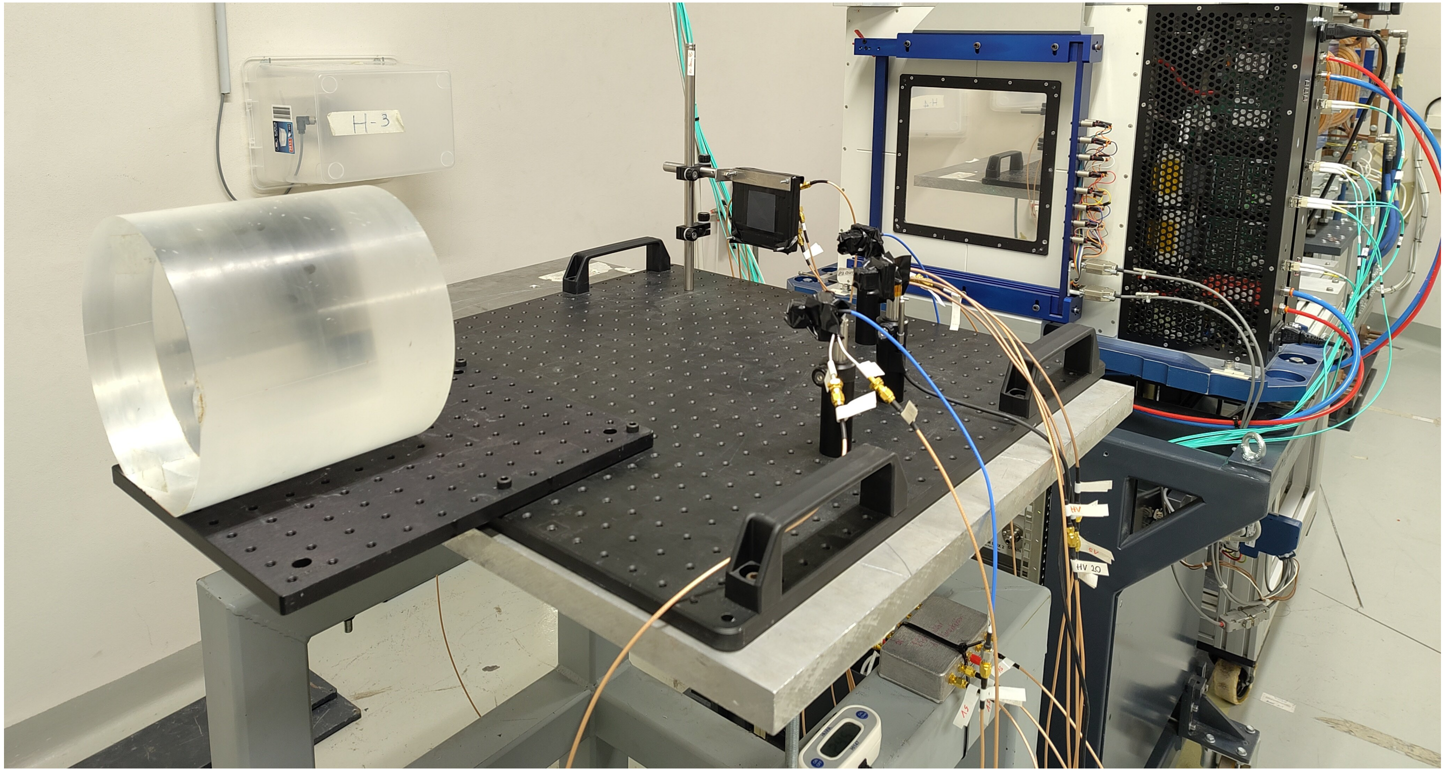
Carbon ion measurements

Thick PMMA target (~ 30 cm)

Energies used :

189.66 MeV/u
195.18 MeV/u
200.61 MeV/u
205.95 MeV/u
211.19 MeV/u

~ 3.5 mm shifts in PMMA in between energies



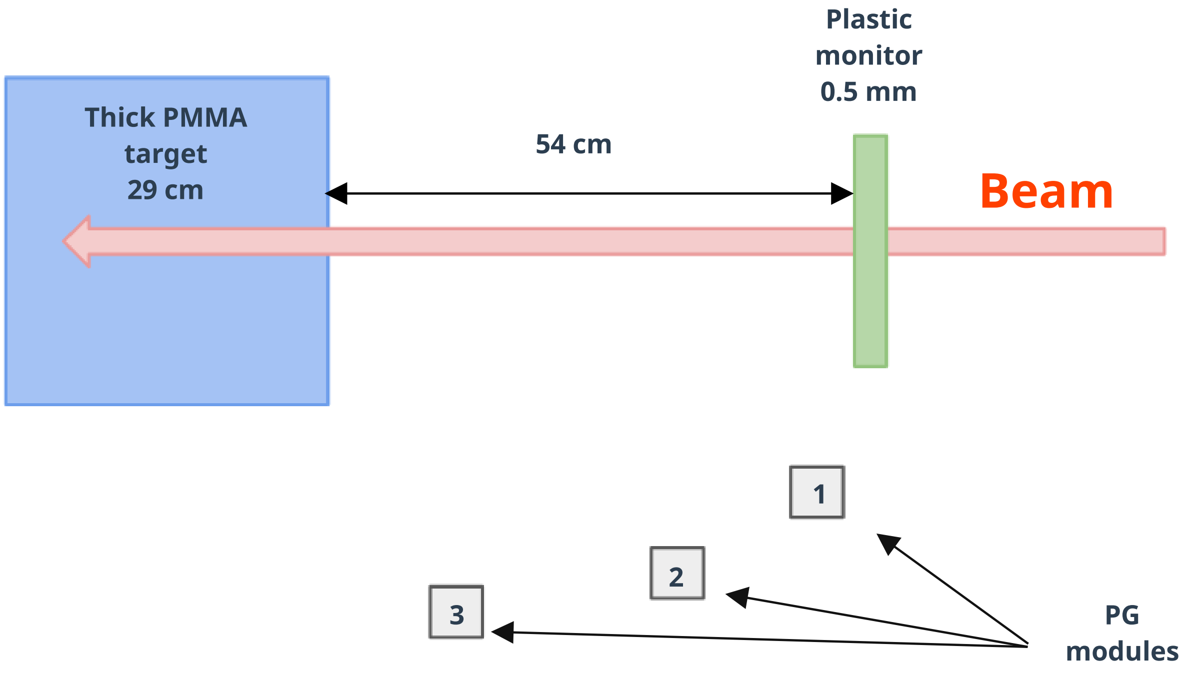
The TIARA system with carbon ion beams at CNAO, Pavia, Italy

Carbon ion measurements

→ TOF histogram analysis + background

→ Small energy shifts to quantify sensitivity

→ Bootstrap technique



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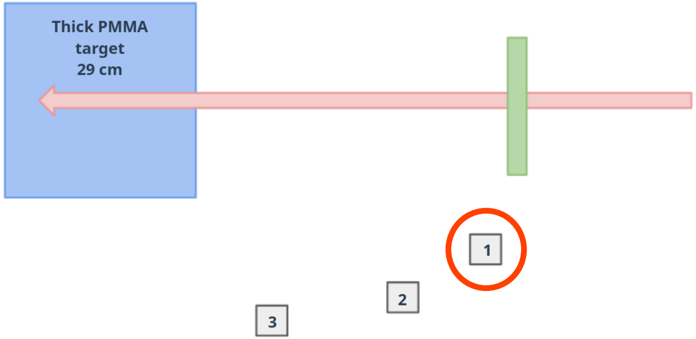
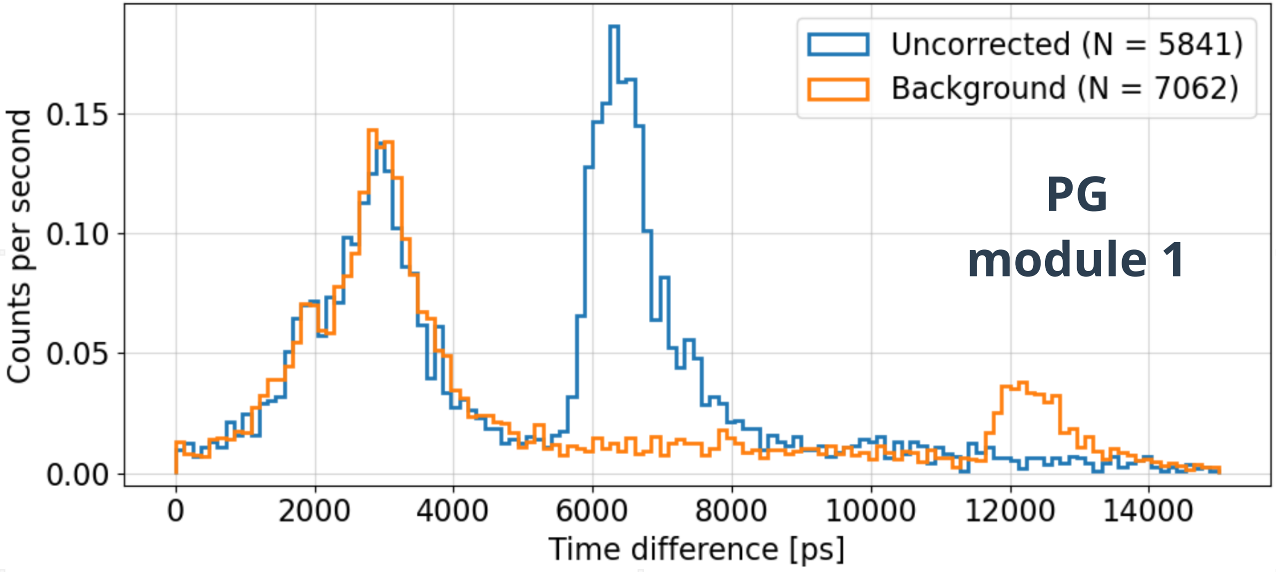


200.61 MeV/u

~ *2 10^6 carbons/s*



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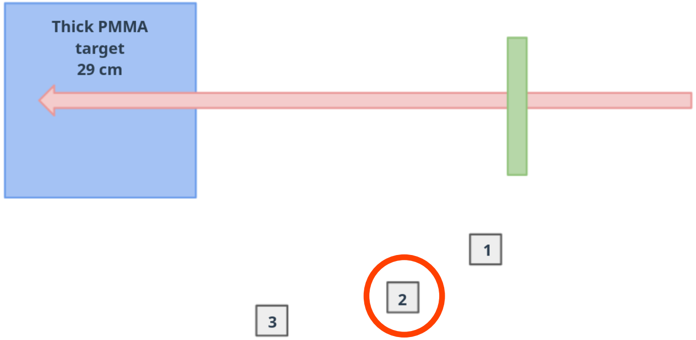

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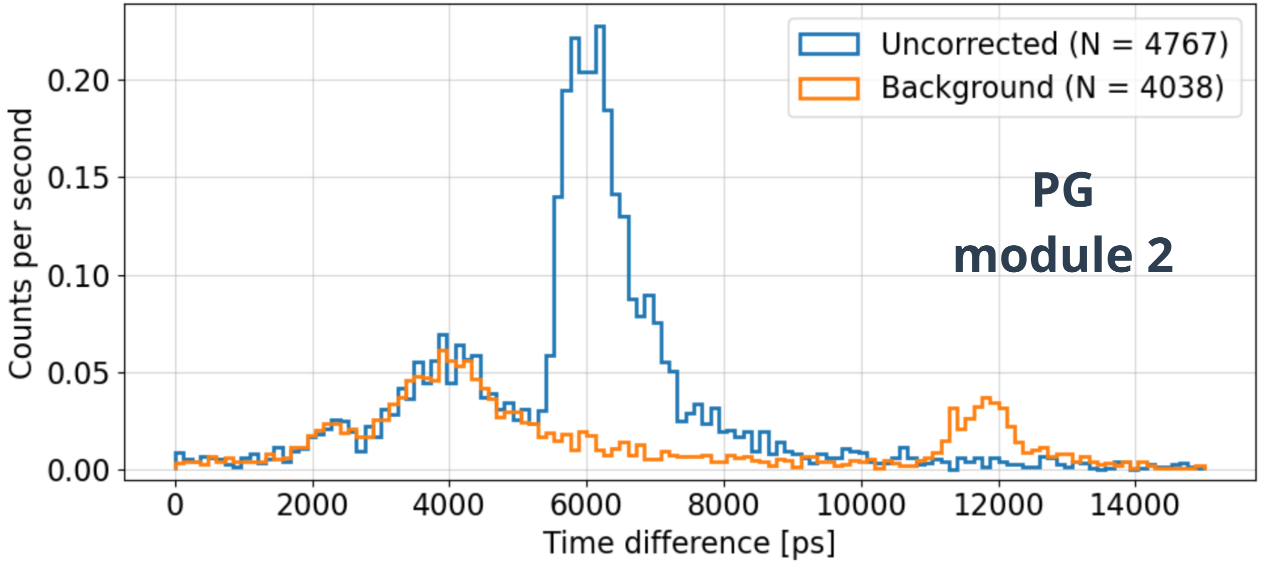

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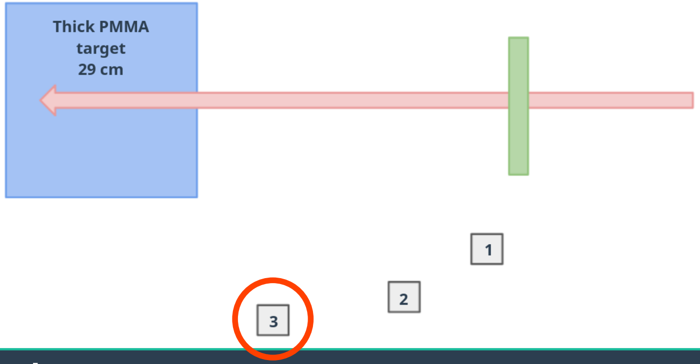

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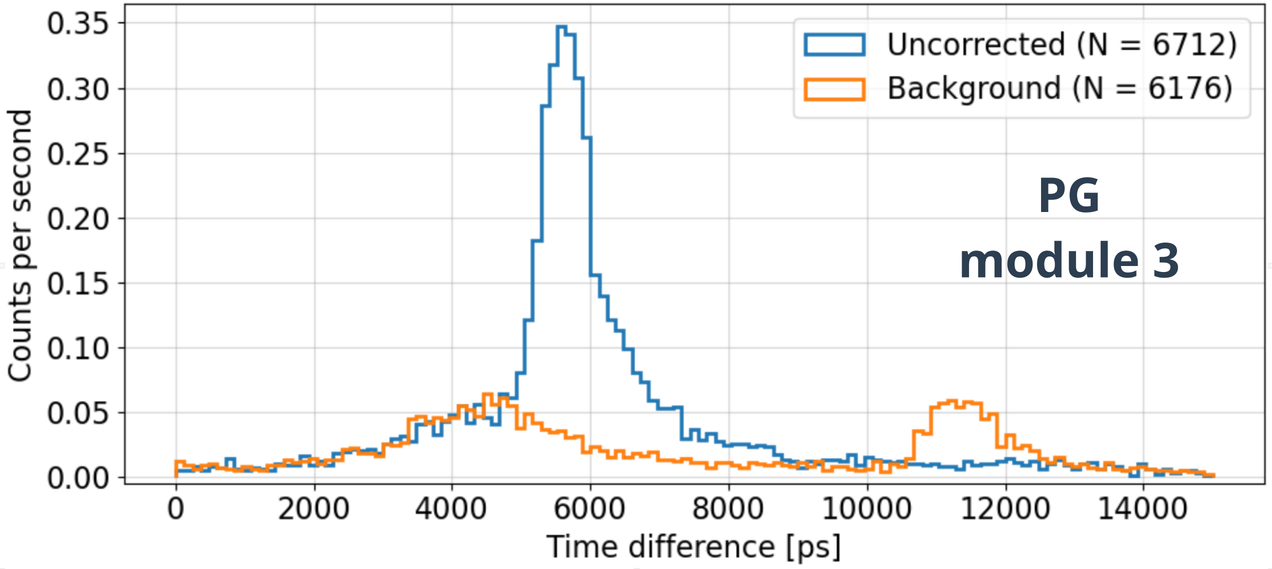

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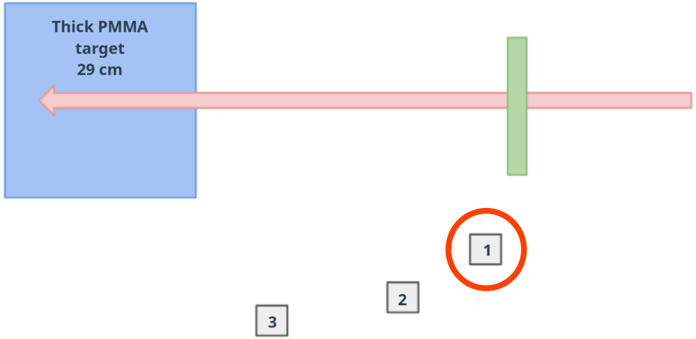

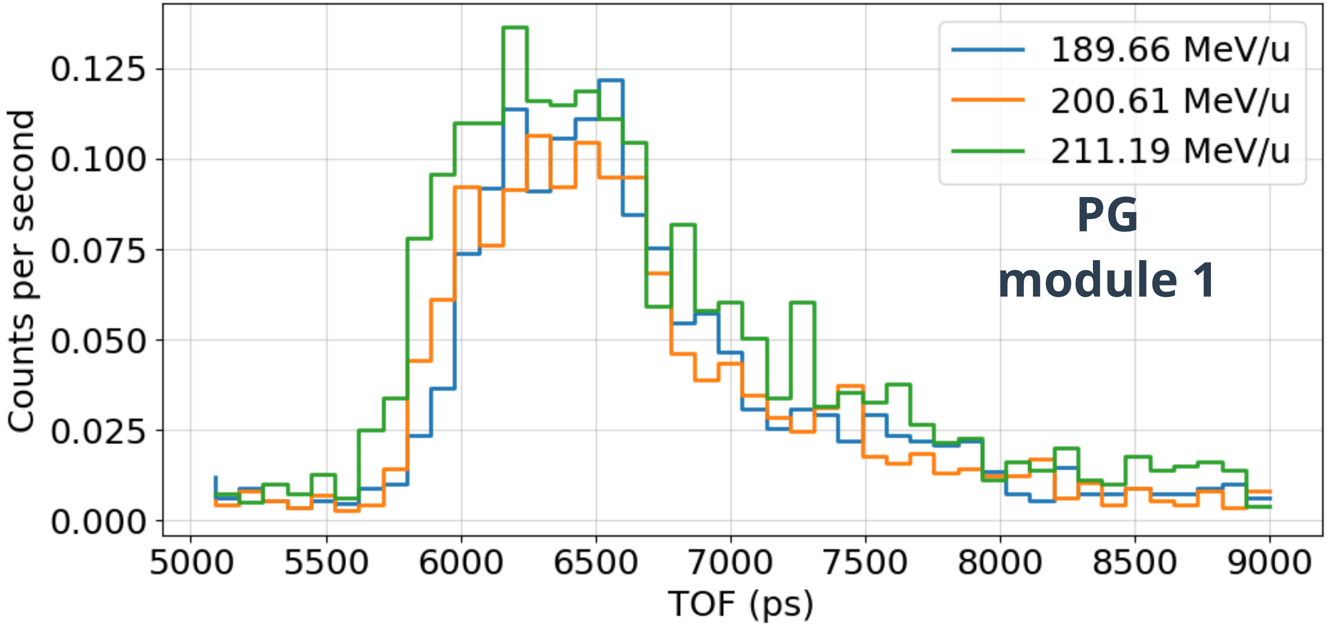

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PROMPT GAMMA TIME IMAGING

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→ TOF histogram analysis + background

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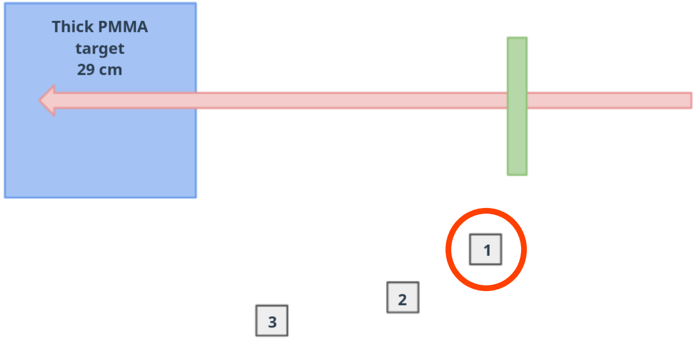
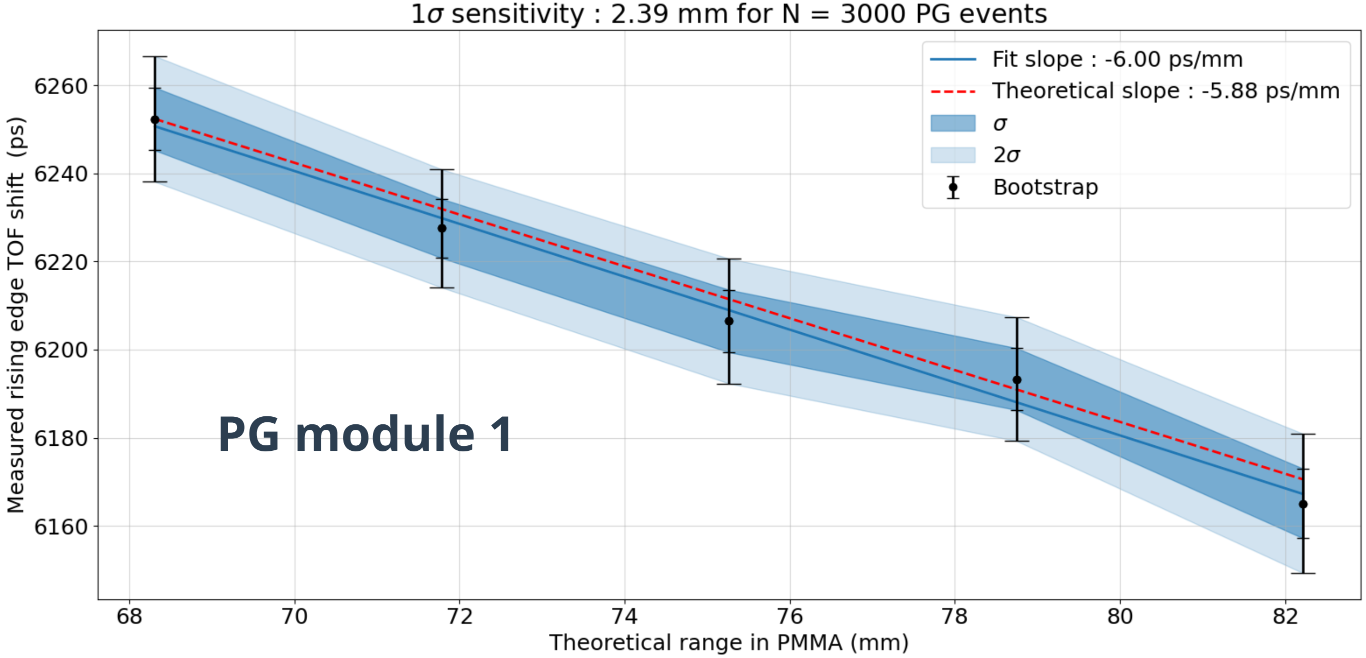
→ **Bootstrap technique**





Conclusion and outlook

Extensive tests of the TIARA system in proton environment

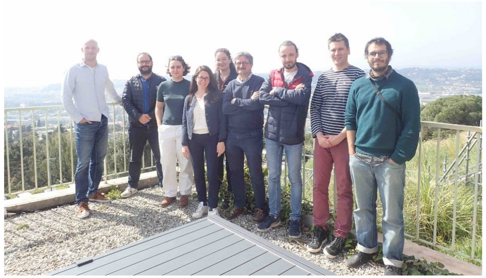
Adpatation of TIARA to a carbon (and synchrotron) environment

Ongoing investigation of sensitivity measurements in carbon setup

Upcoming 30 PG module version

Acknowledgments and credits

The **TIARA Collaboration**



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CAL: D. Maneval, J. Hérault, J-P Hofverberg

Funded projects

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PCSI TIARA (Convention n°20CP118-00)

ERC Starting Grant (project 101040381)

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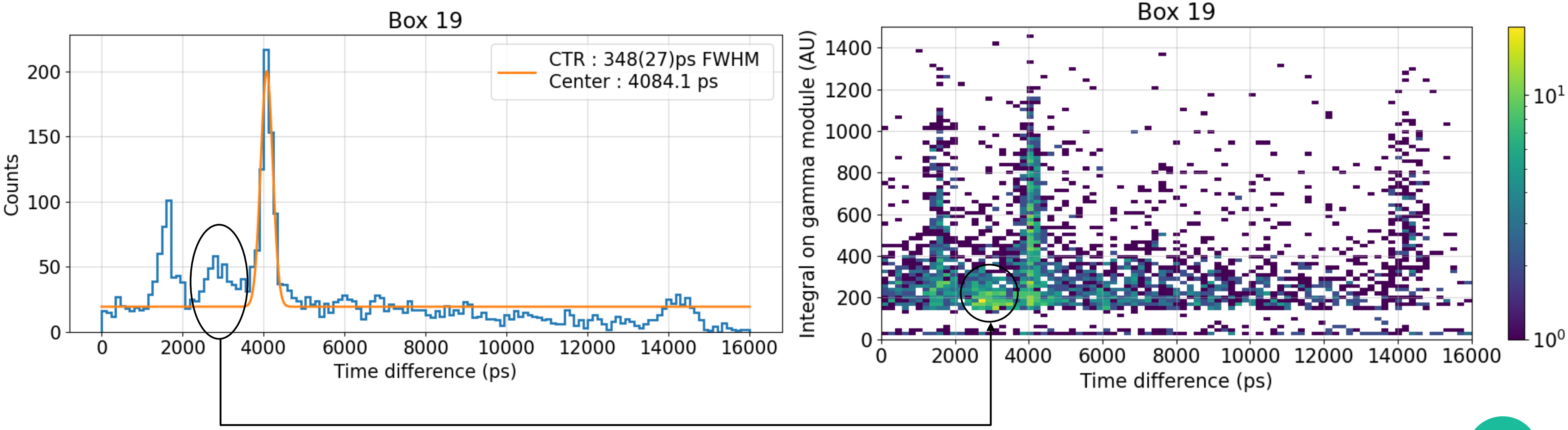
Special thanks to:

- CAL/IN2P3 COMEX for the allocated beam time
- HITRIplus project for beam time at CNAO and related travel expenses
- Marco Pullia (CNAO) and his team for the nice reception
- Labex PRIMES for funding beam time at CAL and two M2 internships

Backup

Proton calibration @ 100 MeV ~ **2-4 10^6 protons/s**

Background contamination from direct protons impacting the PG modules, have different signal signatures than PG rays



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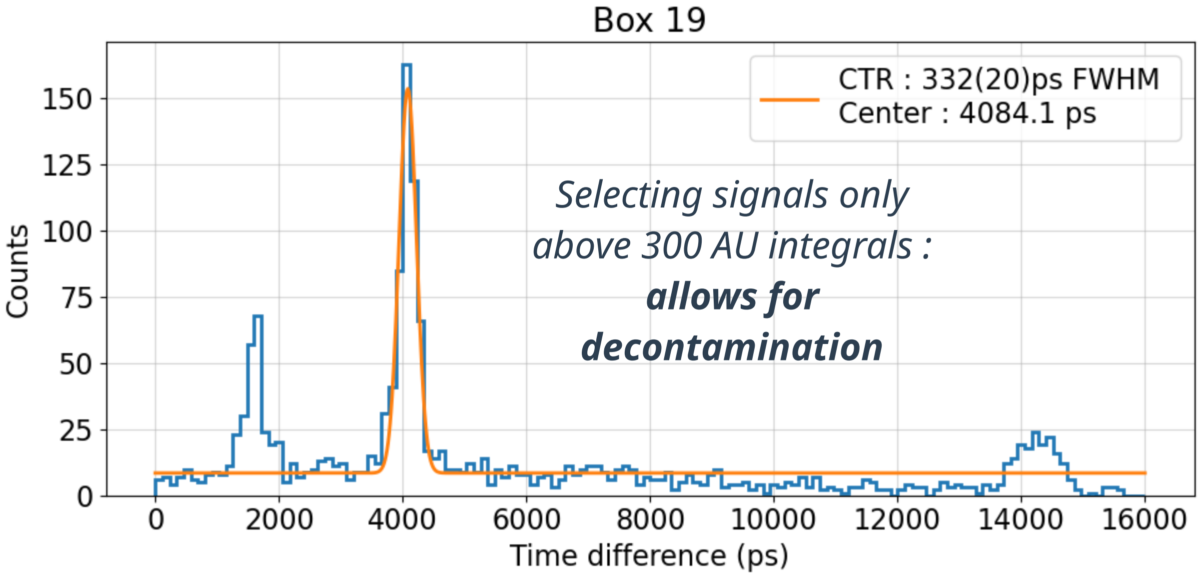
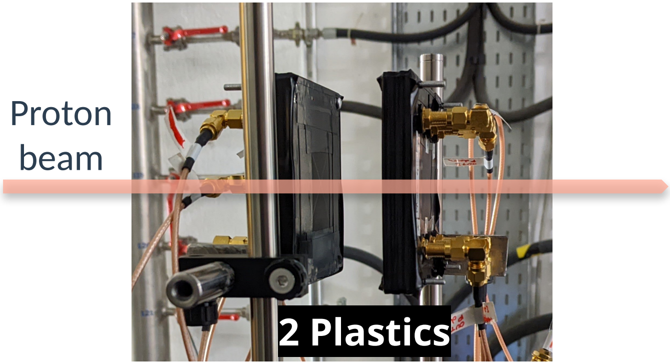
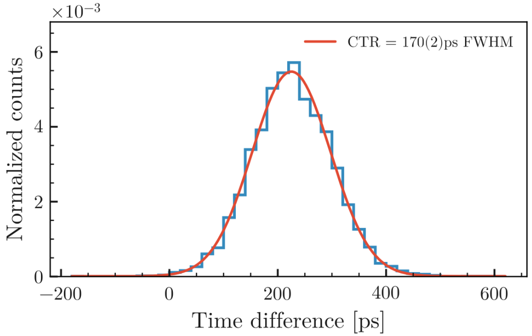


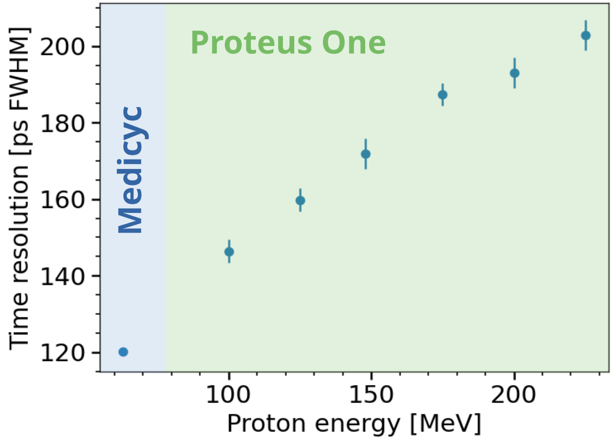
Selecting signals only above 300 AU integrals : ***allows for decontamination***

Beam monitor calibration, proton beam

Coincidence read out of both plastic monitors, assuming identical time resolution for both







A. André et al., "A Fast Plastic Scintillator for Low-Intensity Proton Beam Monitoring," in IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 9, no. 3, pp. 382-387, March 2025, doi: 10.1109/TRPMS.2024.3498959.

Backup

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PG module calibration

- Coincidence read out of two PG modules in between a Cobalt 60 source
- Laser calibration
- Tempeature dependance