Fast Timing Detectors for Prompt Gamma Time Imaging

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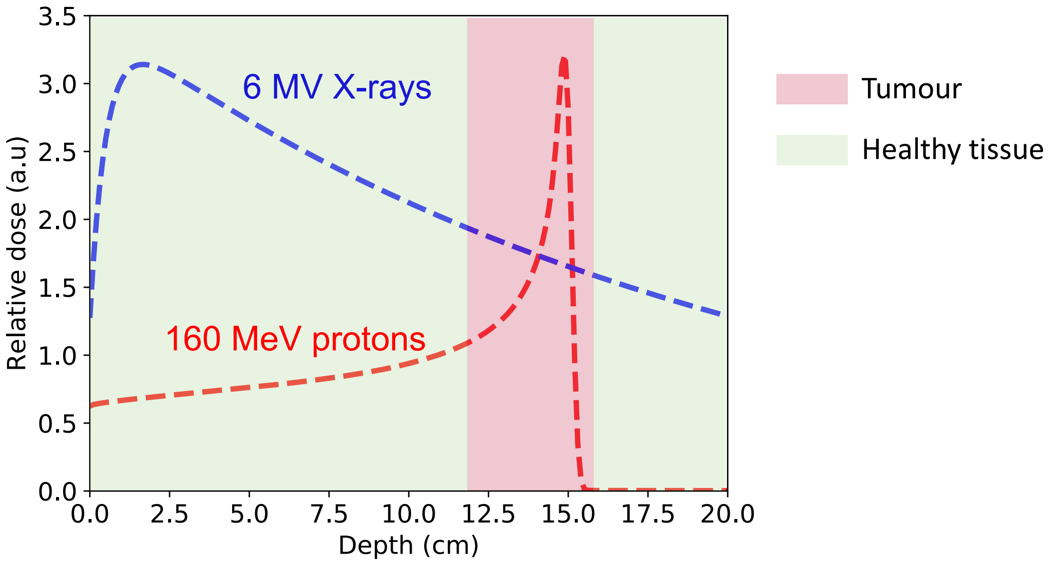
LPSC - Laboratory of Subatomic Physics and Cosmology

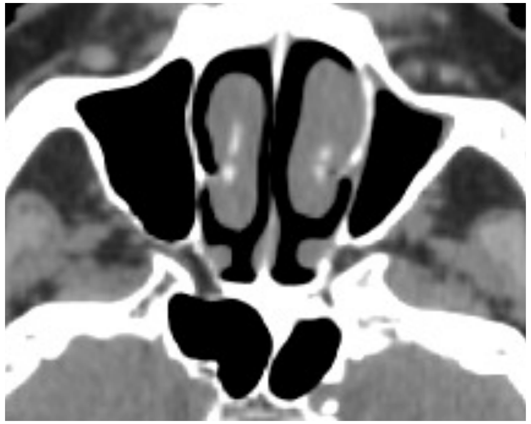
CNRS – National Centre of Scientific Research

Range monitoring in proton therapy

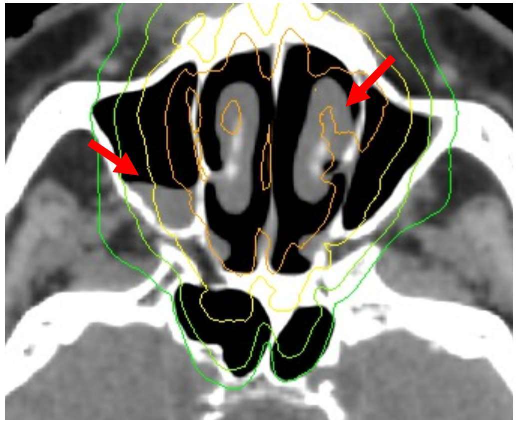
Ballistic advantage => higher sensitivity to irradiation errors



Treatment planning

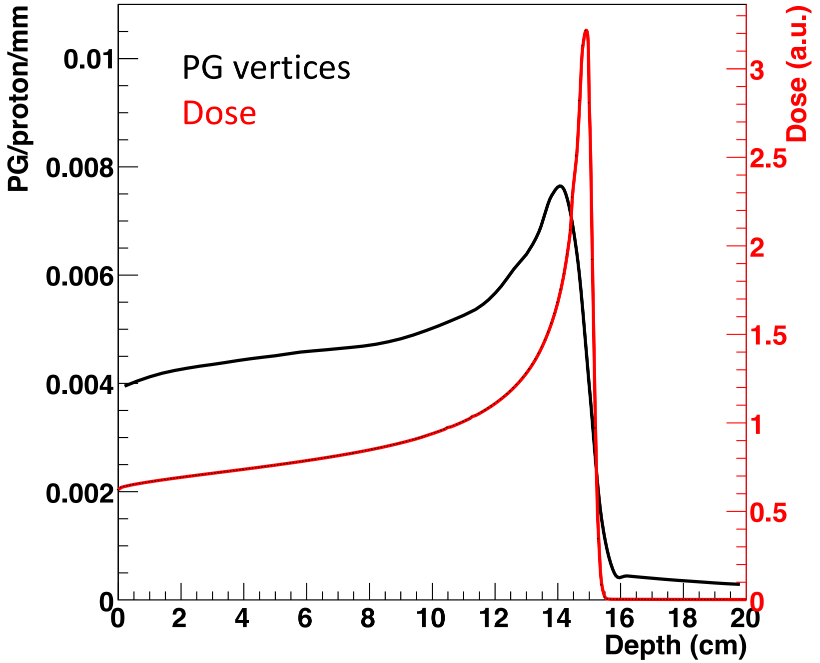


Treatment delivery



Range monitoring with Prompt Gamma (PG) rays

The PG vertex distribution is **spatially** and **temporally correlated** to the absorbed dose

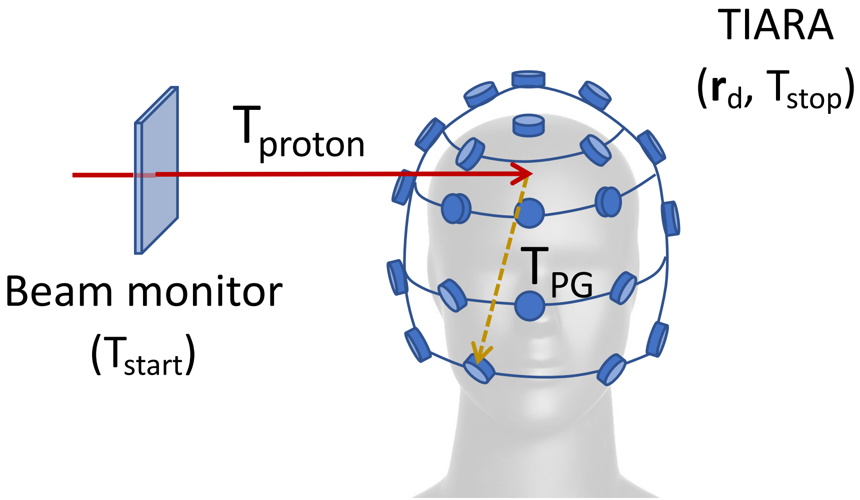


- 1 MeV < E_{PG} < 10 MeV
- PG emission ~ ps
- PG yields ~ 1%/proton/cm

Treatment monitoring through the exclusive measurement of PG TOF

Goal: measure the PG vertex (r_v) distribution and exploit its correlation to the proton range

A dedicated detection system: TIARA



- 30 compact detectors surrounding the anatomical region of interest
- No collimator => high detection efficiency

A dedicated image reconstruction: PGTI

$$TOF = t_{stop} - t_{start} =$$
$$= T_{proton}(\mathbf{r}_v, v_p) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$

2 unknowns: $\mathbf{r}_v$ = PG vertex v_p = ion speed

Allows combining the response of multiple detectors:

- to reach uniform sensitivity all over the ion range
- for IMPT compatibility

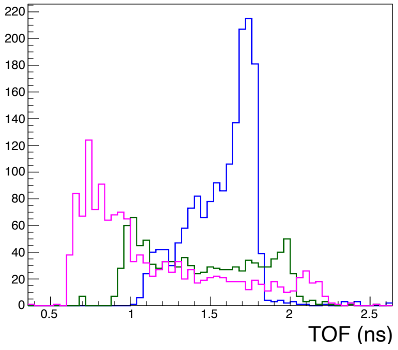
The better the time resolution, the higher the technique accuracy for ion range measurement

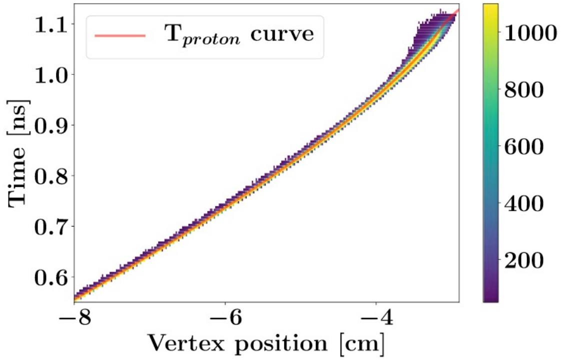
First approach: simplified PGTI reconstruction

$$TOF = T_{proton}(\mathbf{r}_v, v_p) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$

- T_{proton} → Preliminary MC in TPS conditions
- T_{PG} → Trivial function
- TOF → Experimental data
- output → PG vertices distribution

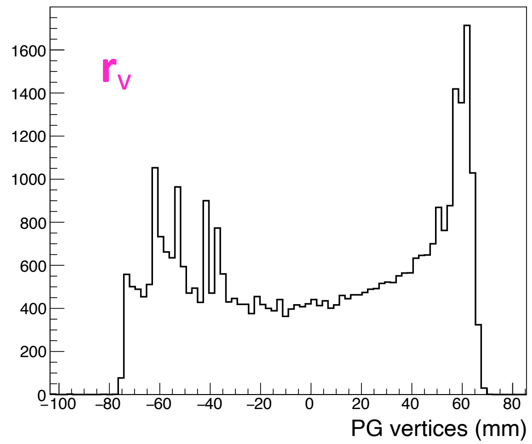
TOF: one histogram per detector





Jacquet et al. Phys. Med. Biol. 66 (2021) 135003;

PG vertices distribution



Method

Non-iterative binary search for zeros to find the PG vertex distribution ($\mathbf{r}_v$)

Input data

- Patient's CT scan to calculate T_{proton}
- Detectors' position $\mathbf{r}_d$ (centroids)

Features

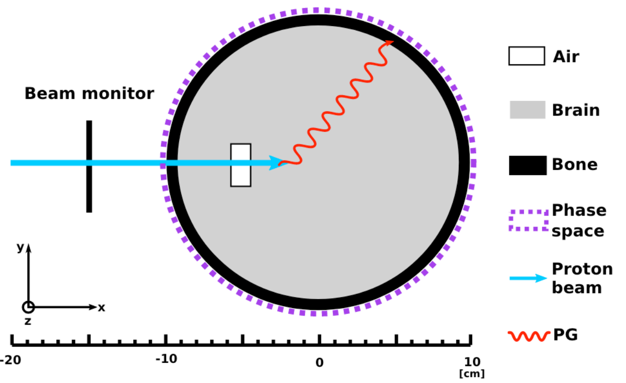
- Event-by-event reconstruction during acquisition and very fast convergence => Real-time first spot probing

DOES NOT provide actual PG distribution in case of anatomical variation but **sensitive enough to detect a variation from TPS**

Simplified PGTI reconstruction: MC validation

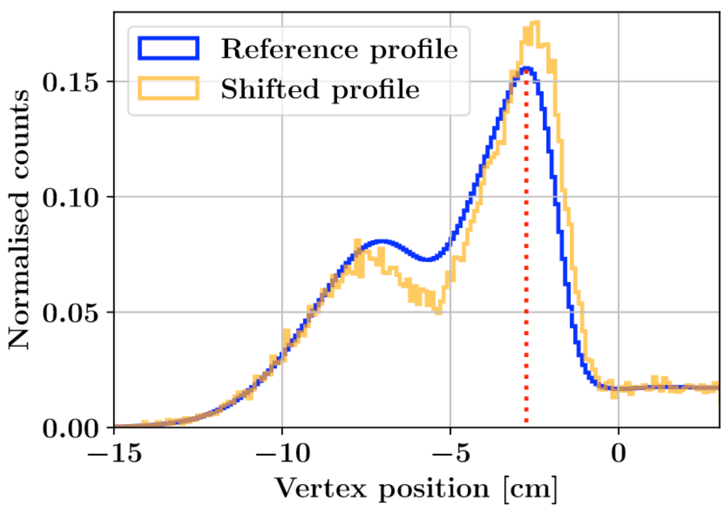
MC validation

- 100 MeV protons
- Air cavity of variable thickness
- 30 detection modules (1 cm^3)
- 0.6% overall detection efficiency

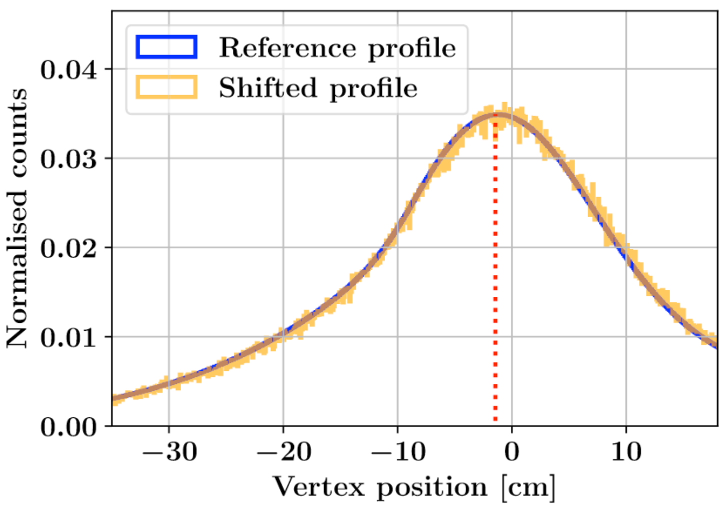


Range accuracy is a compromise between time resolution and proton statistics

SPR scenario: 10^8 protons, 100 ps rms



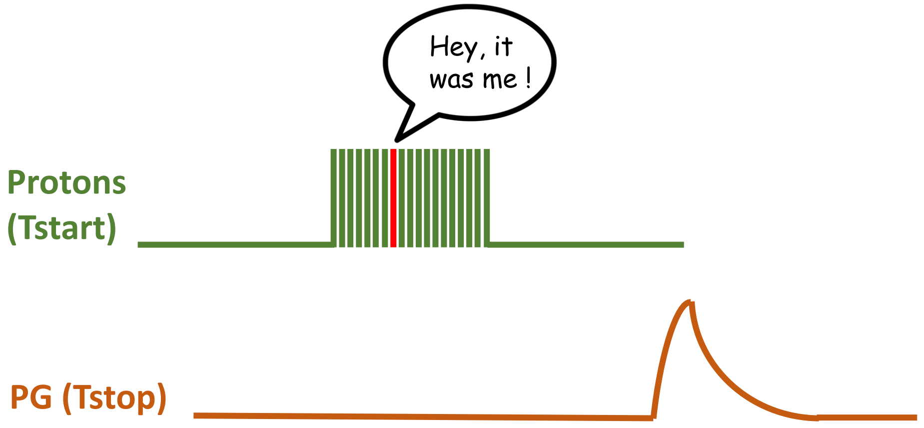
Nominal intensity: 10^9 protons, 1 ns rms



CTR (RMS)	# protons	# PG	Accuracy at 1 σ	Accuracy at 2 σ	Beam Intensity	Goal
100 ps	10^7	3 x 10^3	2	3	Single proton regime	Pre-treatment probing
100 ps	10^8	3 x 10^4	1	1		
1 ns	10^9	3 x 10^5	1	2	Nominal	On-line monitoring
n.a.	10^8	3 x 10^4	2	4		

Jacquet et al. Phys. Med. Biol. 66 (2021) 135003;

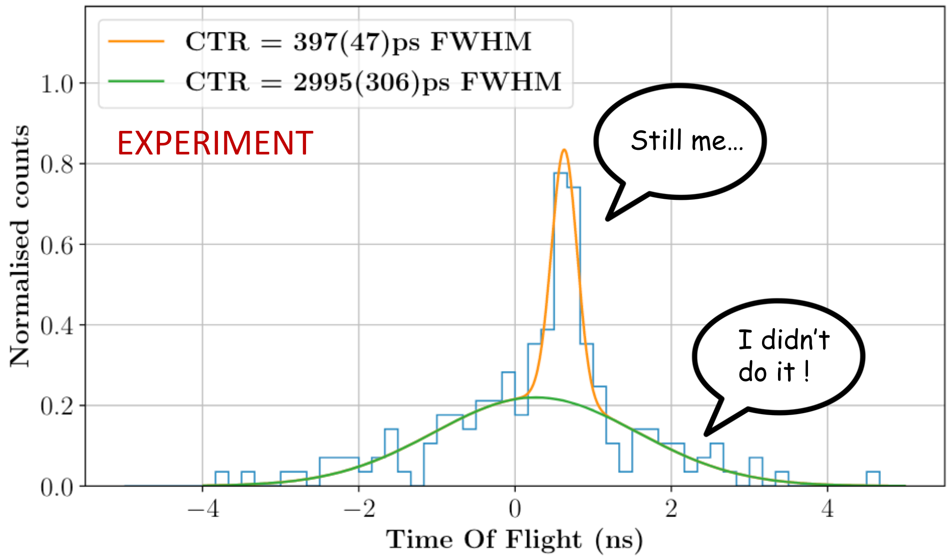
Reducing bunch-width related time uncertainties



		Synchrotron (CNAO, HIT)		Cyclotron (IBA, Varian)	Synchro-cyclotron (S2C2 IBA)
		^{12}C	Protons		
Typical intensity (ions/s)		10^7	10^9	10^{10}	10^{11}
Macro-structure	Period (s)	1 - 10		Ø	10^{-3}
Micro-structure	Bunch width (ns)	20 - 50		0.5 - 2	8
	Period (ns)	100 - 200		10	16
	Ions/bunch	2-5	200 - 500	200	10^5

Source: CLaRys collaboration

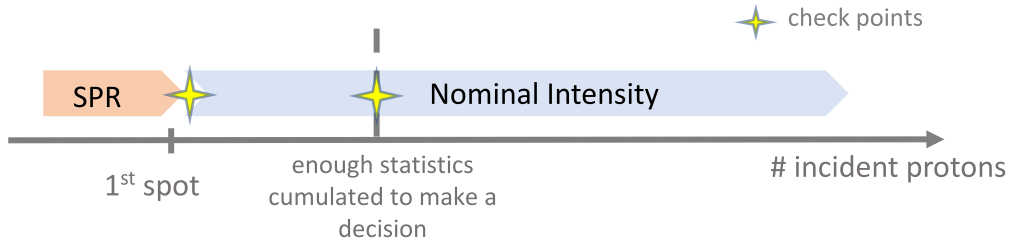
S2C2 synchro-cyclotron: 8 ns bunch width, 7 p/bunch, thin target



Jacquet et al. Scientific report (2023) 13:3609

Proposed strategy.

lower the beam intensity to Single Proton Regime (SPR)

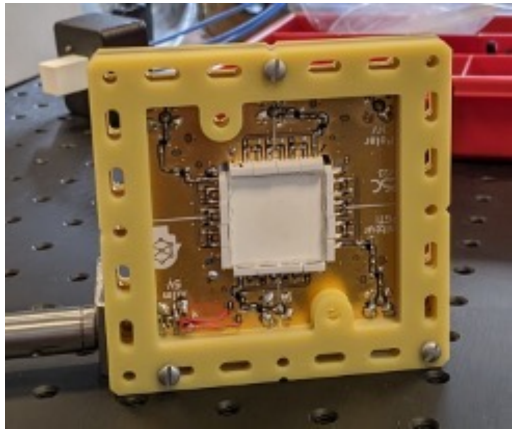


Dauvergne et al, Front. Phys. 8:567215 (2020)

- SPR is the intensity allowing single proton tagging
- It depends on the accelerator time structure

TIARA beam monitor

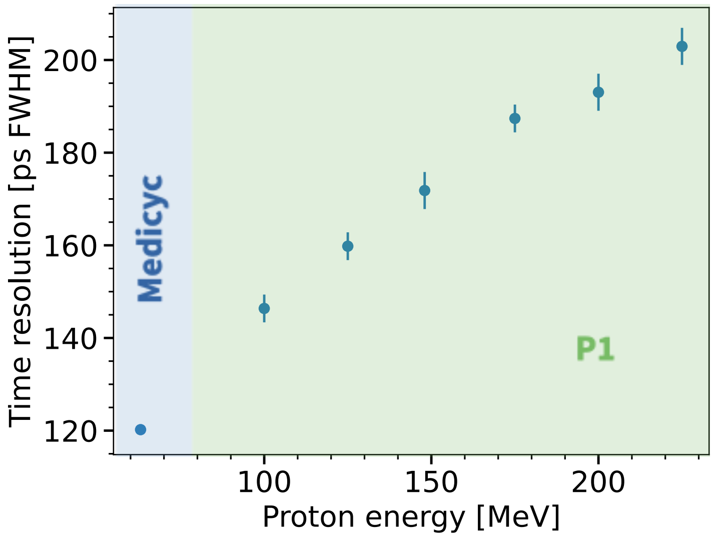
25 x 25 x 1 mm^3 plastic scintillator (EJ-204) readout by SiPMs



Performances for single protons

- DTR= 51 ps σ at 63 MeV
- Detection efficiency = 100%
- Spatial resolution =
  ~1.9 mm σ for single proton
  <<1 mm for the beam barycentre

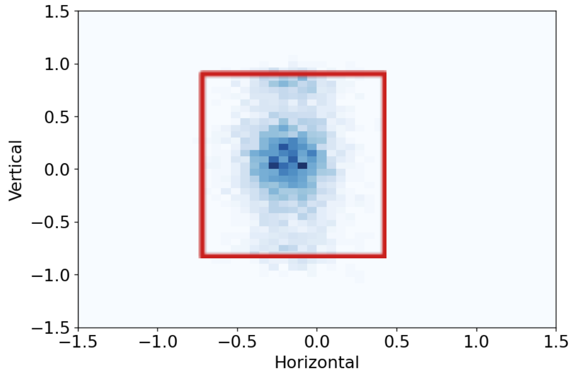
Time resolution

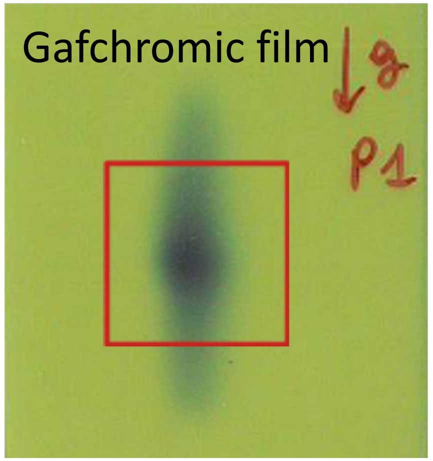


Time resolution < 100 ps σ in the clinically relevant energy range

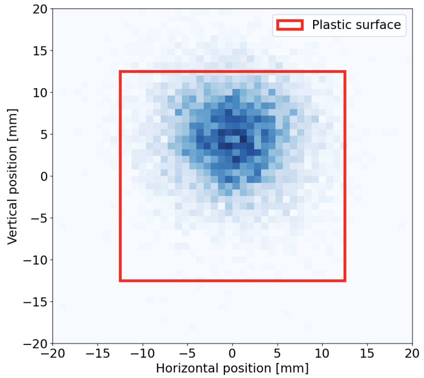
Spatial resolution

Medicyc at 63 MeV

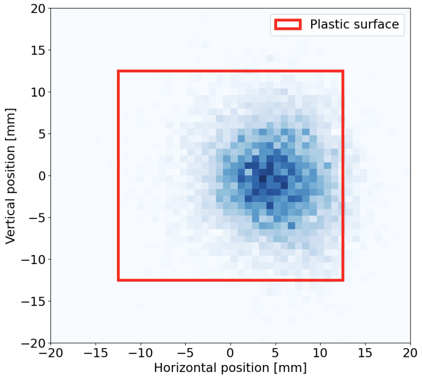




Proteus One at 148 MeV

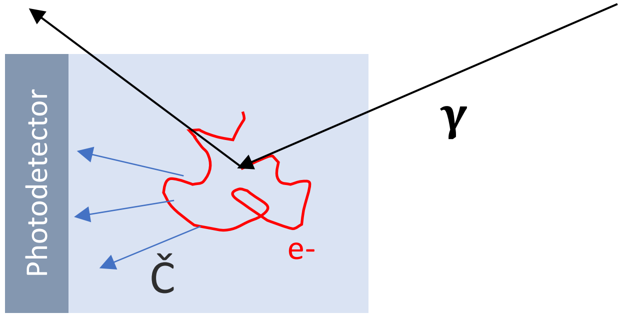


Position (0, 5) mm

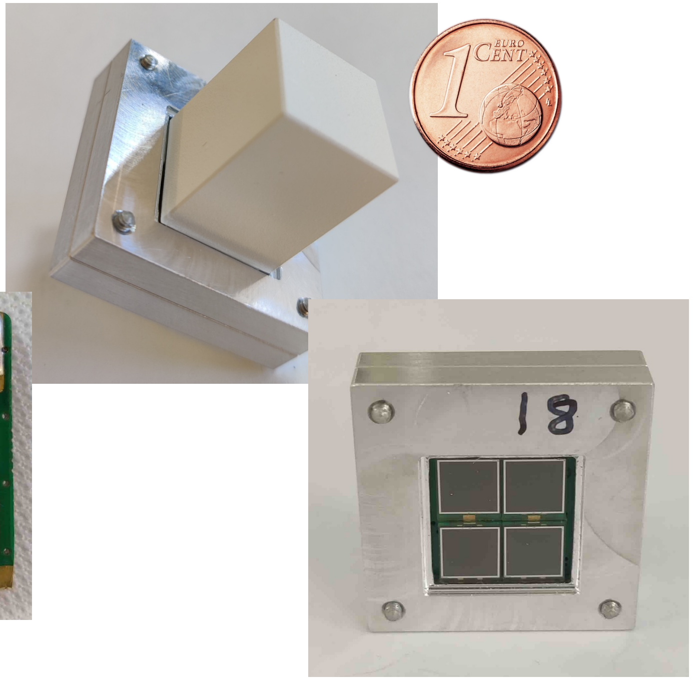


Position (5, 0) mm

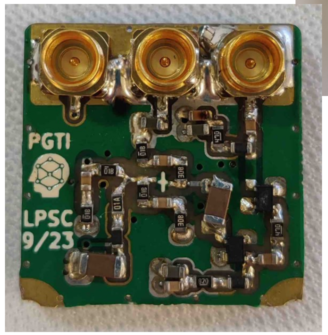
TIARA block detector



TIARA module

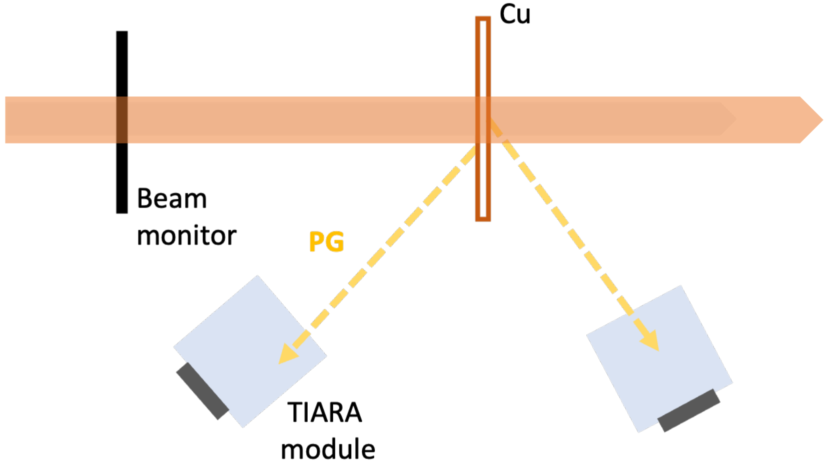


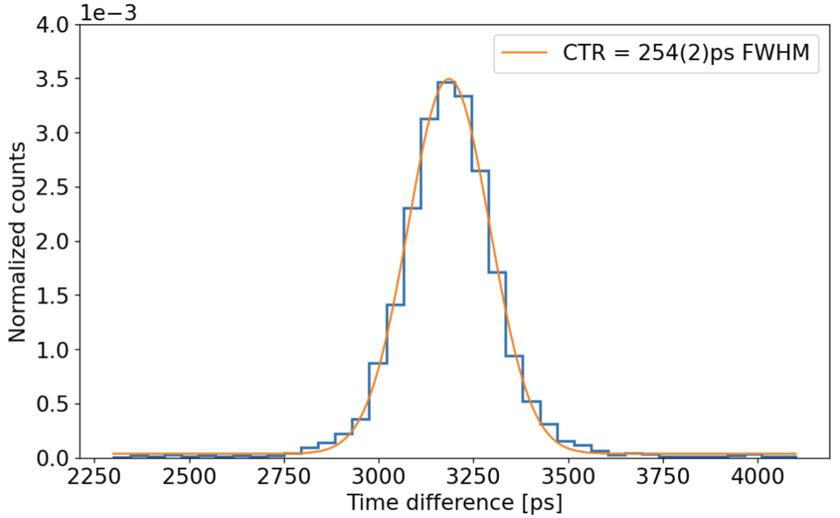
Custom front-end



Read-out:
Wavecatcher IJCLAB

How we measure the CTR





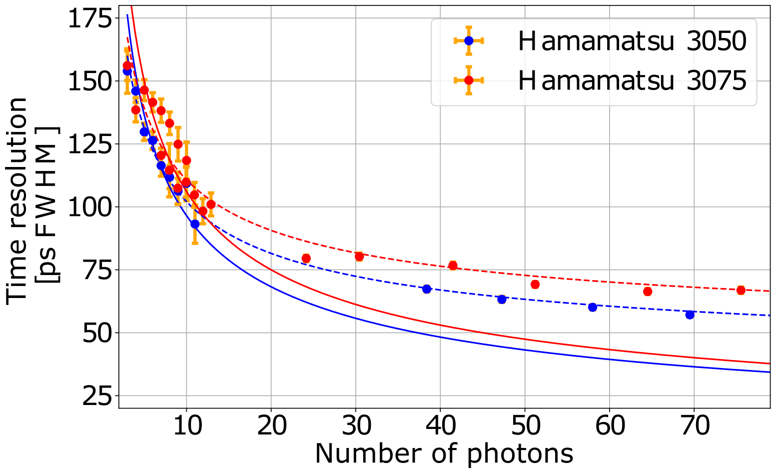
Cherenkov detectors (PbF_2) coupled to SiPMs HPK 6075

- short pulses and low LY (pile-up)
- high density => high det. efficiency, very compact
- very low sensitivity to background (threshold process)!
- NO energy measurement

TIARA block detector: optimisation of time resolution

SiPM Time Resolution

Data from 2020 (obsolete front-end), shown as an example

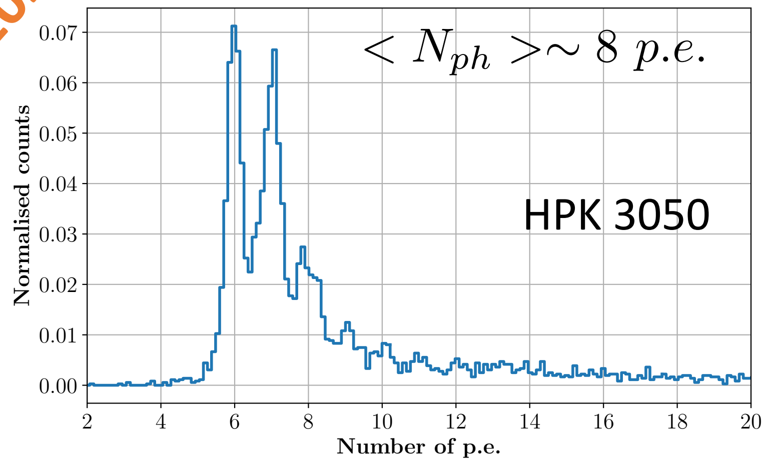


Goal: simultaneous optimisation of time resolution and detection efficiency

- Larger u-cells (no need for high dynamic range)
- Larger SiPMs (HPK-6075)

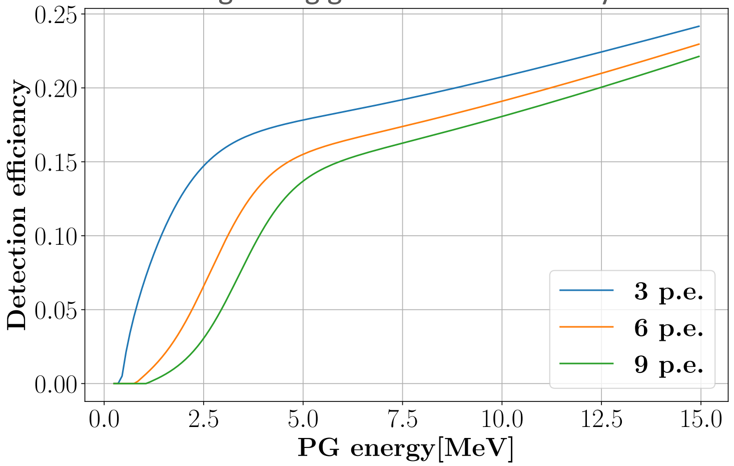
2021

Energy response (experiment)



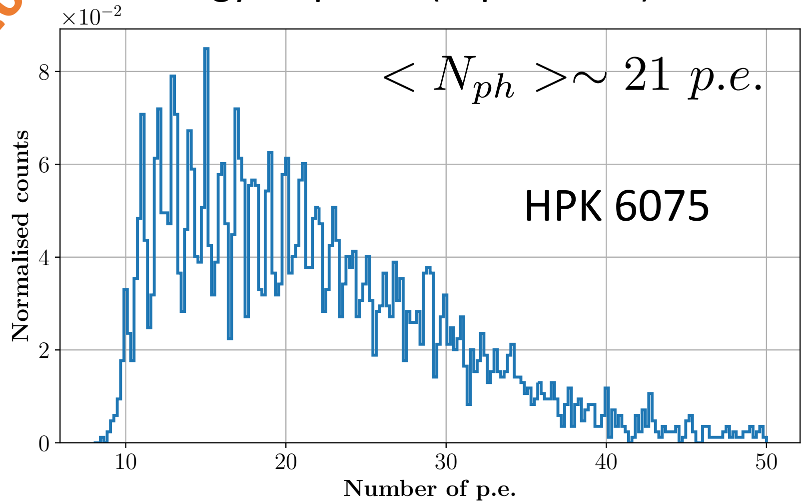
Module detection efficiency (MC)

Neglecting geometrical efficiency



2023

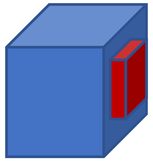
Energy response (experiment)

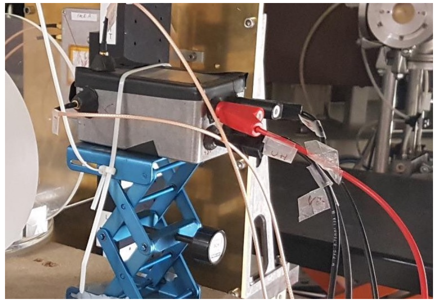


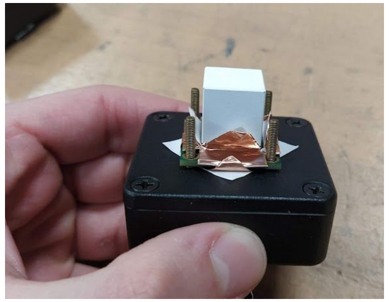
MC simulation on-going to establish the module optical response, but:

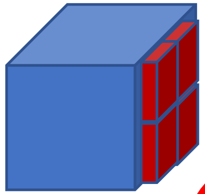
- Crystal is 2 times thicker
- Photodetector coverage is 7 time better

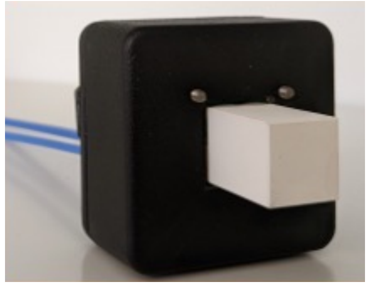
TIARA block detector: improvement of CTR and detection efficiency

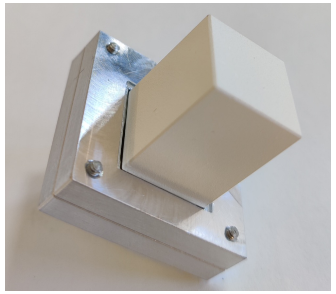












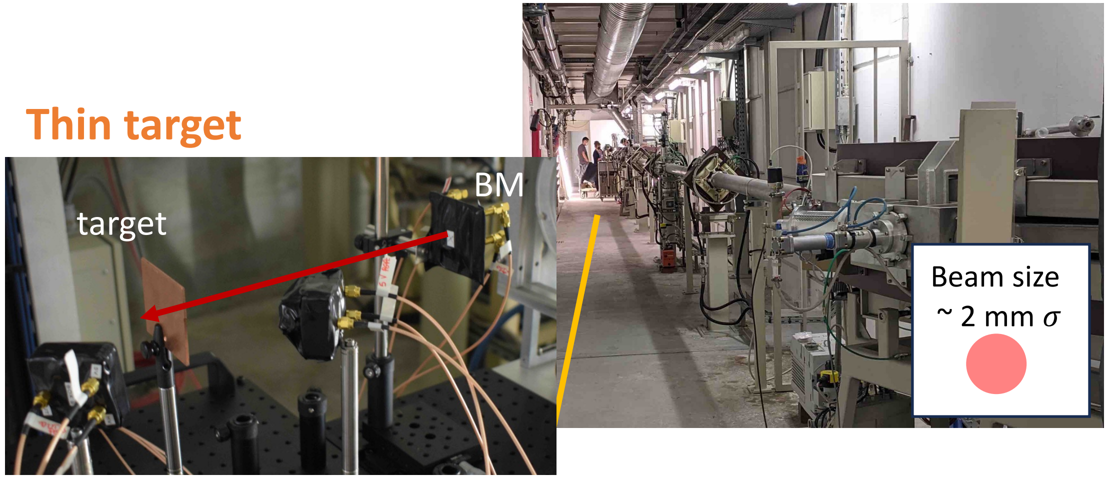
Prototype	v1	v2	v3	v4	v5
Crystal	1 cm^3 PbF_2	2 cm^3 PbF_2	$(1.5\ cm)^3$ PbF_2	1.5×1.5×2 cm^3 PbF_2	
SiPM	HPK3050	HPK6075			
Nb. of SiPMs	1		4		
Objective	Simple design		Improve detection efficiency Improved or equal time resolution		Compact layout Compact layout
Front-end	Commercial	LPSC, single channel	Hybrid read-out	Parallel read-out	Hybrid read-out
Beam monitor FE	Cividec C2		LPSC		LPSC
Beam test	June 2021	April 2022	December 2022	June 2023	December 2023
CTR (ps FWHM)	317	256	222	208	251**
beam monitor DTR (ps FWHM)	157	157	68	68	120
PG DTR (ps FWHM)	275	202	211	197	220

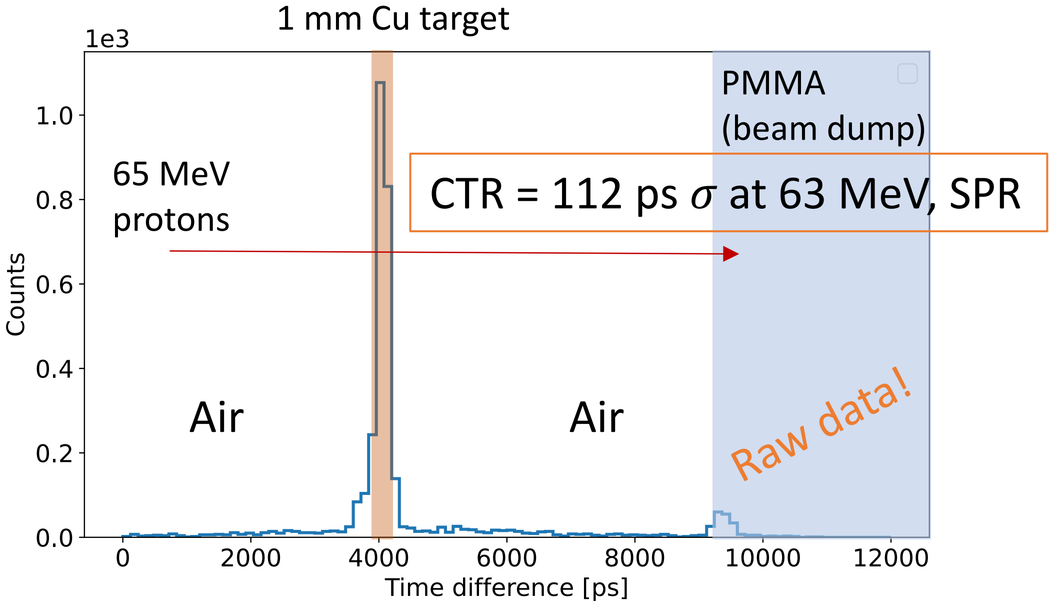
All data are for 63 MeV protons and 3V OV. ** coincidence with plastic monitor

TIARA gamma module: SNR (version v3)

Irradiations at Medicyc (cyclotron, 63 MeV)

Thin target

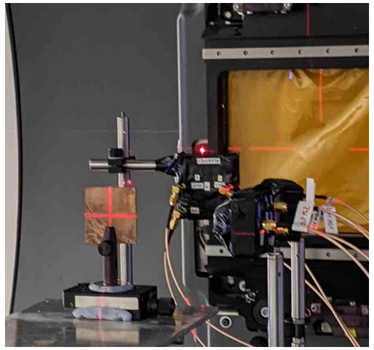


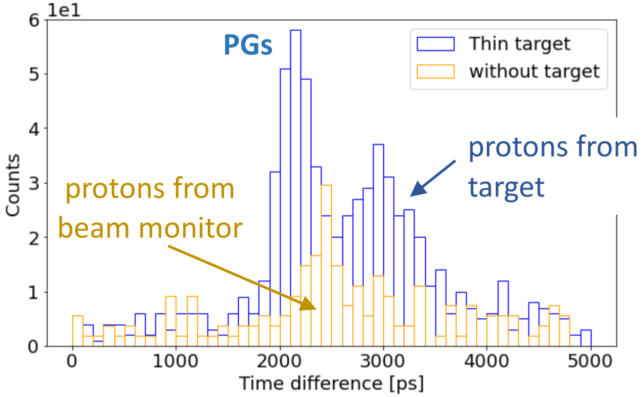


Irradiations at IBA S2C2 (100 MeV)

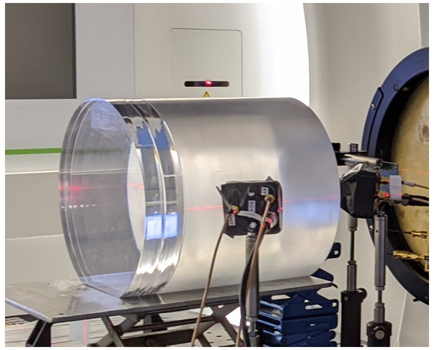
Two sources of background
- protons from beam monitor
- protons from target

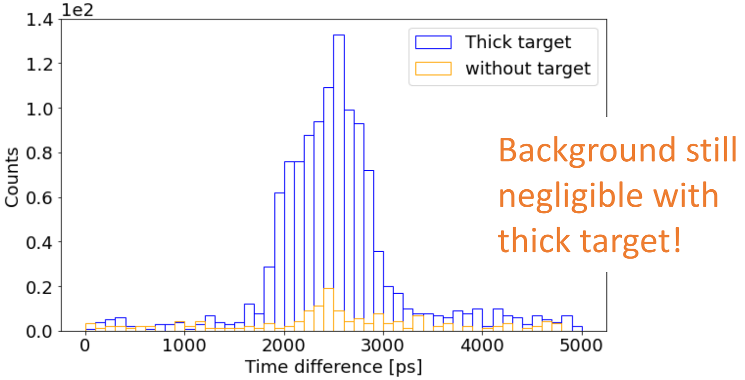
Thin target





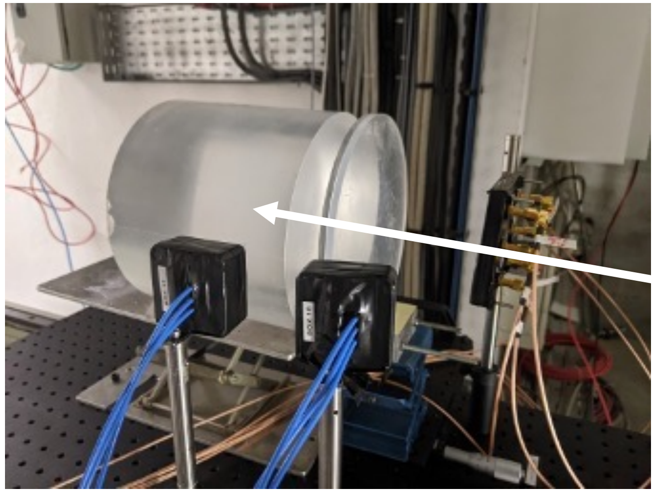
Thick target



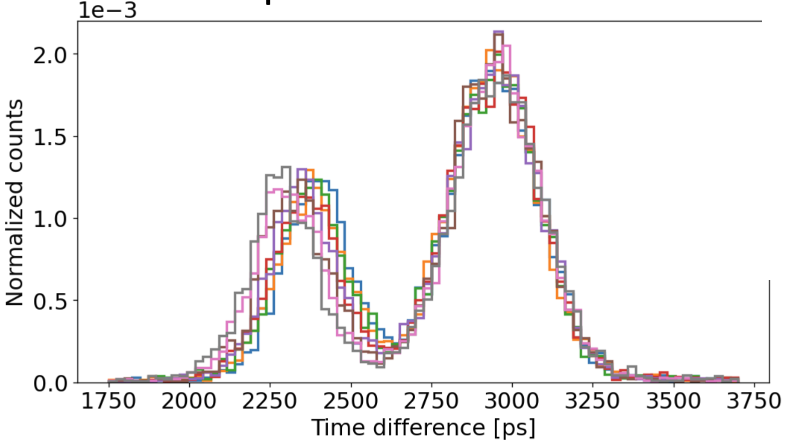


2023. Experimental validation with version v5 (63 MeV, Single Proton Regime)

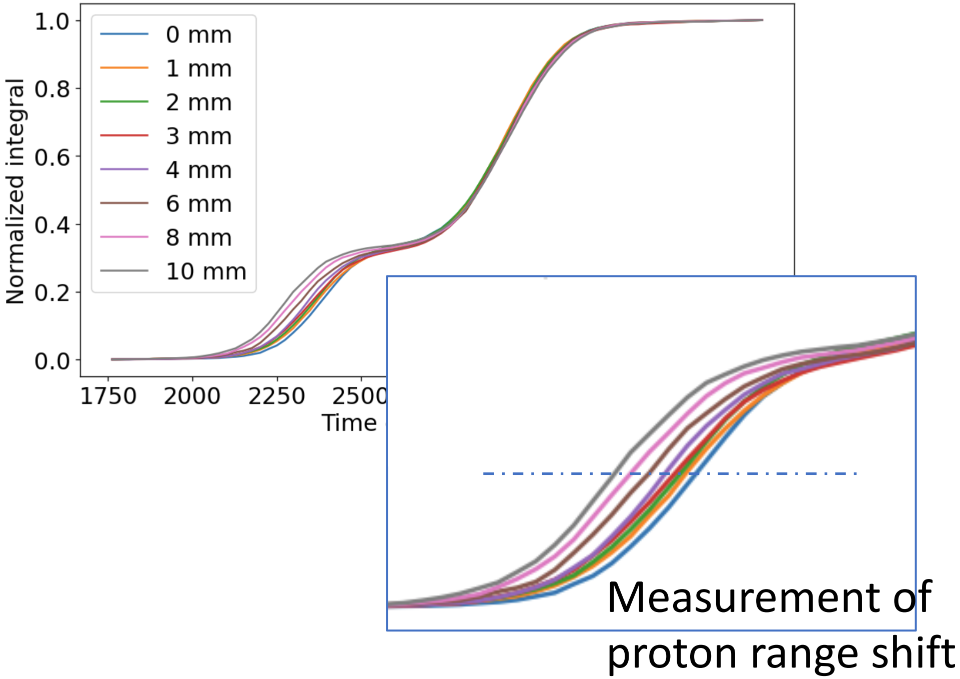
The thin target is translated
from 0 to 10 mm in steps of 1 mm



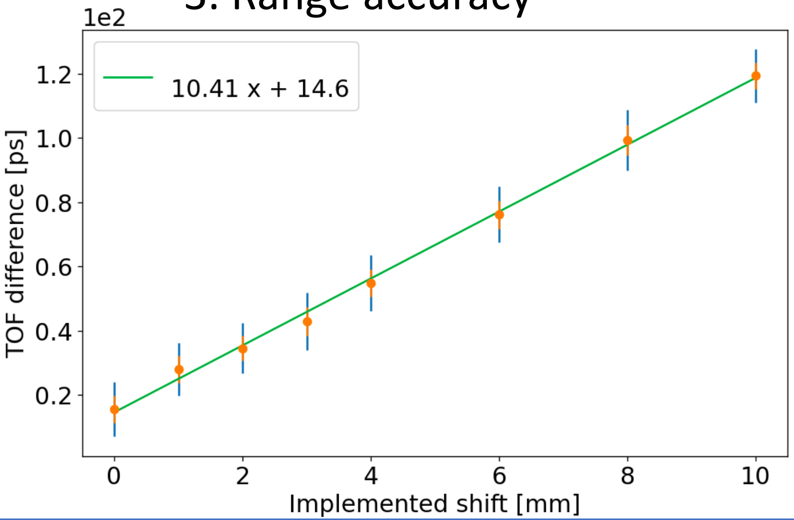
1. TOF distributions (~6600 PGs) upstream module



2. TOF integral distributions



3. Range accuracy



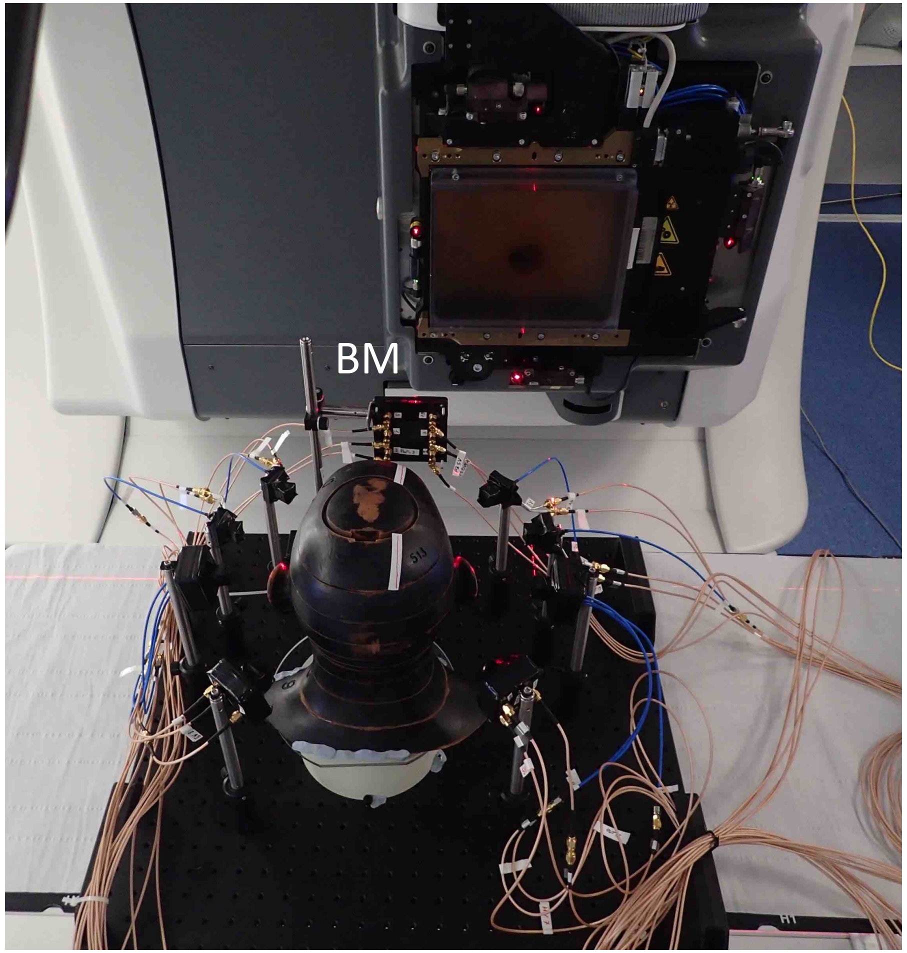
Experimental proton range accuracy:
1.8 mm at 2σ for 3000 PGs (~ 10^7 protons)

Initial MC prediction

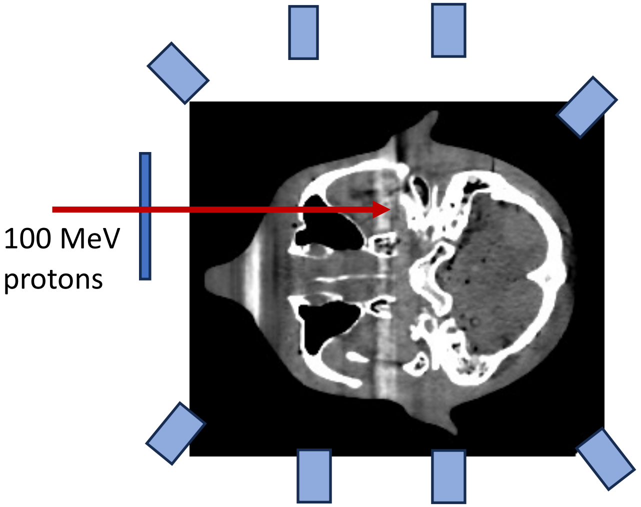
CTR (RMS)	# protons	# PG	Sensitivity at 1 σ	Sensitivity at 2 σ	Beam Intensity	Goal
100 ps	10^7	3 x 10^3	**2**	3	Single proton regime	Pre-treatment probing
100 ps	10^8	3 x 10^4	1	1		

2024. Experimental validation with version v5 (100 MeV, Single Proton Regime)

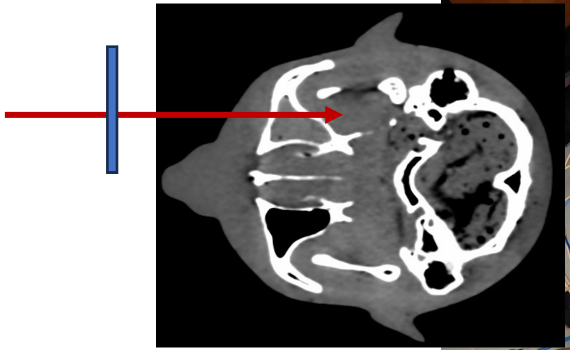
8 channels TIARA protototype

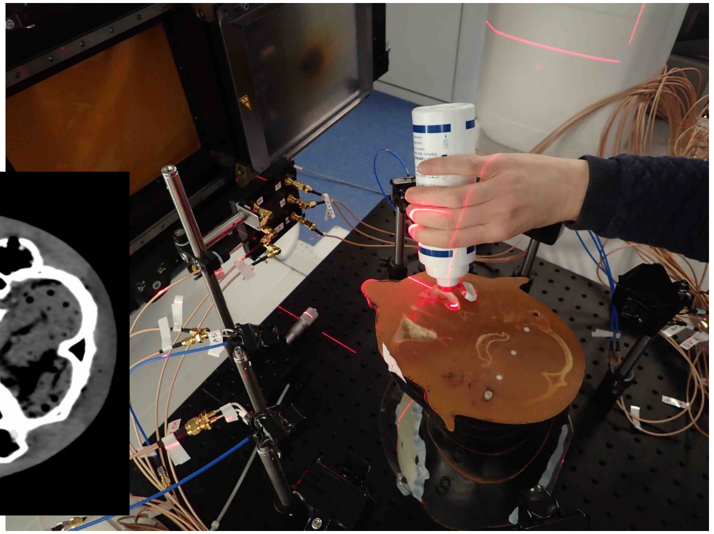


Irradiation of RANDO anthropomorphic phantom with **sinus empty**…



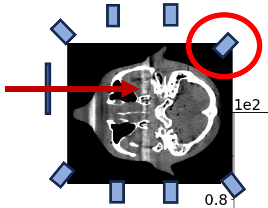
… and **sinus filled** with ultrasound gel.



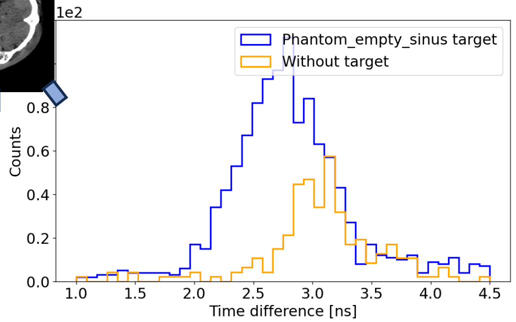


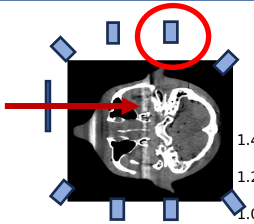
2024. Experimental validation with version v5 (results)

Example of background analysis

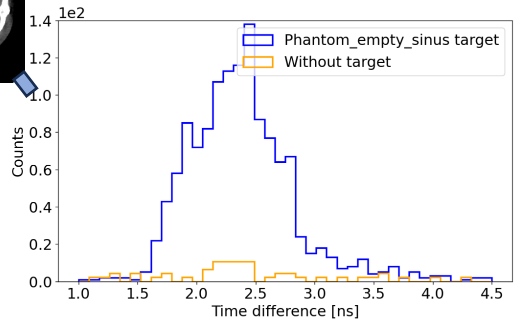


Worst case, downstream

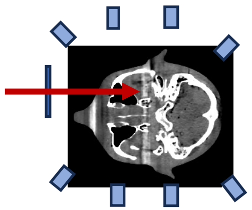


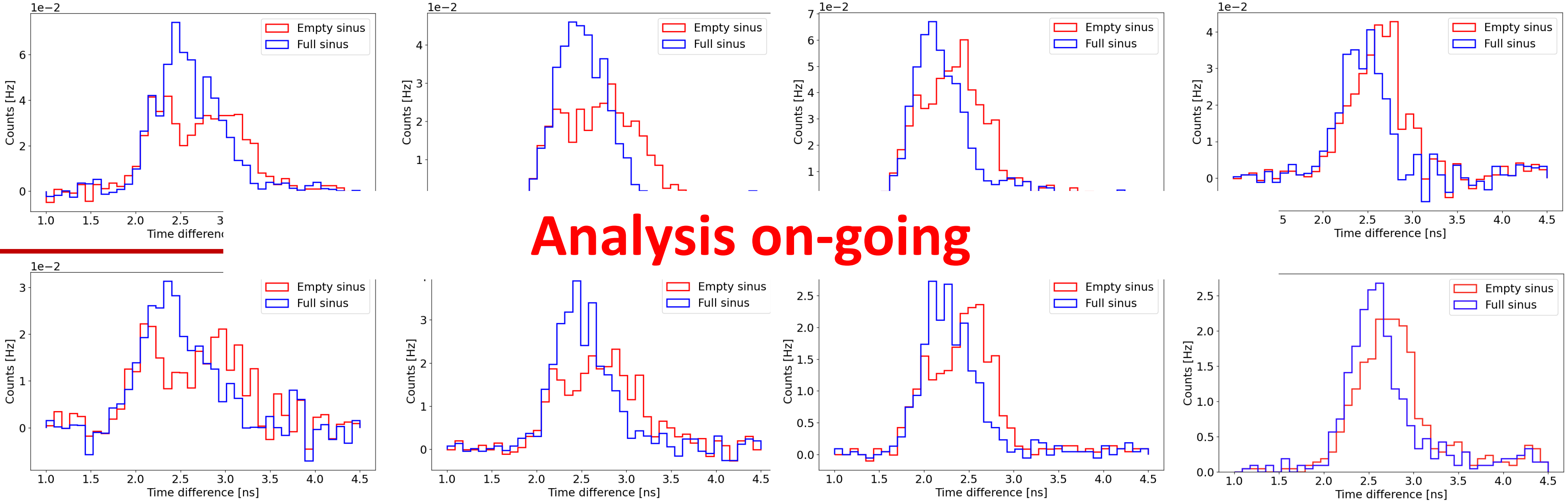


Other modules have negligible background



All data after background subtraction: comparison sinus empty/filled





Analysis on-going

Conclusions and perspectives

1. We have developed a new detector for PG timing with the following characteristics

- Millimetric proton range accuracy
- Very high sensitivity (statistically significant information within a single spot in SPR)
- Low sensitivity to background radiation
- Capable of measuring proton beam deviations in any direction thanks to 3D coverage (IMPT)

2. So far validated in SPR with cyclotron and synchrocyclotron at CAL

On-going tests and developments

- Tests at nominal intensity with 8 modules prototype (analysis on going)
- Tests with carbon ions (CNAO, July 2024)
- Reconstruction algorithm with no a priori information
- DAQ for the 30 channels prototype

Acknowledgements and credits

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