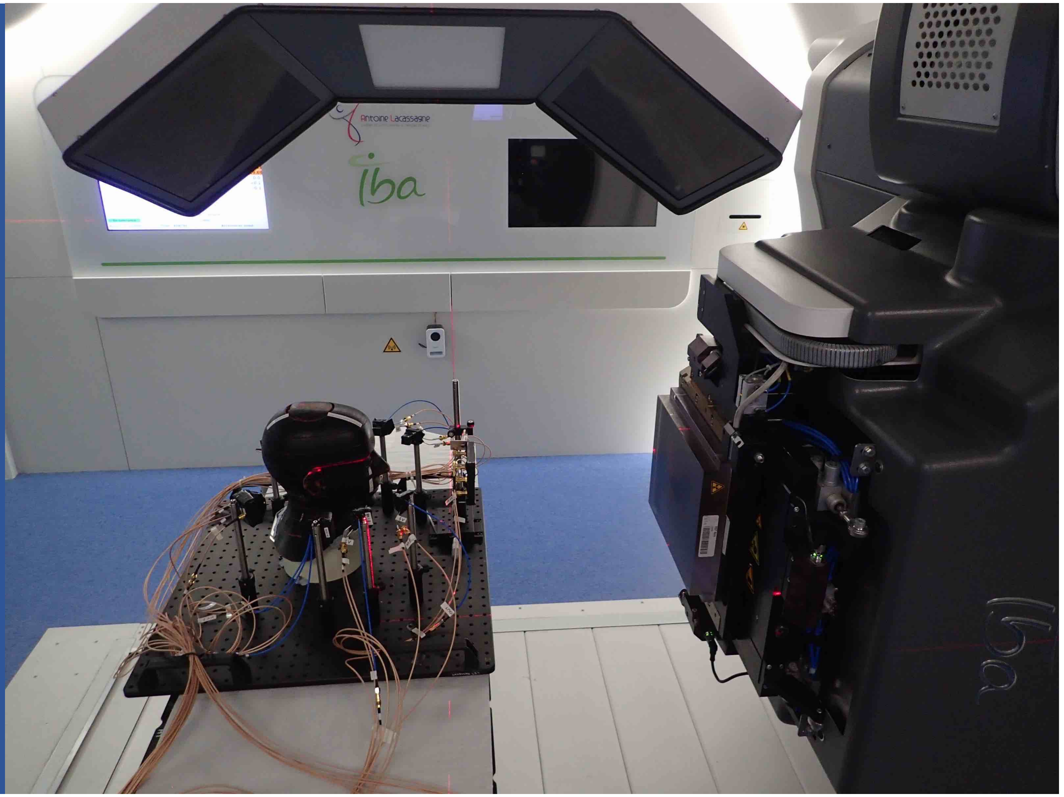
Time-Of-Flight based Prompt Gamma detection with TIARA



Sara Marcatili

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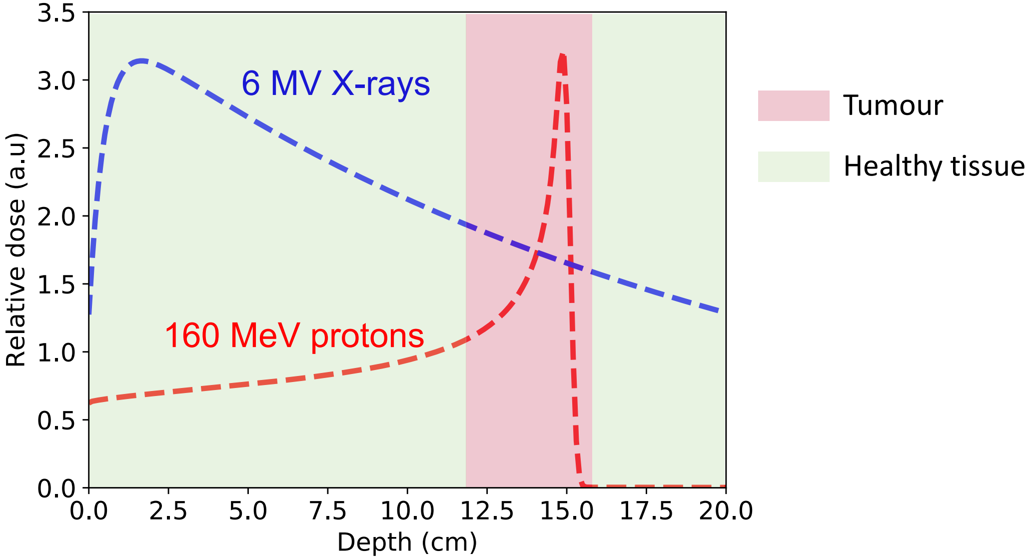
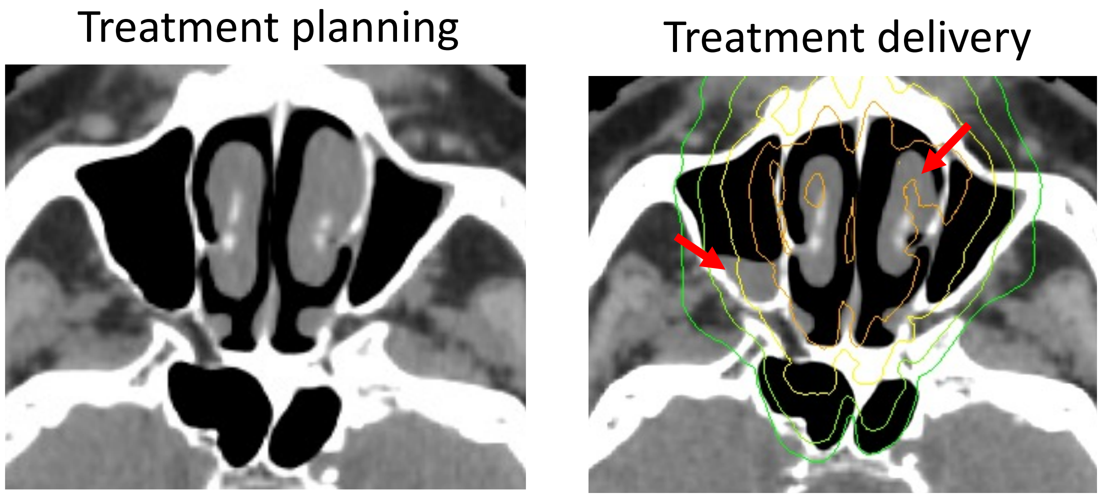
INFN Pisa and Pisa University, 27th January 2024

Range monitoring in proton therapy

Ballistic advantage
=> higher sensitivity to irradiation errors

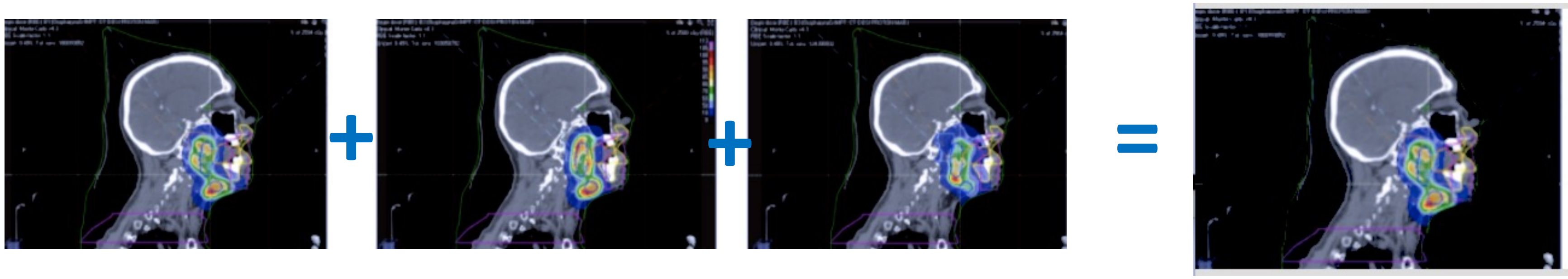


<u>Example</u>: anatomical modifications between treatment and treatment planning



Courtesy of CAL

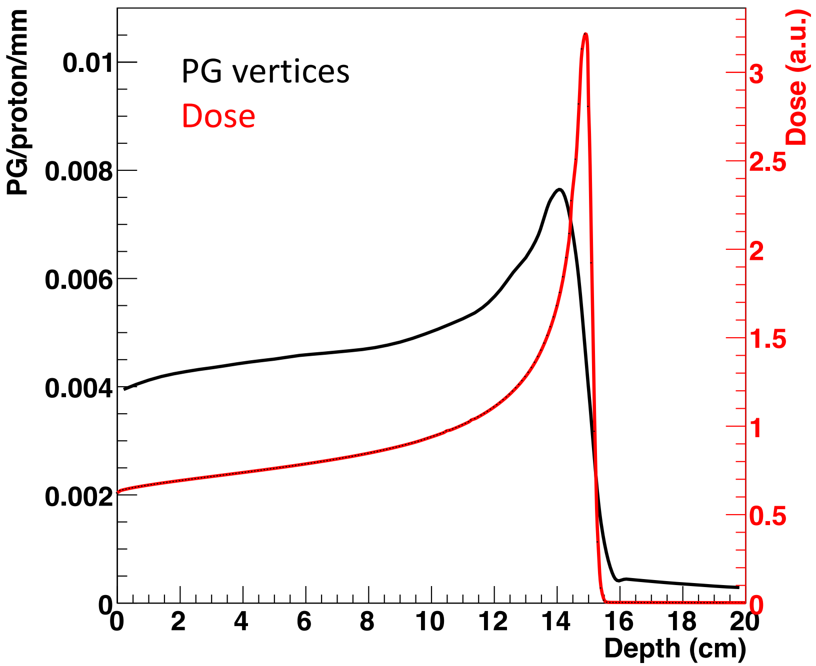
Range uncertainties are especially critical in Intensity Modulated Proton Therapy (IMPT)



Courtesy of CAL

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

Range monitoring with Prompt Gamma (PG) rays

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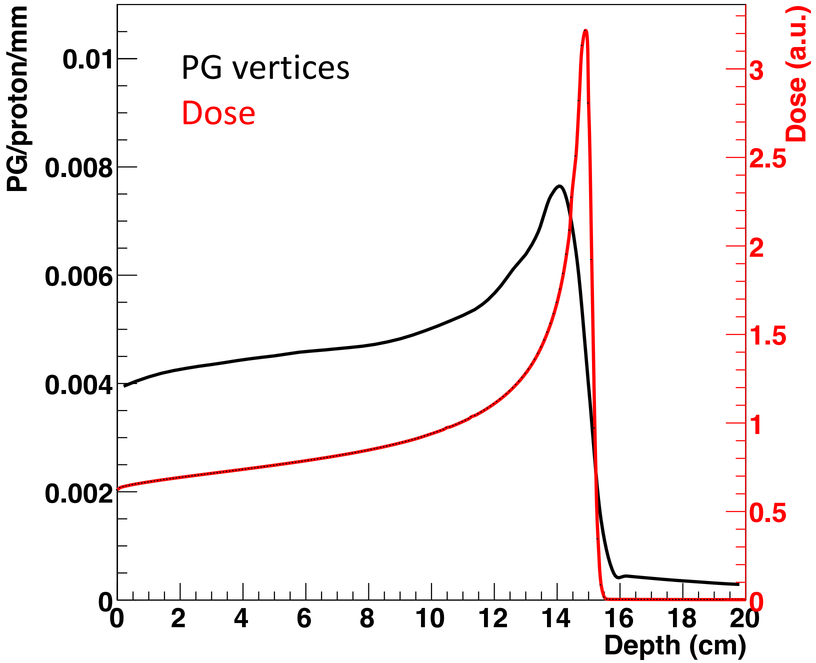
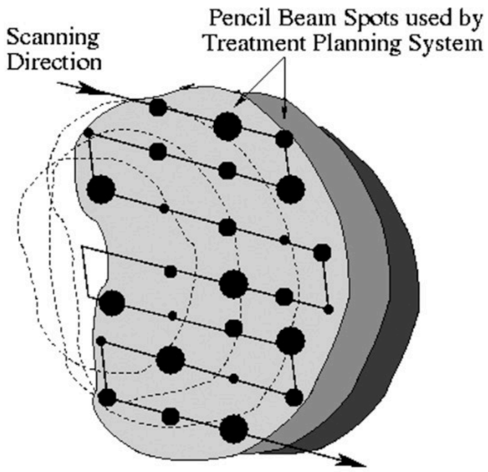


- 1 MeV < E_{PG} < 10 MeV
- PG emission ~ ps
- PG yields ~ 1%/proton/cm

Constraints and expected performances

Pencil Beam Scanning in proton therapy



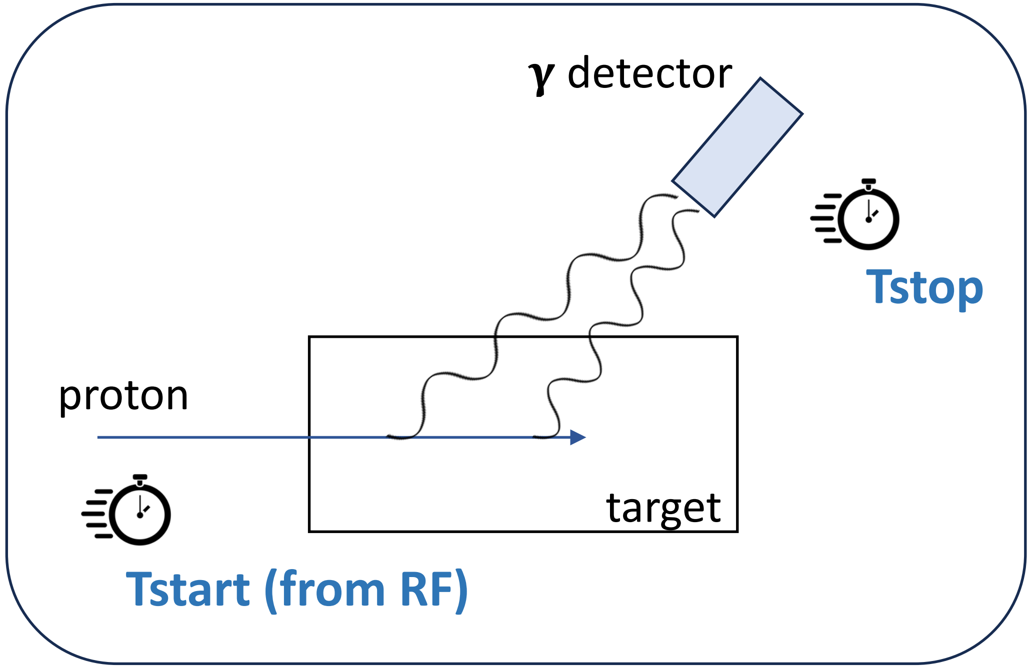
Standard approach:
$10^6 \div 10^8$ protons delivered per spot

@ S2C2 accelerator:
IBA "blind golfer" algorithm

- Ideally, one PG profile per spot, or spot grouping to increase statistics
- Millimetric proton range accuracy with limited statistics

Development of dedicated detectors with high sensitivity

Prompt Gamma Timing (PGT)



Indirect measurement of proton range from the distribution characteristics of:

TOF = Tstop – Tstart

Tstart from:

- Beam RF signal (original approach)
- Beam monitor

Proposed by G. Pausch team at Oncoray

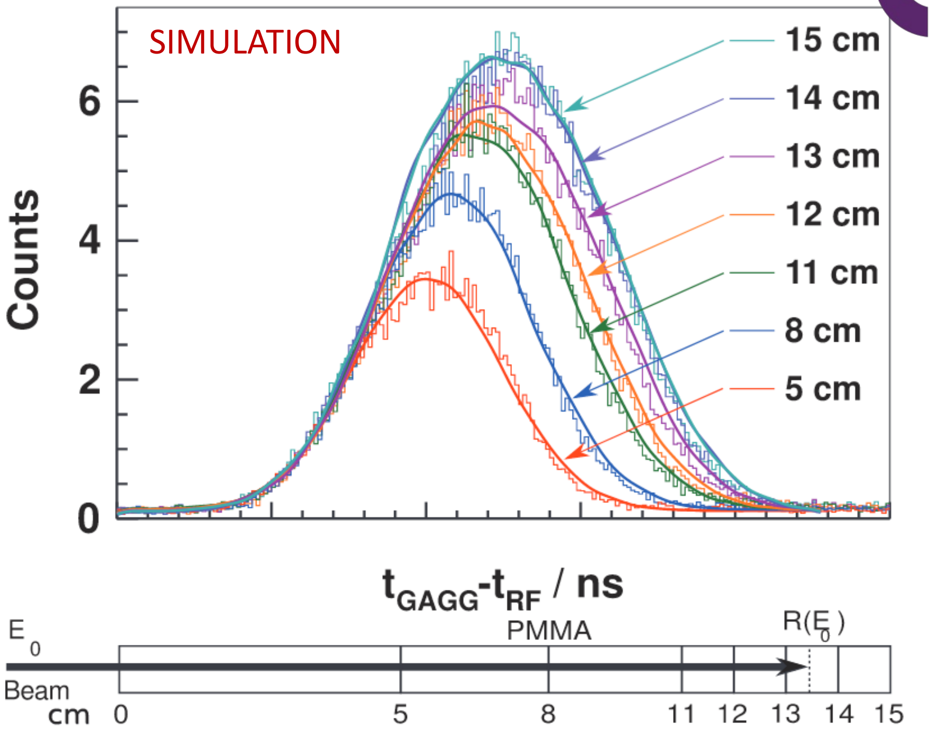


Figure 9. Comparison of experimental (histograms) and modeled time profiles (solid lines) of a PMMA target varied in thickness. All experimental curves are normalized to one incident gigaproton (10^9 protons). The experimental PGT spectra energy ROI is *All*4440 (3.2 MeV–4.6 MeV). The modeled PGT spectra are based on the *simG*4 profile for g_x. The absolute time offset of the modeled data was set to fit the mean for 5 cm PMMA thickness. The experimental detector setup (figure 7) was taken into account to incorporate the influence of the prompt γ-ray time of flight on the spectral shape. The modeled system time resolution is $\sigma_\Sigma = 450$ ps (9).

Golnik et al. Phys. Med. Biol. 59 (2014) 5300

Outline

Advantages and challenges in Prompt Gamma Timing (PGT)

Towards a new approach: Prompt Gamma Time Imaging (PGTI) with TIARA

- Detector development
- Experimental validation of TIARA
- Future perspectives

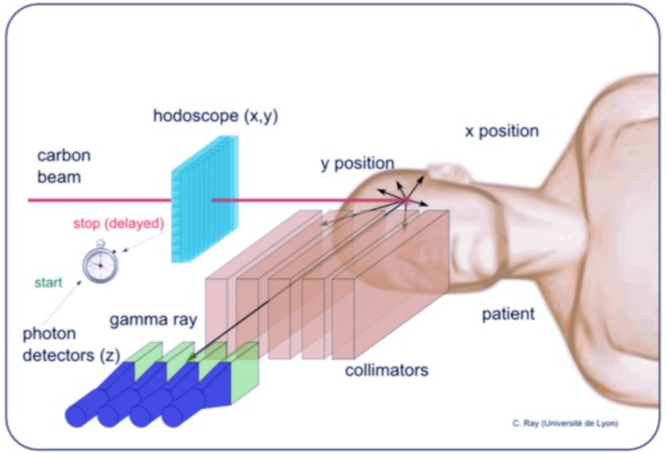
Advantages : no need for collimation

Gamma camera

Det. Efficiency :

$\epsilon \sim 10^{-5}$

Physical collimator

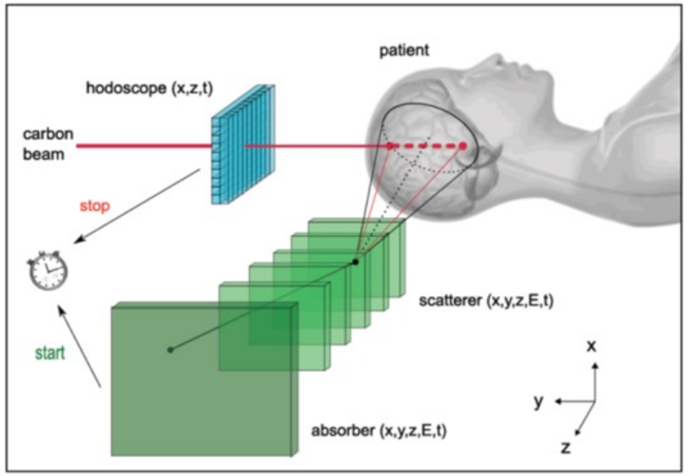


Compton camera

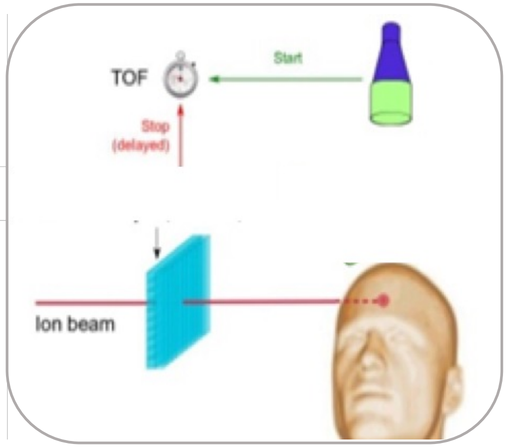
Det. Efficiency :

$\epsilon \sim 10^{-5} \div 10^{-4}$

Electronic collimation



Prompt Gamma Timing



$$\epsilon = \epsilon_\gamma \times \frac{S}{4\pi r^2}$$

e.g.

$\epsilon_\gamma \sim 0.2$; S = 4 cm^2 ; r = 20 cm

$\epsilon \sim 10^{-4}$ per detector module

No collimation means:

- Relatively high detection efficiency (easy to upgrade)
- Compact and light detection system
- Reduced amount of material to avoid secondary neutrons and PGs

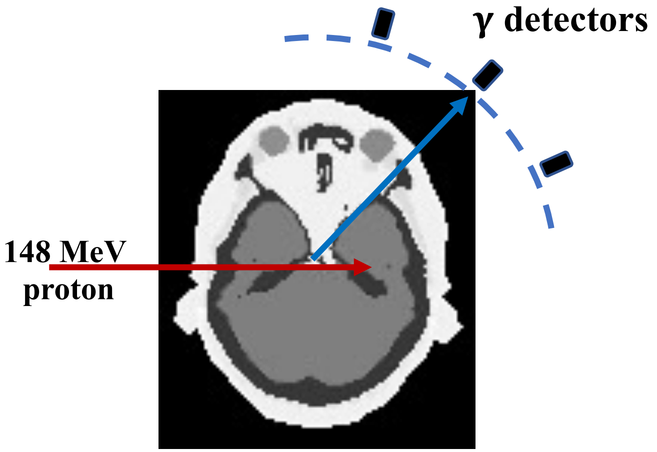
=> Impact on Signal To Noise ratio

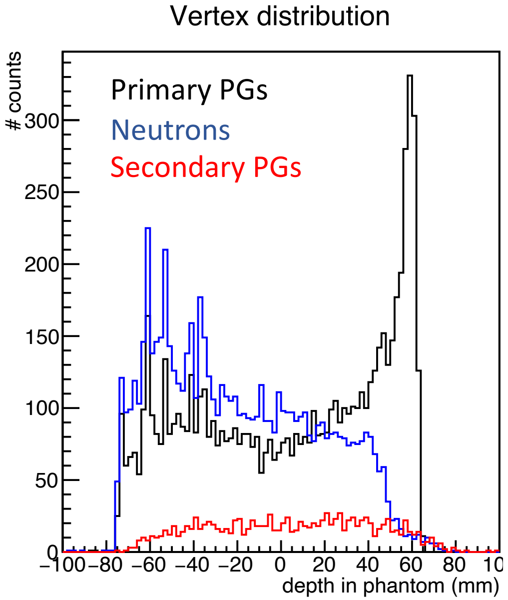
*Pictures from CLaRyS collaboration

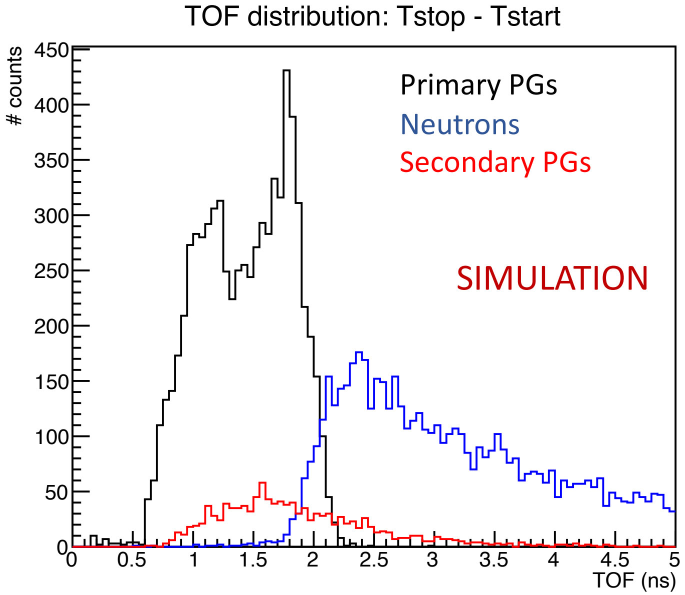
Advantages: TOF neutron rejection

Ideal example

- 148 MeV protons impinging on a human head phantom (ICRP110)
- 30 perfect detectors surrounding the phantom (d=15 cm)
- Ecut = 3 MeV

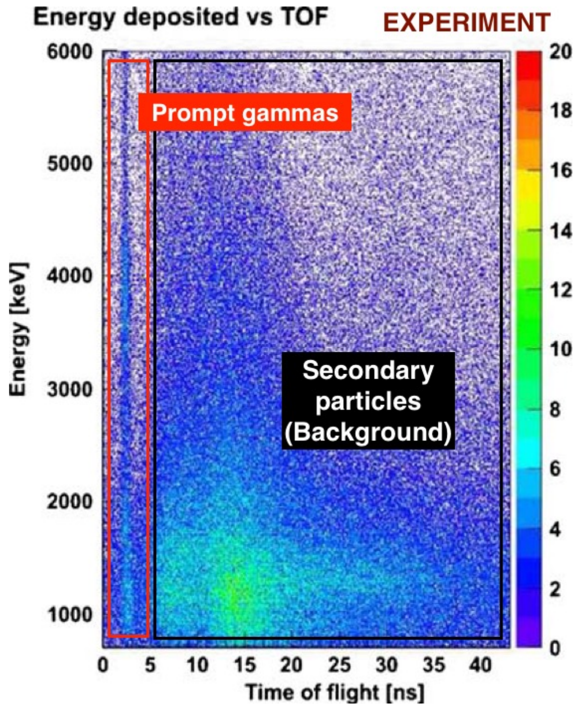






Experimental proof (CLaRyS* collaboration)

- 95 MeV/u ^{12}C beam on PMMA
- BaF_2 at d>50cm from target



Testa et al. Radiat Environ Biophys ***49****, 337–343 (2010)*

A TOF resolution of ~ 1 ns is enough to reject most neutrons

* IP2I, LPSC, CPPM, CREATIS

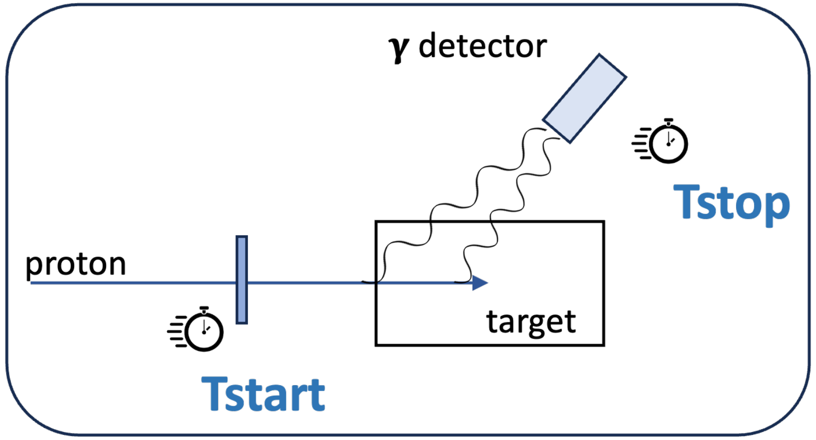
Challenges in PGT optimisation

At single-event scale : improve time resolution

1) Time resolution on reference time (Tstart)
   => Development of a dedicated beam monitor

2) Time resolution of PG detector (Tstop)
   => Development of a dedicated γ detector (**TIARA**)

3) Beam temporal structures

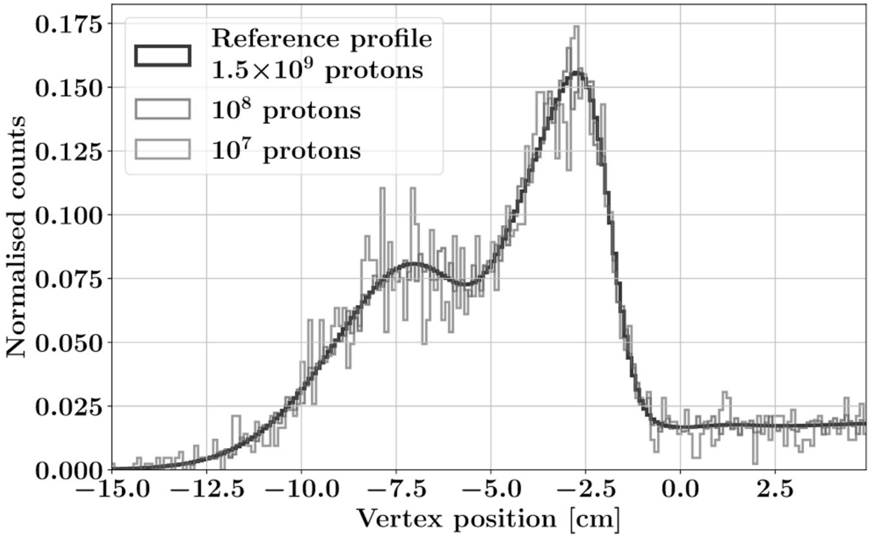


At pencil beam scale : improve detector sensitivity

1) SNR and background

2) Detector arrangement

SIMULATION



Improve time resolution: beam temporal structure

Temporal structures of main accelerators

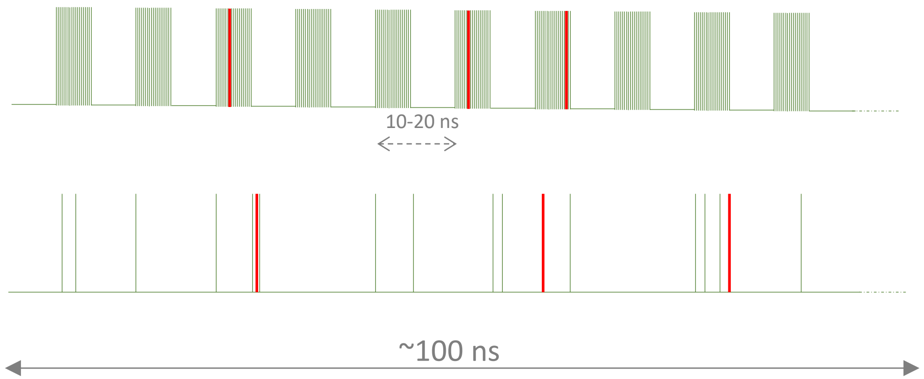
		Synchrotron (CNAO)		Cyclotron (IBA, Varian)	Synchro-cyclotron (S2C2 IBA) *
		^{12}C	protons		
Typical intensity (ions/s)		10^7	10^9	10^{10}	10^{11}
Macro-structure	Period (s)	4–5		∅	10^{-3}
	Spill duration (s)	~2		∅	8×10^{-6}
	Ions/spill	10^7	10^9	∅	10^8
Micro-structure	Period (ns)	~500		10	16
	Bunch width (ns)	~100		0.5–2	8
	Ions/bunch	1–10	n.a.	200	10^5

* values at extraction

At the time-scale of γ detectors (ns)

Cyclotron/
synchro-cyclotron

Synchrotron



In red, protons producing a PG

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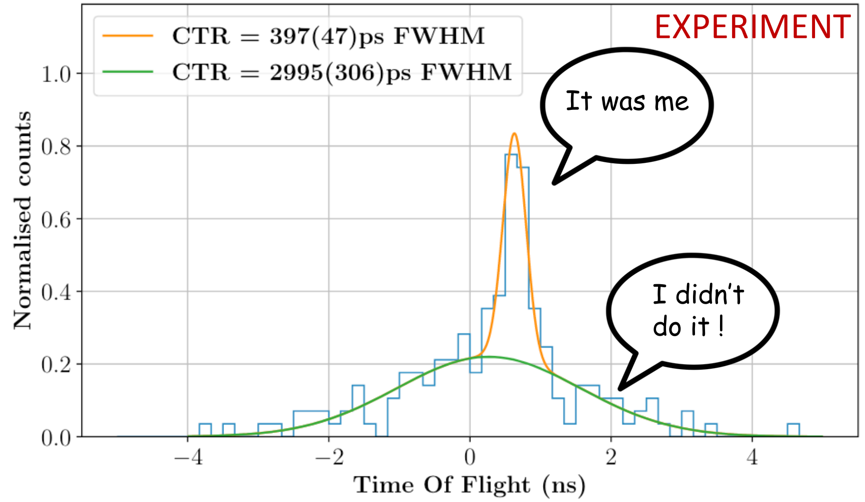
S2C2 synchro-cyclotron: 8 ns bunch width, 7 p/bunch, thin target

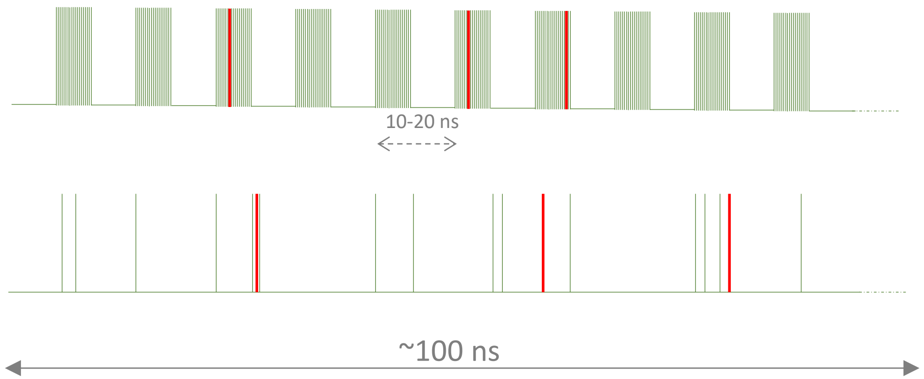


Jacquet et al. Scientific report (2023) 13:3609

At the time-scale of γ detectors (ns)

Cyclotron/ synchro-cyclotron

Synchrotron



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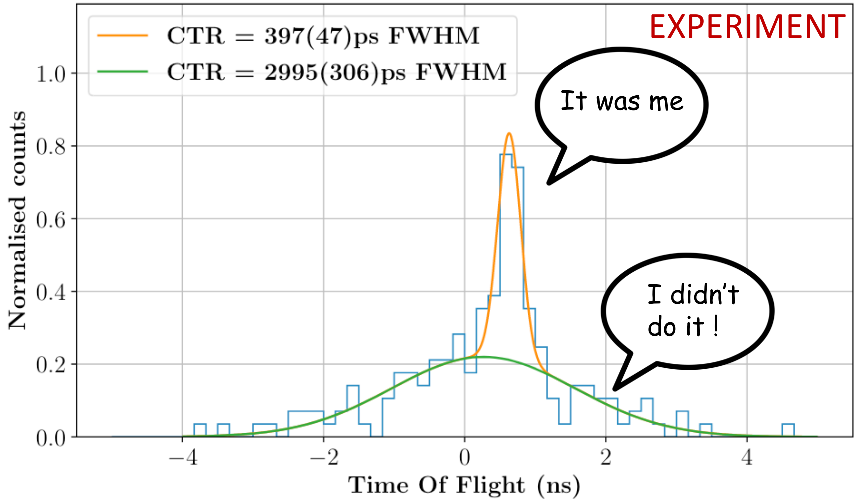

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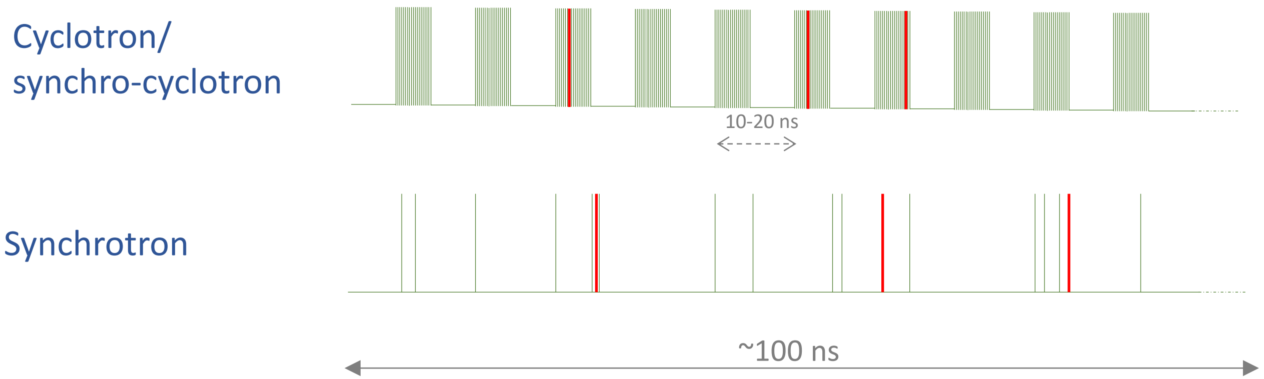
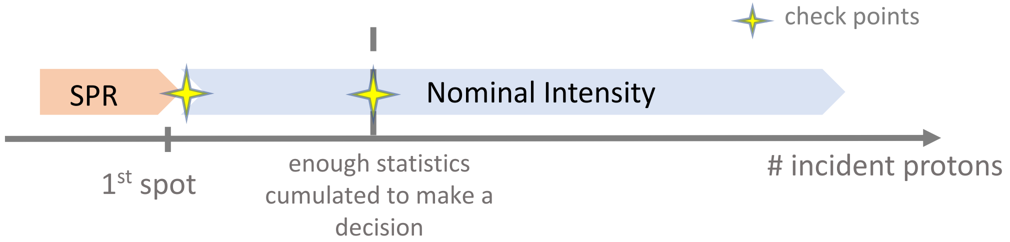
At the time-scale of γ detectors (ns)



In red, protons producing a PG

Reduce bunch-width related time uncertainty

Lower the beam intensity to Single Proton Regime (SPR)



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

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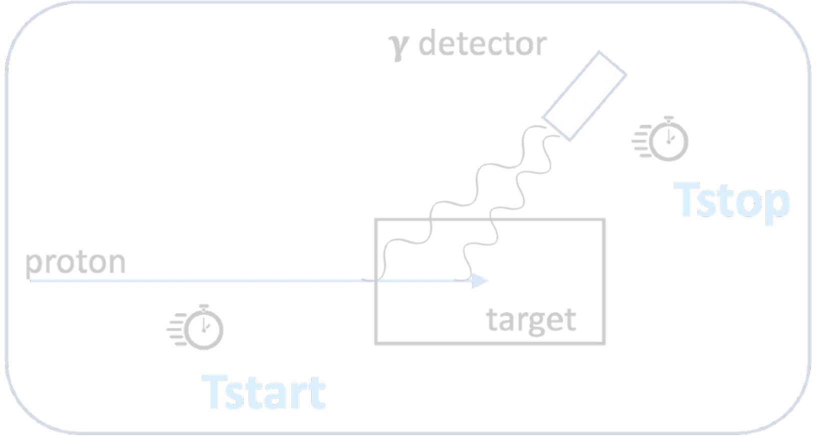
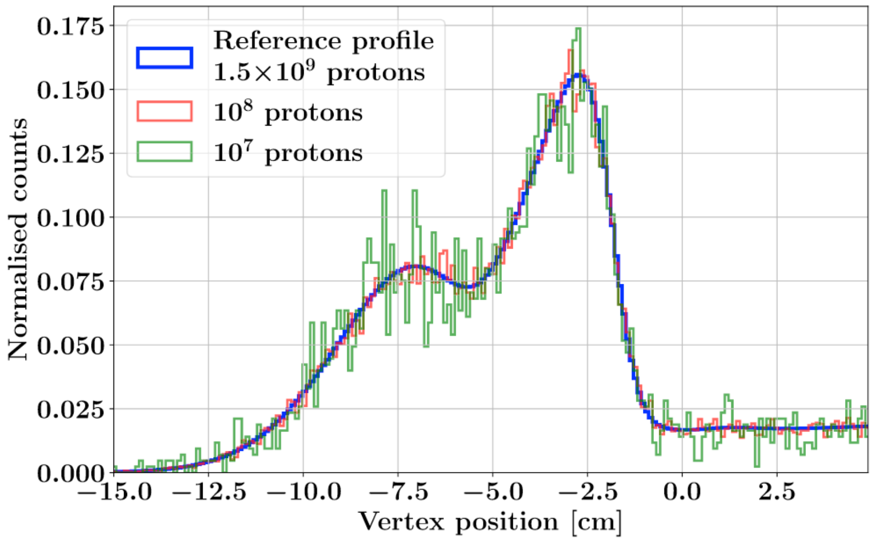


At pencil beam scale : improve detector sensitivity

1) SNR and background

2) Detector arrangement

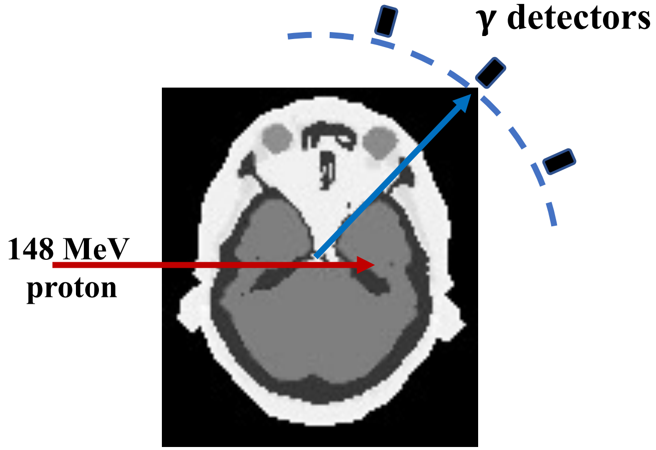
SIMULATION



Improve detector sensitivity: SNR and background

In order to maximise the SNR

- Increase detection efficiency
- Avoid detector pile-up
- Reject background



A practical example

- 148 MeV protons
- 30 perfect detectors
- Energy threshold = 3 MeV

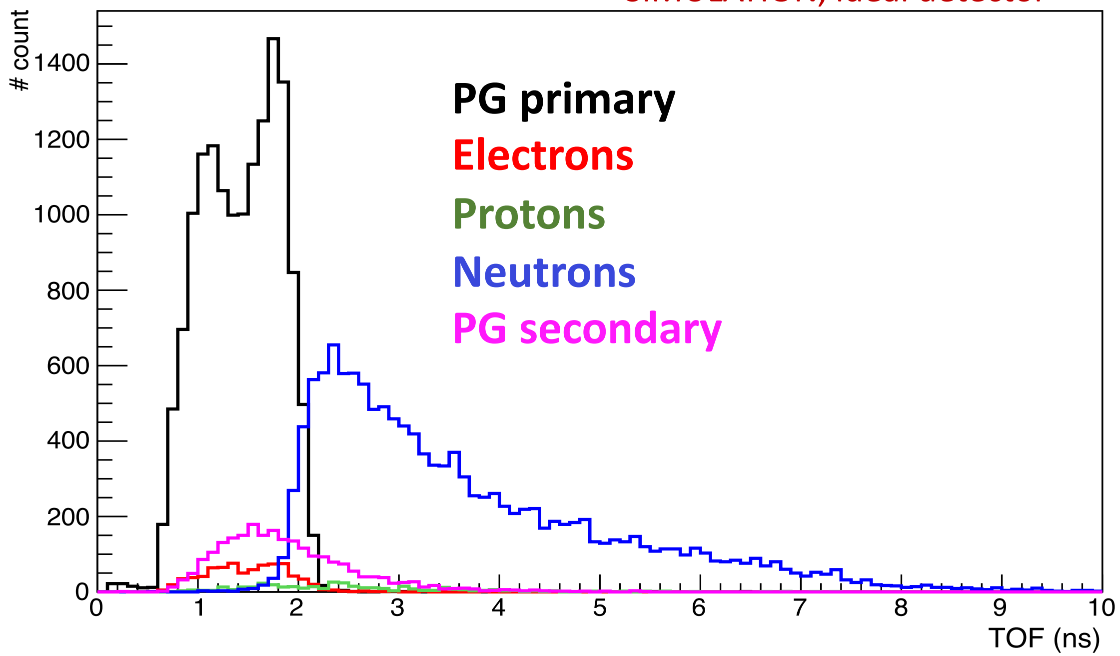
Electrons
Few, mostly rejected with acquisition threshold

Protons
Few, cut on the E vs TOF distribution

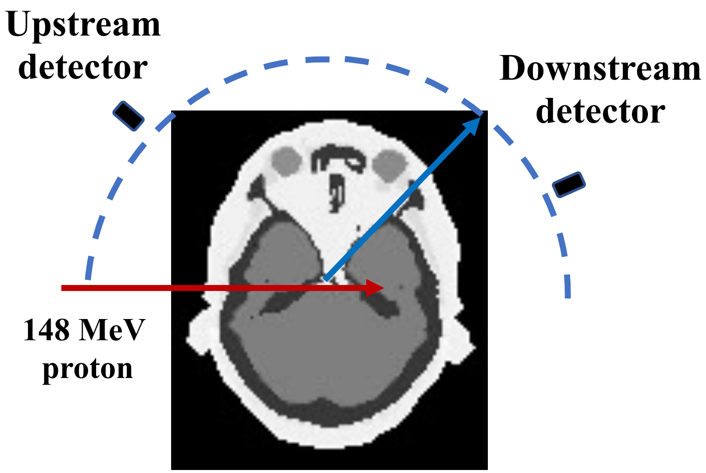
Neutrons
TOF rejection does not work at PG profile fall-off
⇒ Affect proton range measurement

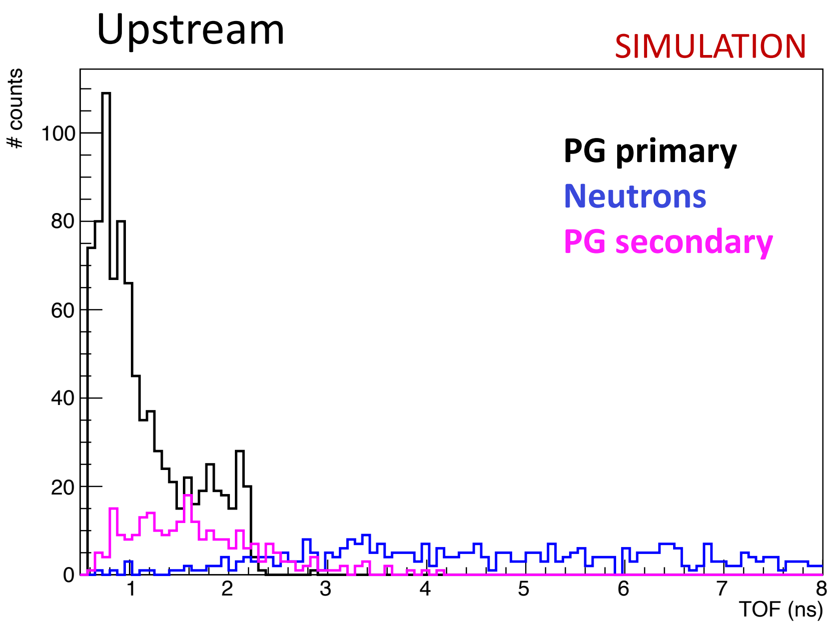
Secondary PGs
Same energy and timing of primary PGs.
=> Affect proton range measurement

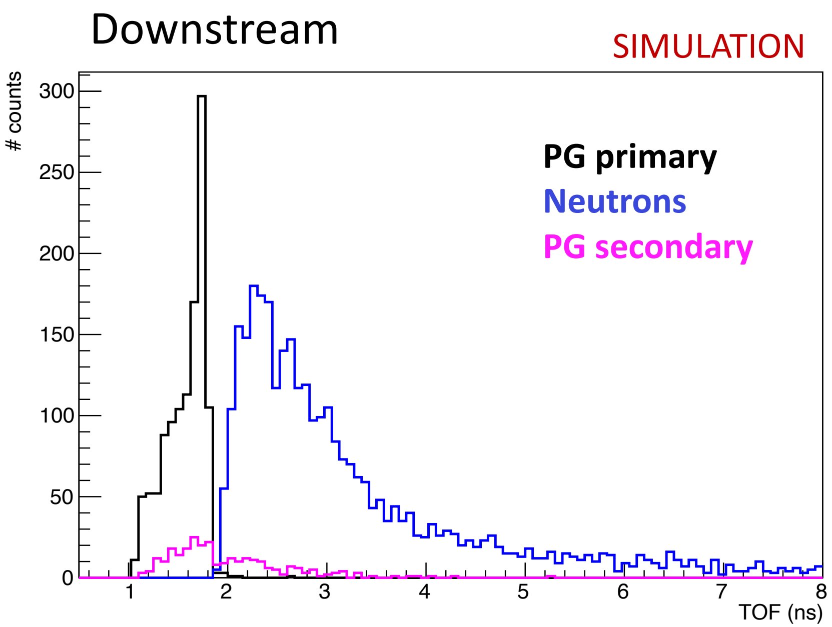
SIMULATION, ideal detector



Improve detector sensitivity: detector arrangement





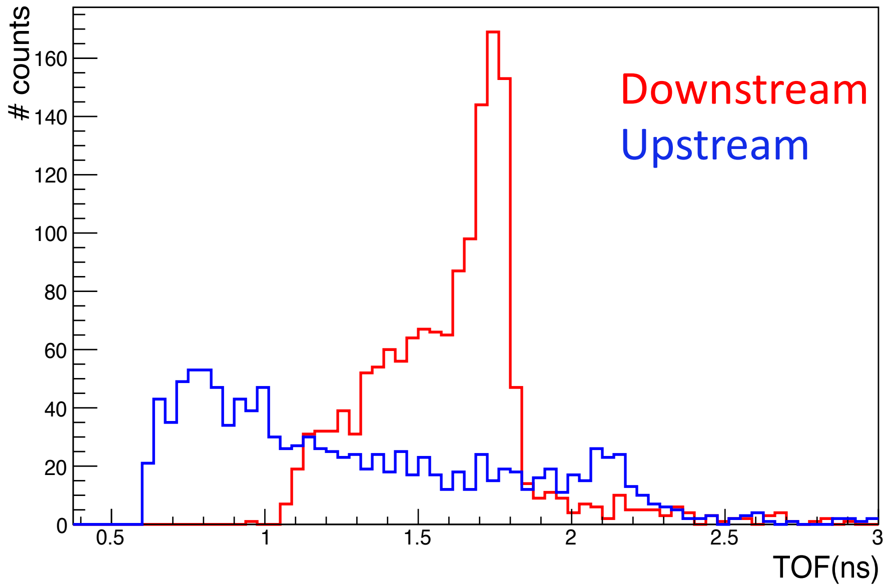


Placing the gamma detector upstream is more advantageous for background reduction, but the fall-off is less sharp

Downstream detectors could provide a more accurate proton range measurement but neutrons affect the determination of the fall-off.

Improve detector sensitivity: detection efficiency

MC simulation, ideal detectors



Experiment, CTR=124 ps rms

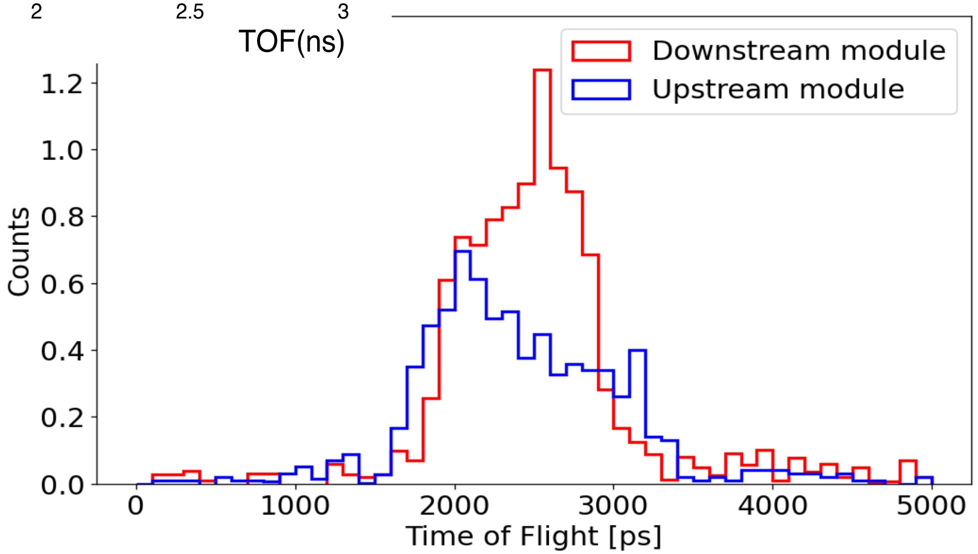


Fig. The two TOF distributions are produced by the same proton beam, but they extend on different time ranges as the PG TOF contribution depends on the detector position.

TOF distributions from detectors placed at different angles **cannot be summed up in the time domain**.

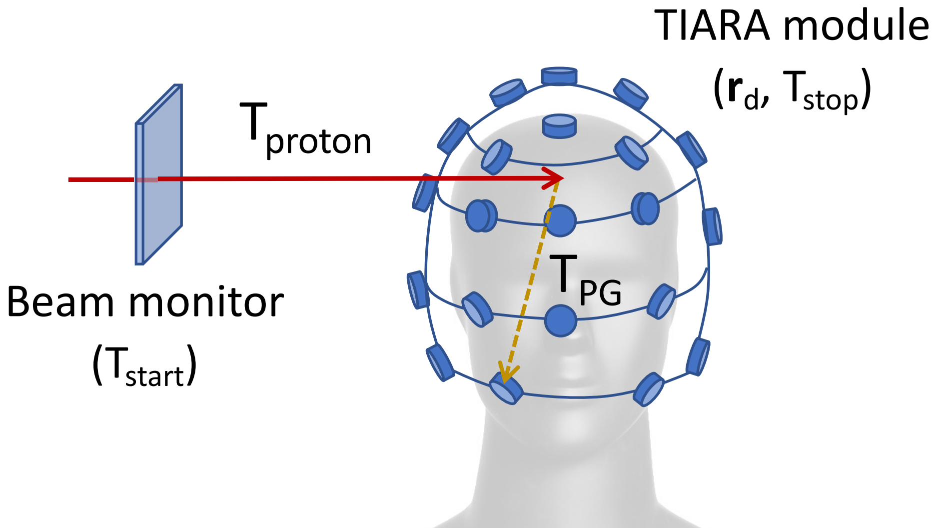
But, we need to increase the number of detectors in order to:

- Increase the detection efficiency
- Have a uniform response all over the proton range (for dosimetry)
- Build a system compatible with IMPT

Towards a new approach: Prompt Gamma Time Imaging (PGTI) with TIARA

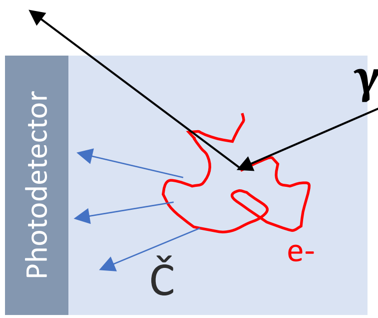
The TIARA (Tof Imaging ARrAy) detector

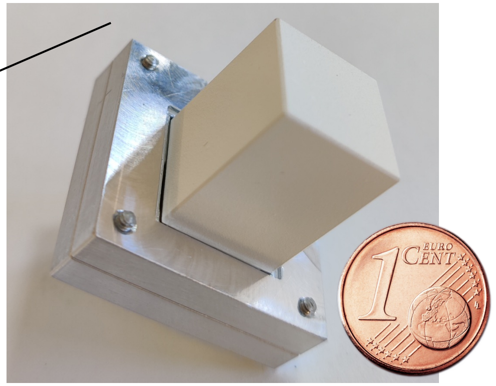
A dedicated detection system: TIARA



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

Cherenkov-based gamma detector



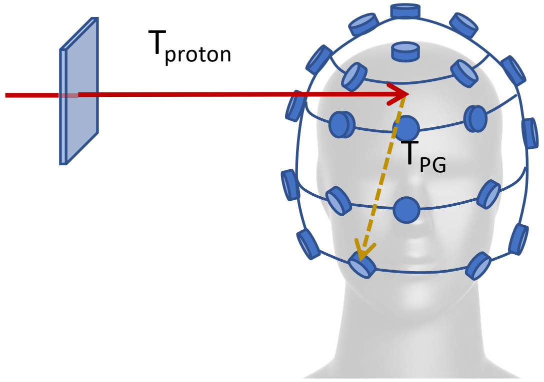


Targeted time resolution = 100 ps rms

Cherenkov detectors instead of conventional scintillators

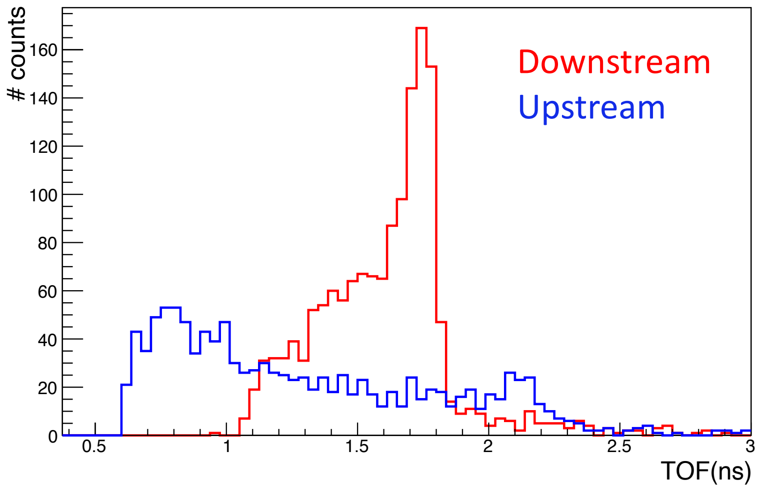
- Faster
- Shorter pulses and low LY (pile-up)
- Higher density => higher det. efficiency
- Very low sensitivity to background (threshold process)!

From PGT to Prompt Gamma Time Imaging



Issue: TOF distributions from detectors placed at different angles **cannot be summed up in the time domain**.

SIMULATION: ideal detectors



A dedicated image reconstruction: PGTI

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

2 unknowns: $\mathbf{r}_v$ = PG vertex $\mathbf{v}_p$ =proton speed

Allows combining the response of multiple detectors:

- Increase the detection efficiency
- to reach uniform sensitivity all over the ion range
- for IMPT compatibility
- From range monitoring to PG imaging

First approach: biased PGTI reconstruction

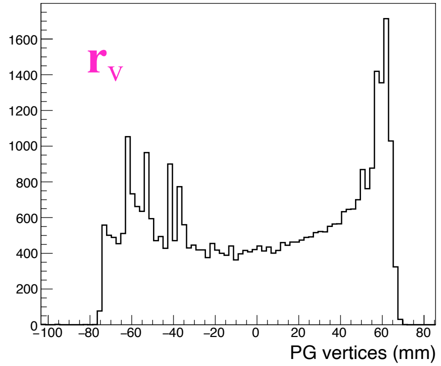
M. Jacquet
PhD thesis

Hypotheses: 1) solution along the beam axis (1D)
2) proton time curve is known

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

output →

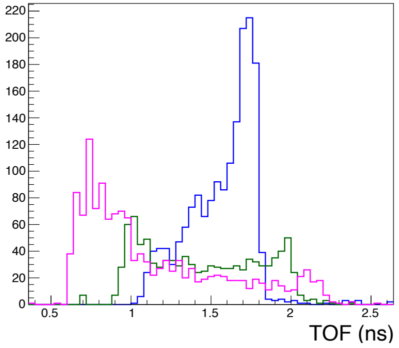
A unique PG vertex distribution

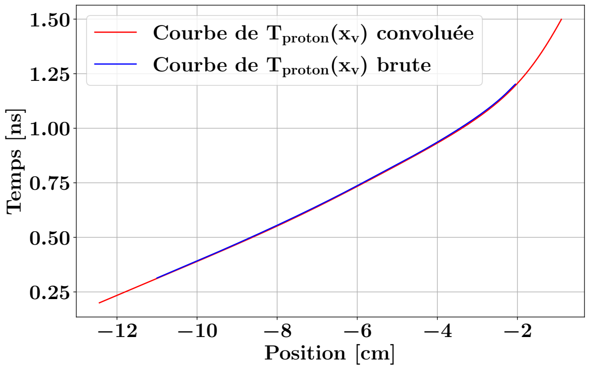


From range monitoring to PG imaging

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

TOF: one histogram per detector





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

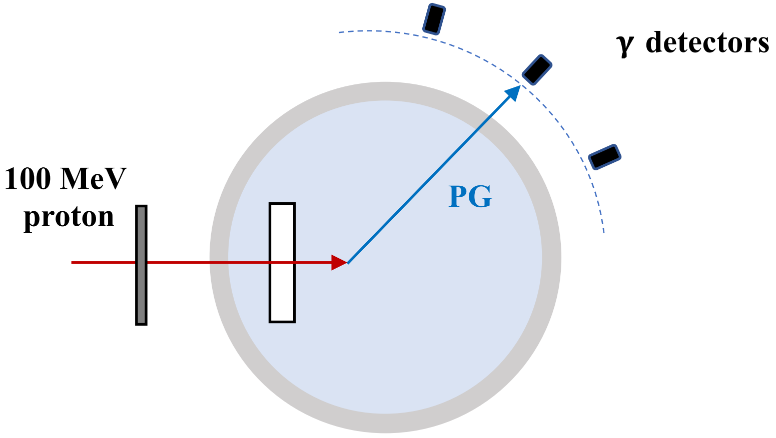
DOES NOT provide actual PG distribution in case of anatomical variation but **sensitive enough to detect a variation from TPS**

Biased PGTI reconstruction: MC validation

M. Jacquet
PhD thesis

MC validation

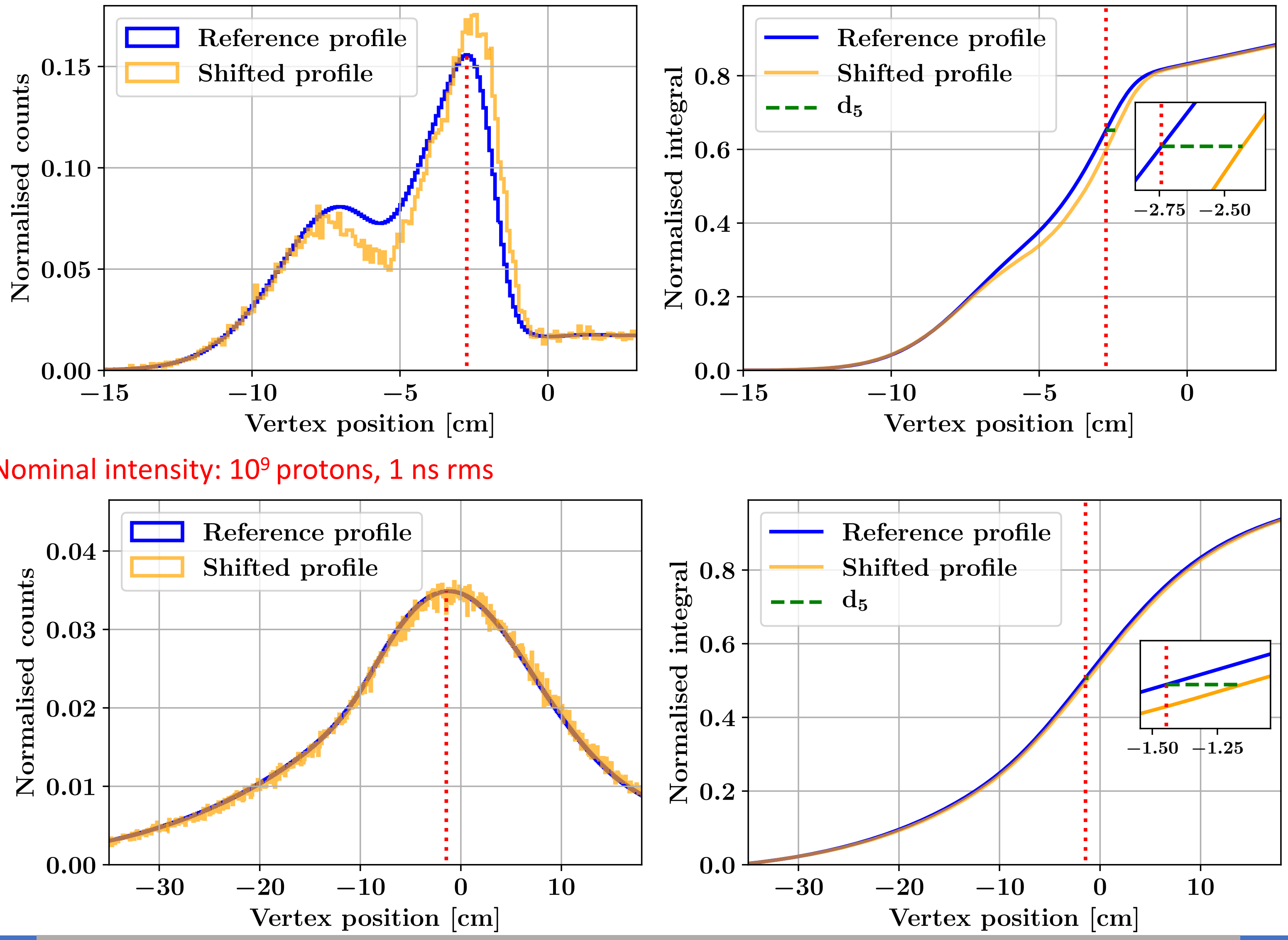
- 100 MeV protons
- **Air cavity of variable thickness (1 mm steps)**
- 30 detection modules (1 cm^3)
- 0.6% overall detection efficiency
- **SNR = 1** (very conservative!)



Reference profile = 1 cm thick air cavity

SPR scenario: 10^8 protons, 100 ps rms

Nominal intensity: 10^9 protons, 1 ns rms



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

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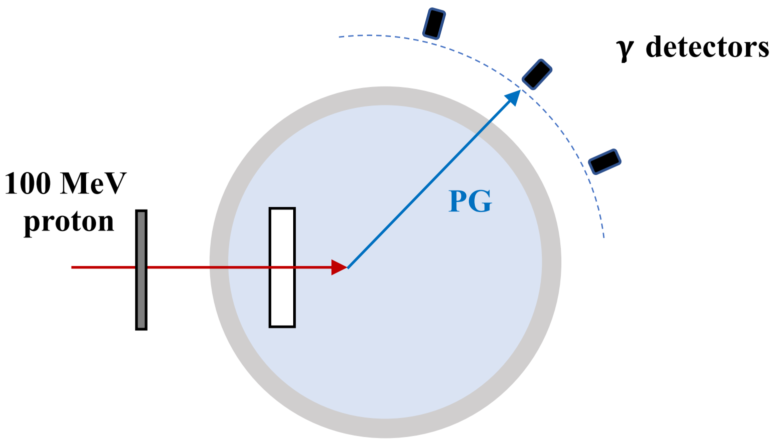
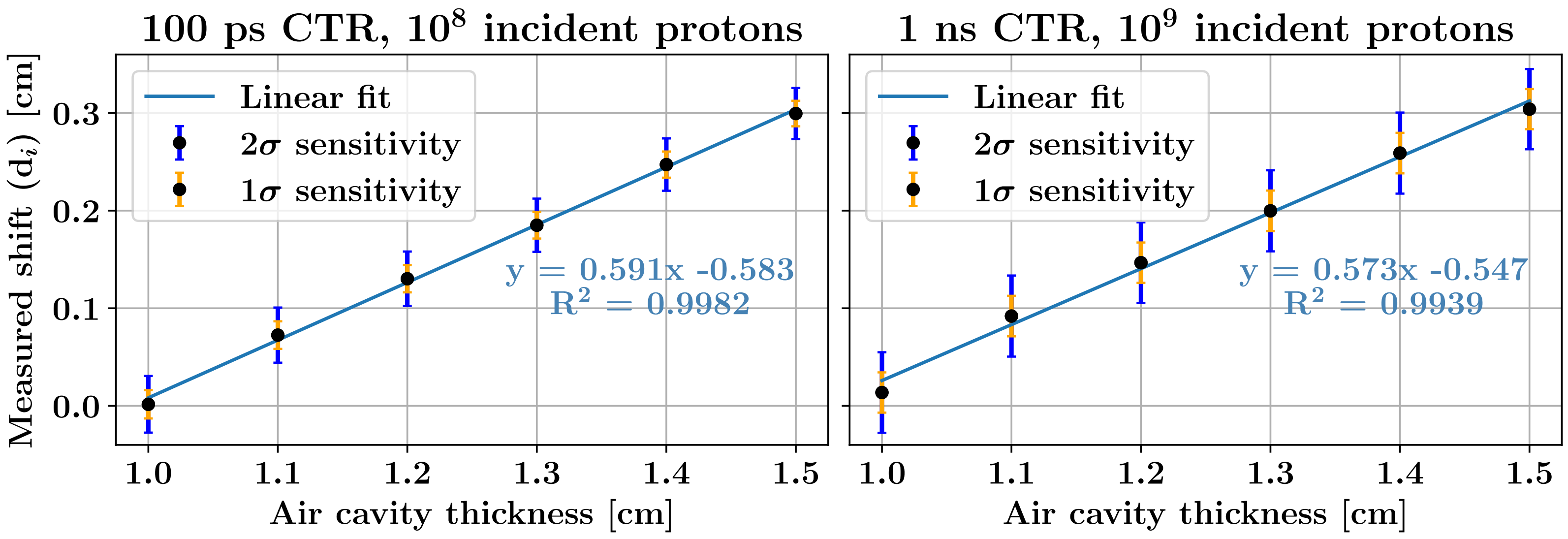


Range accuracy is a compromise between time resolution and proton statistics

Reference profile = 1 cm thick air cavity

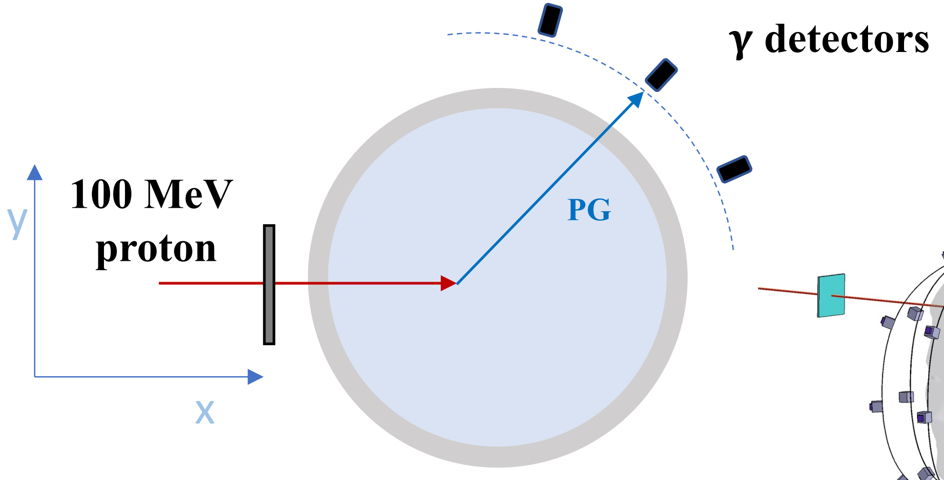


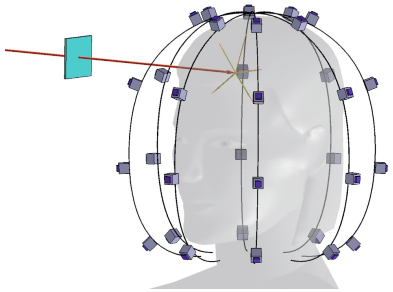
Measured parameter	CTR (RMS)	# protons	# PG	Accuracy at 1 σ	Accuracy at 2 σ	Beam Intensity	Goal
Range shift	100 ps	10^7	3 x 10^3	2	3	SPR	Pre-treatment probing
	100 ps	10^8	3 x 10^4	1	1		
	1 ns	10^9	3 x 10^5	1	2	Nominal	On-line monitoring

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

Measurement of lateral beam displacement with TIARA and COG

M. Jacquet PhD thesis

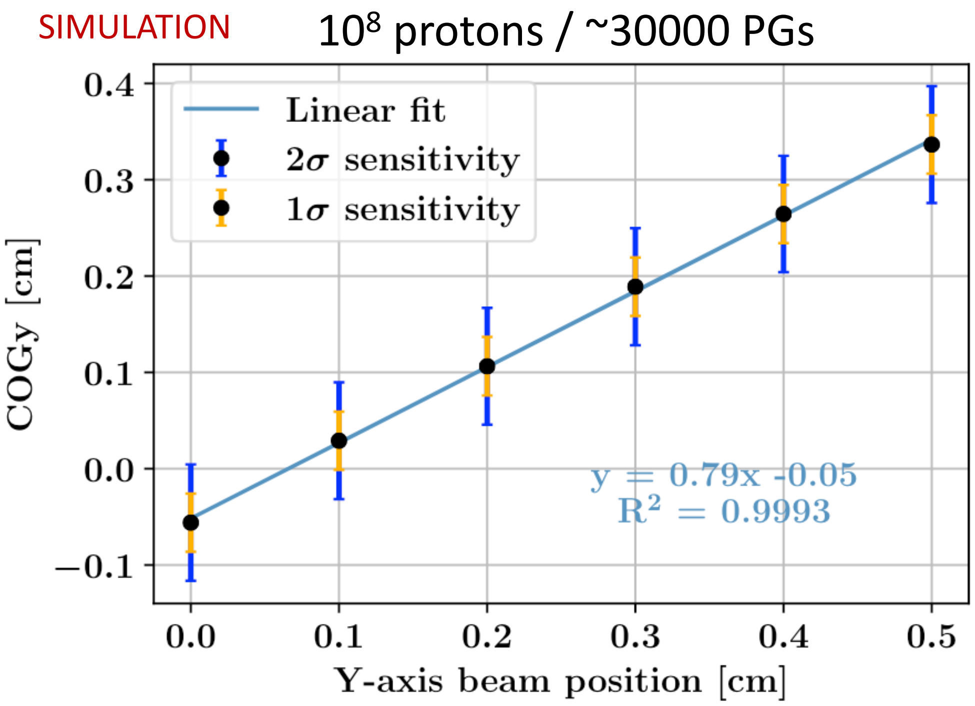




$$Y_{COG} = \frac{1}{N}\sum_{i=1}^{N_{Det}} y_i n_i$$

N = total number of PG detected
n_i = number of PG detected in module $_i$
Y_i = x coordinated of gamma detector

SIMULATION



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

Possible to distinguish a lateral beam displacement of **2 mm (2σ) at PB scale**

With a position sensitive beam monitor, possible to determine the beam direction
=> 1D PGTI reconstruction is relevant

Detector development

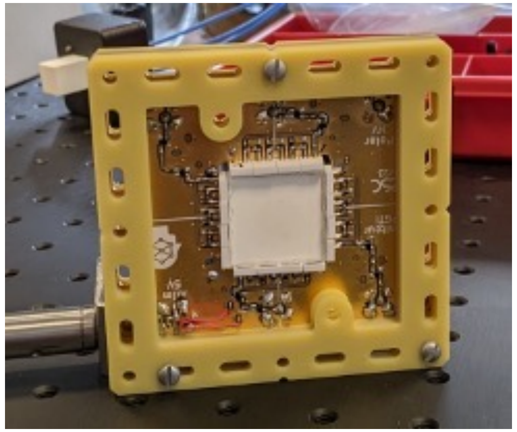
Beam monitor

The TIARA block detector

TIARA beam monitor

A. André
PhD thesis

25 x 25 x 1 mm³ plastic scintillator (EJ-204) readout by SiPMs

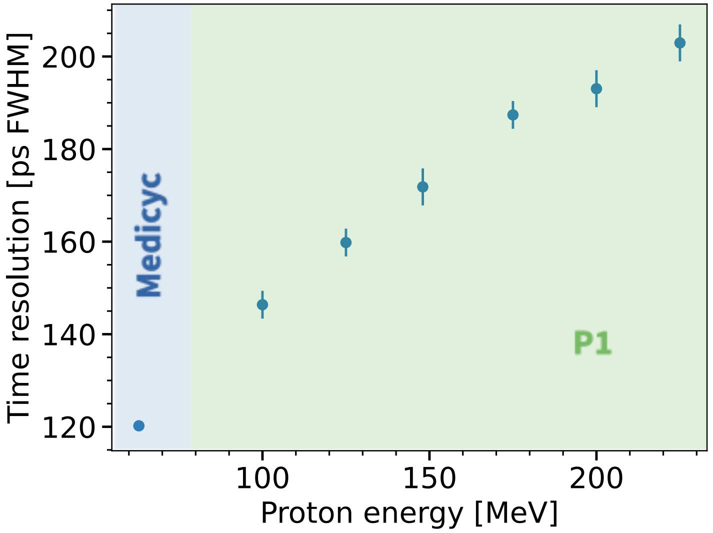


Performances for single protons

- DTR = **51 ps σ at 63 MeV**
- Detection efficiency = 100%
- Spatial resolution =
  ~1.8 mm σ for single protons
  <<1 mm for the beam barycentre

Time resolution

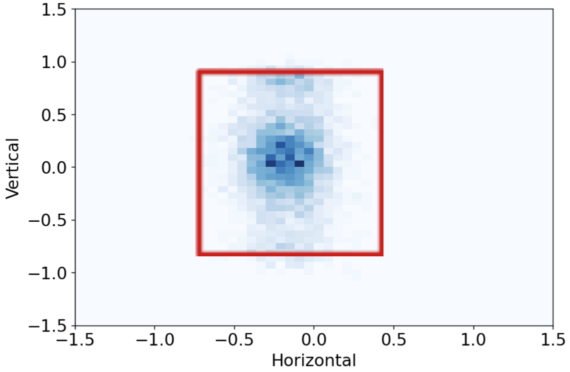
- **Time resolution < 100 ps σ** in the clinically relevant energy range
- Beam energy measured by TOF at Medicyc (63 MeV) with 0.3% accuracy.

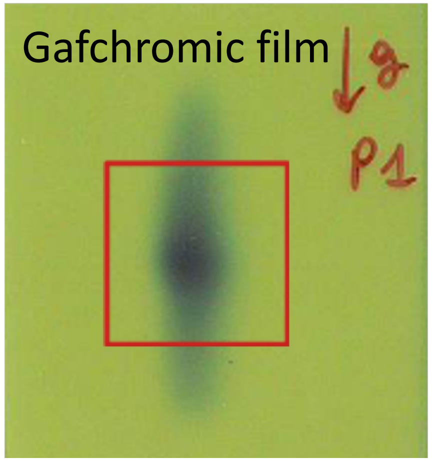


André et al. IEEE TRSMS 2024

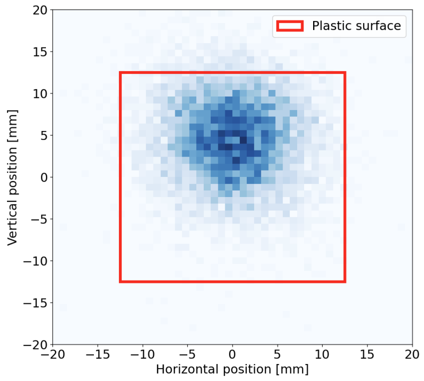
Spatial resolution

Medicyc at 63 MeV

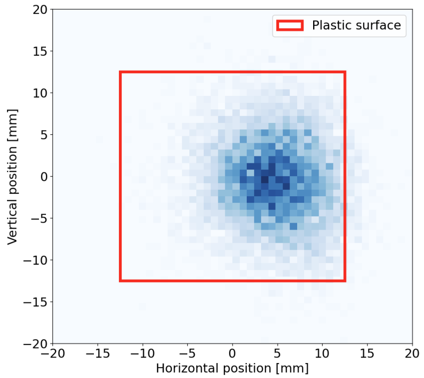




Proteus One at 148 MeV

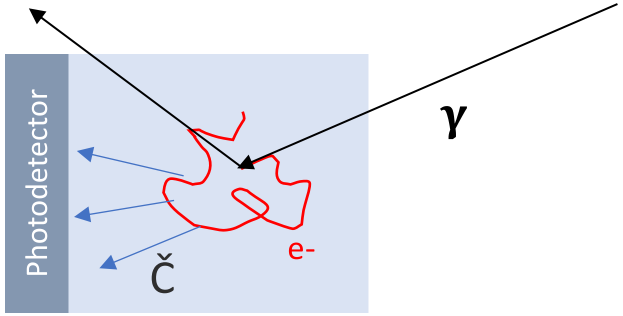


Position (0, 5) mm

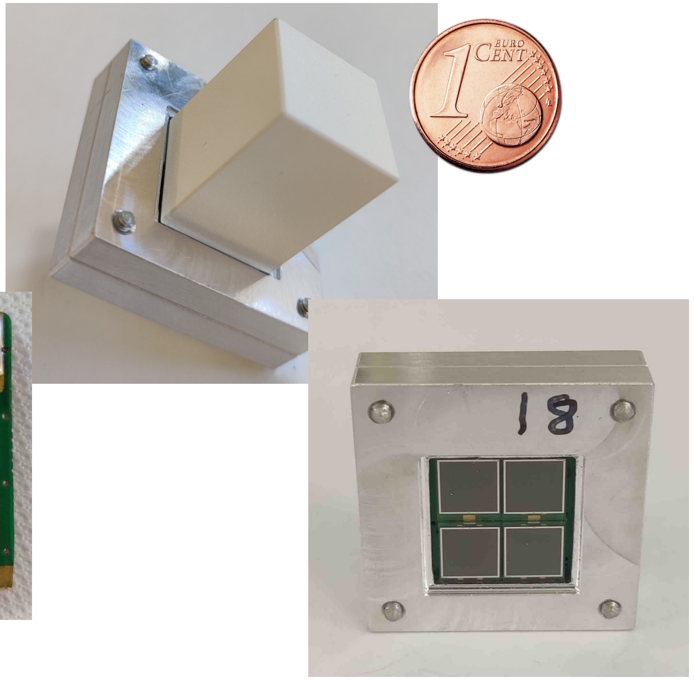


Position (5, 0) mm

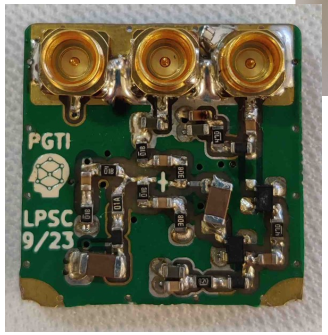
TIARA block detector



TIARA module



Custom front-end

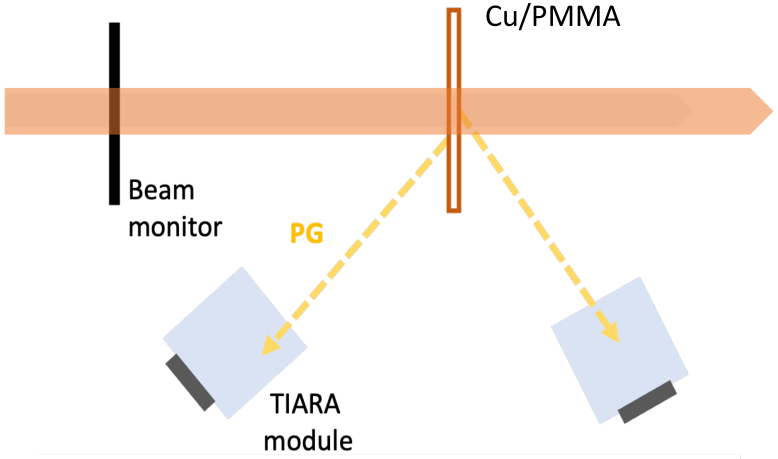


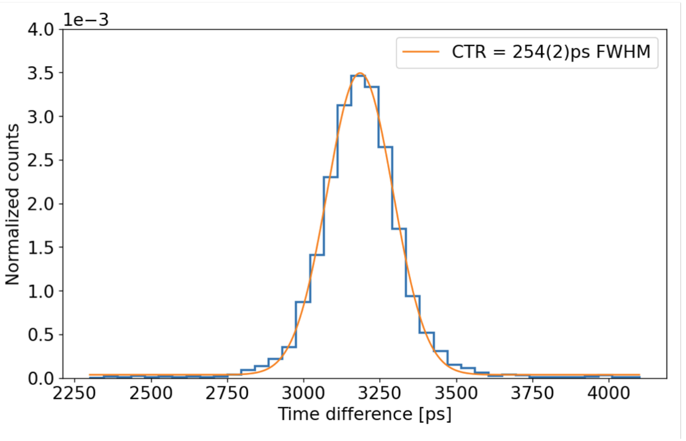
Read-out:
Wavecatcher IJCLAB

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

How we measure the CTR

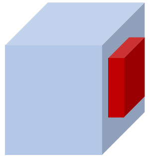


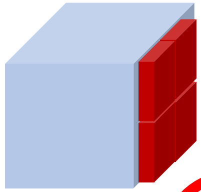


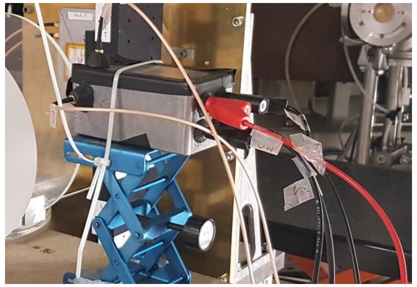
$$CTR^2 = DTR_{mon}^2 + DTR_{\gamma}^2$$

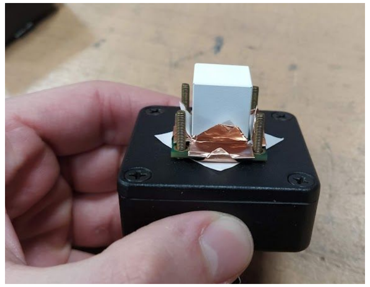
CTR = Coincidence Time Resolution; DTR = Detector Time Resolution

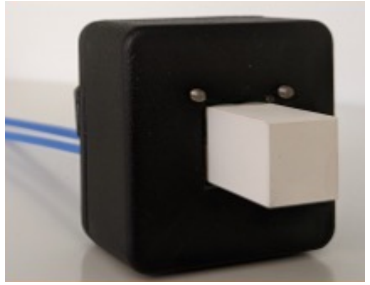
3 years of R&D

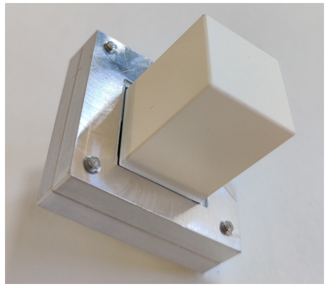












Prototype	v1	v2	v3	v4	v5
Crystal	1 cm^3 PbF_2	2 cm^3 PbF_2	$(1.5\ cm)^3$ PbF_2	$1.5\times1.5\times2$ cm^3 PbF_2	
SiPM	HPK3050	HPK6075			
Nb. of SiPMs	1		4		
Objective	Simple design		Improve detection efficiency Improved or equal time resolution		Compact layout
Front-end	Commercial	LPSC, single channel	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

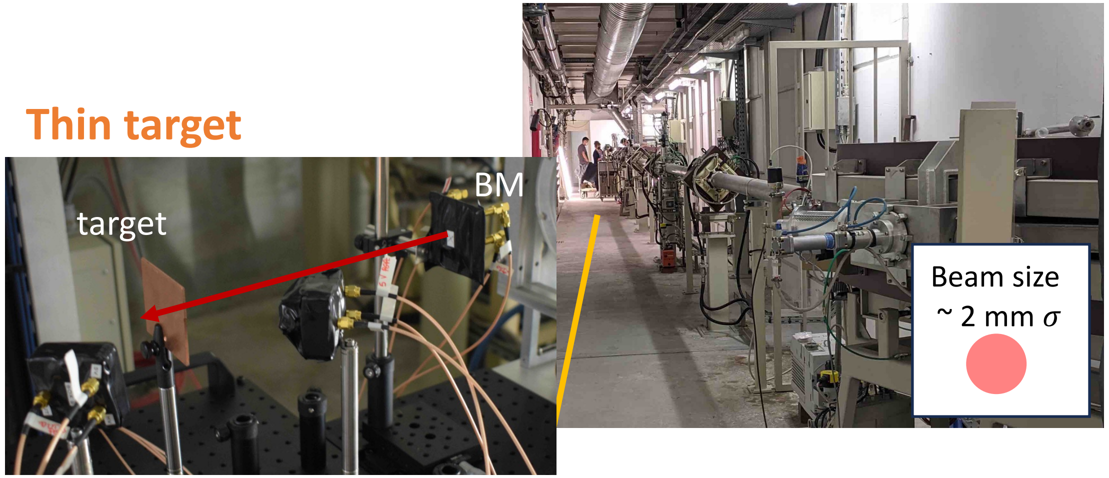
TIARA block detector: SNR (version v3)

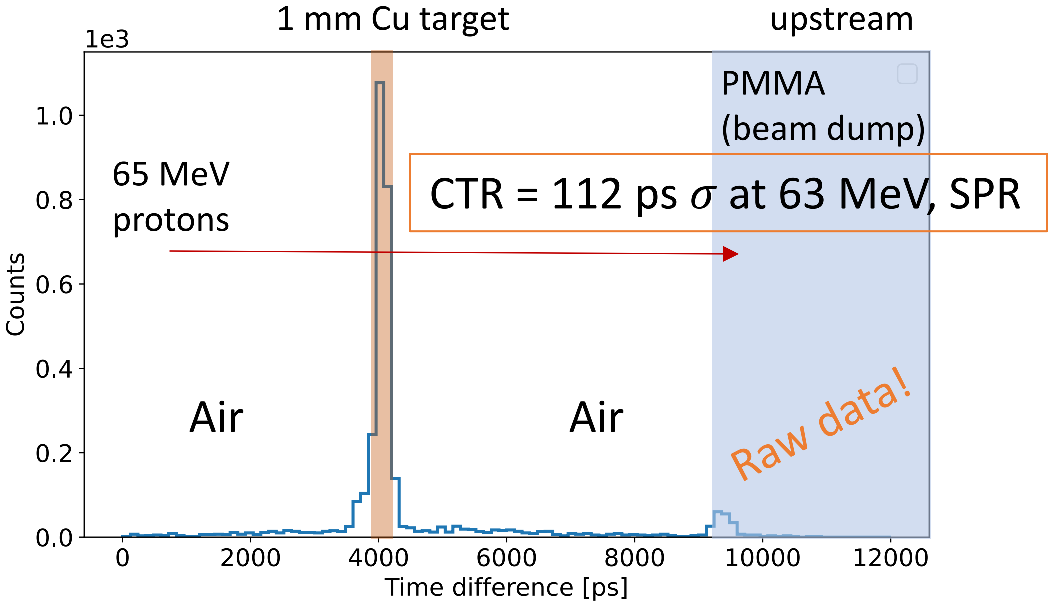
Antoine Lacassagne
CENTRE DE LUTTE CONTRE LE CANCER
unicancer NICE

A. André
PhD thesis

Medicyc (cyclotron, 63 MeV)

Thin target



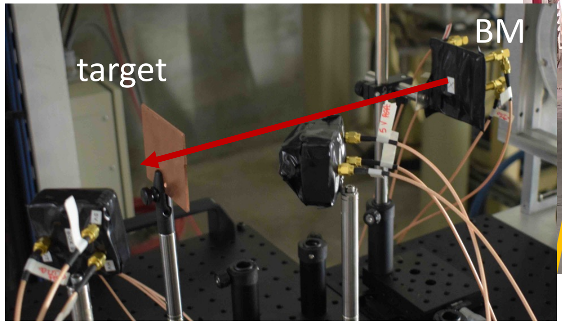


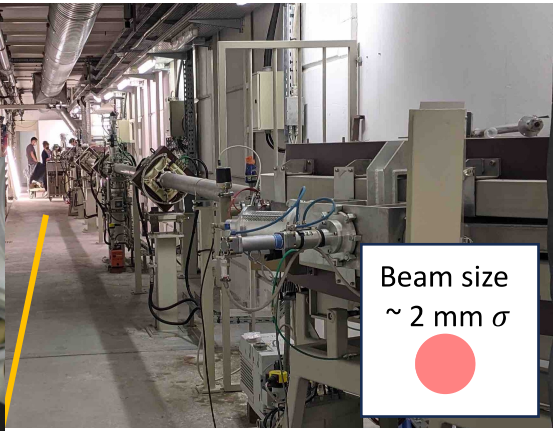
TIARA block detector: SNR (version v3)

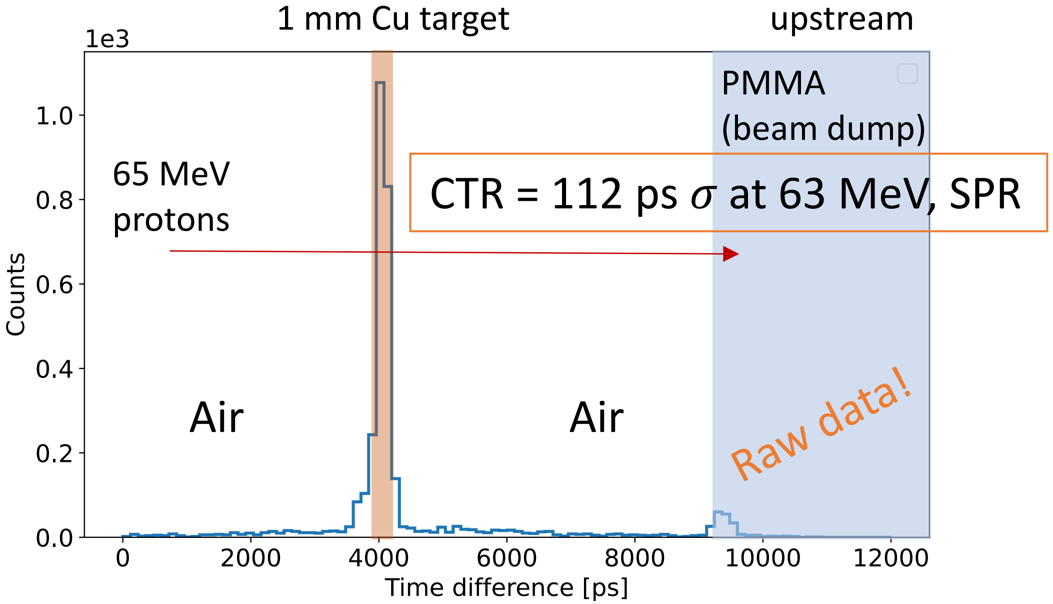
A. André
PhD thesis

Medicyc (cyclotron, 63 MeV)

Thin target





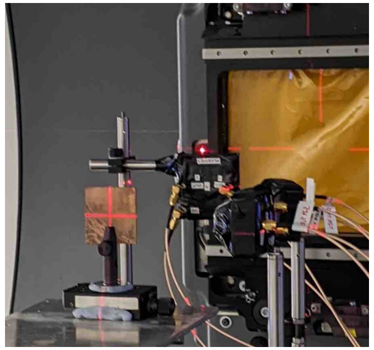


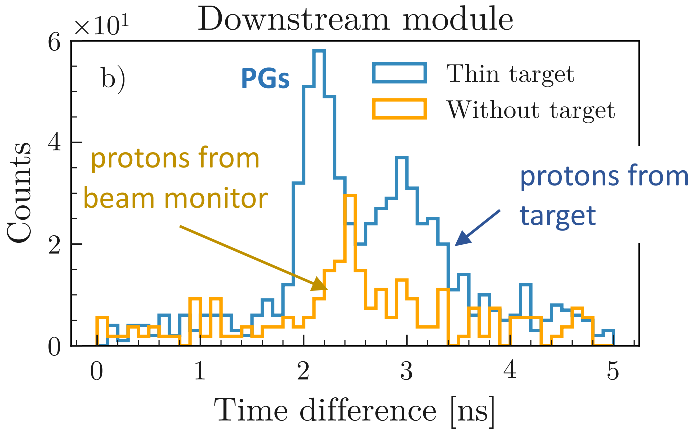
IBA S2C2 (synchro-cyclotron, 148 MeV)

Two sources of background

- protons from beam monitor
- protons from target

Thin target



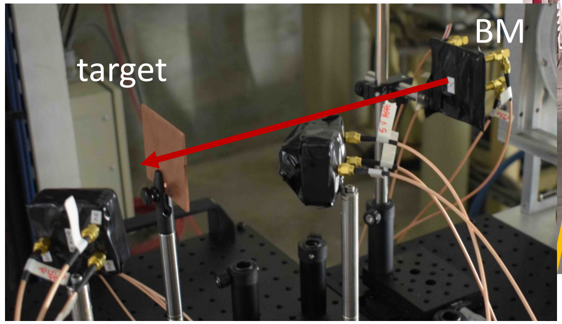


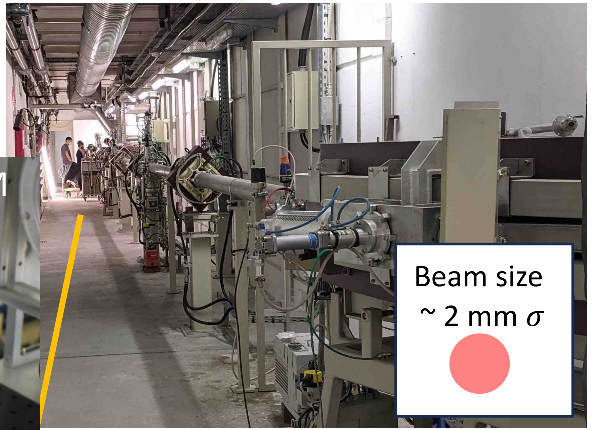
TIARA block detector: SNR (version v3)

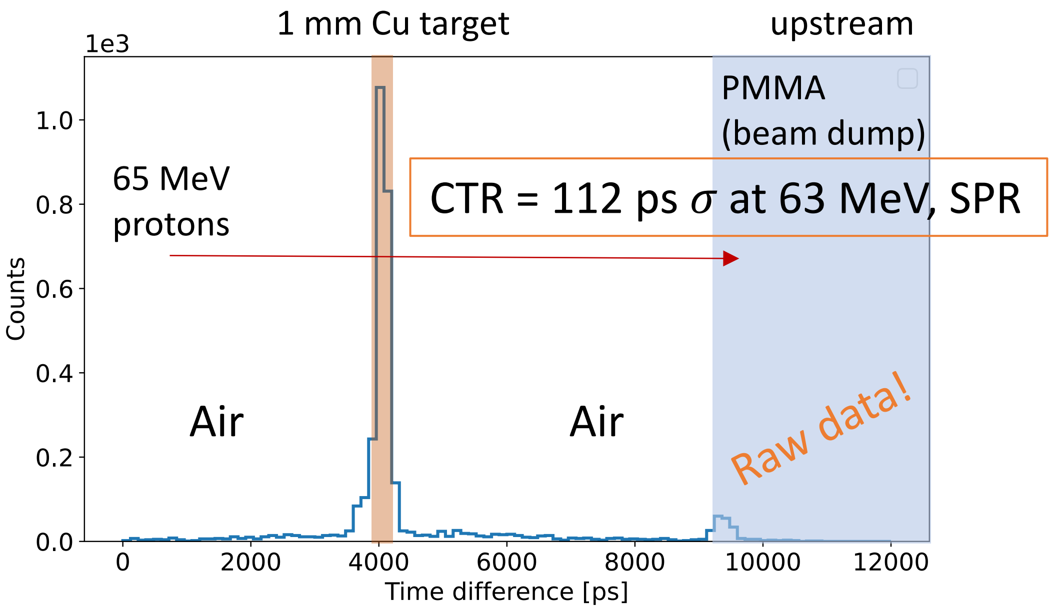
A. André
PhD thesis

Medicyc (cyclotron, 63 MeV)

Thin target



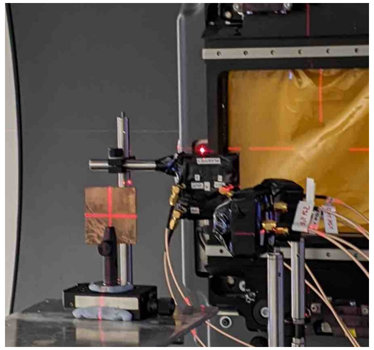


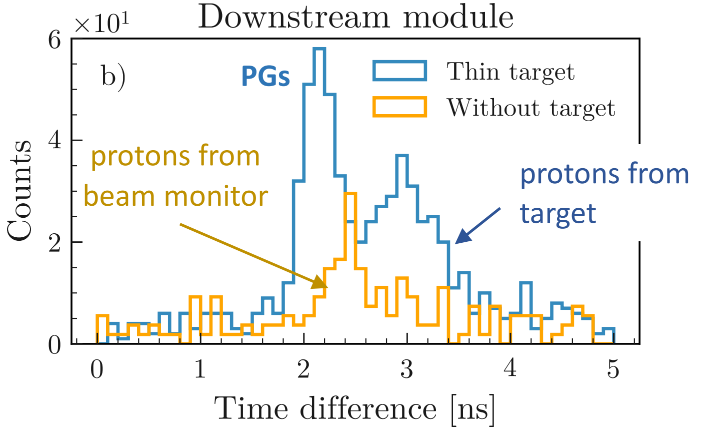


IBA S2C2 (synchro-cyclotron, 148 MeV)

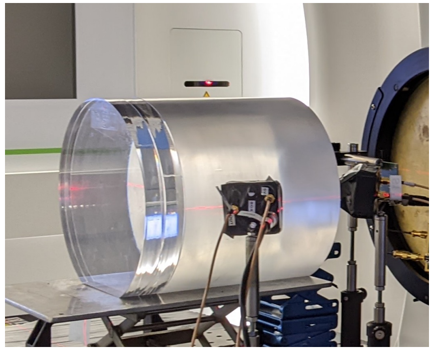
Two sources of background
- protons from beam monitor
- protons from target

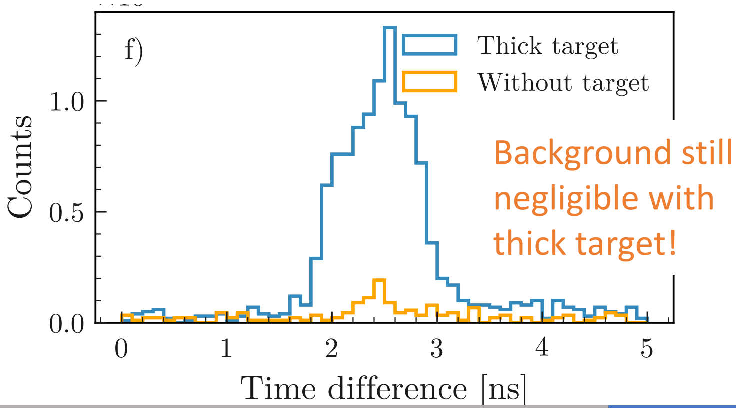
Thin target





Thick target

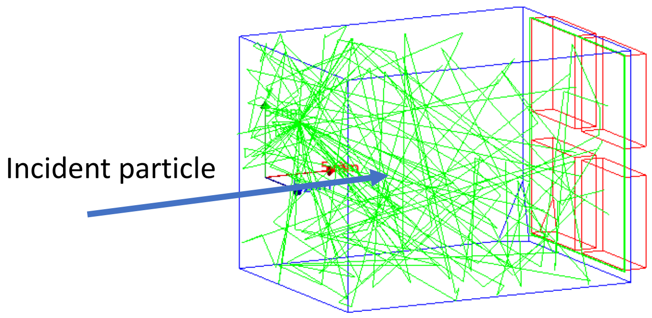




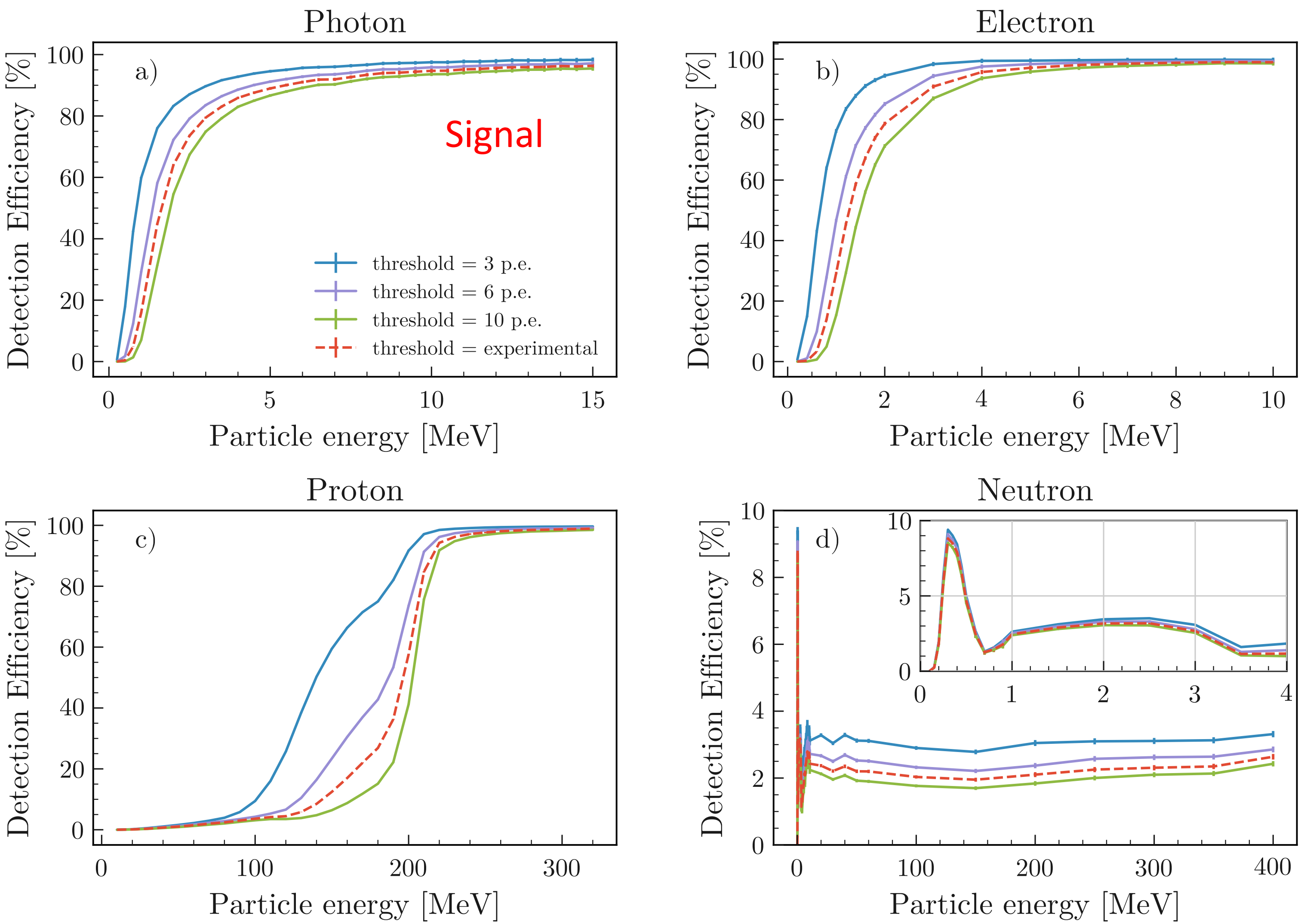
TIARA block detector: detection efficiency

Very low light yield of Cherenkov detectors:
The optical efficiency gives the probability that an event occurring in the crystal is actually detected by the SiPMs.

$$\epsilon = \epsilon_{geo} \times \epsilon_{int} \times \epsilon_{opt}$$



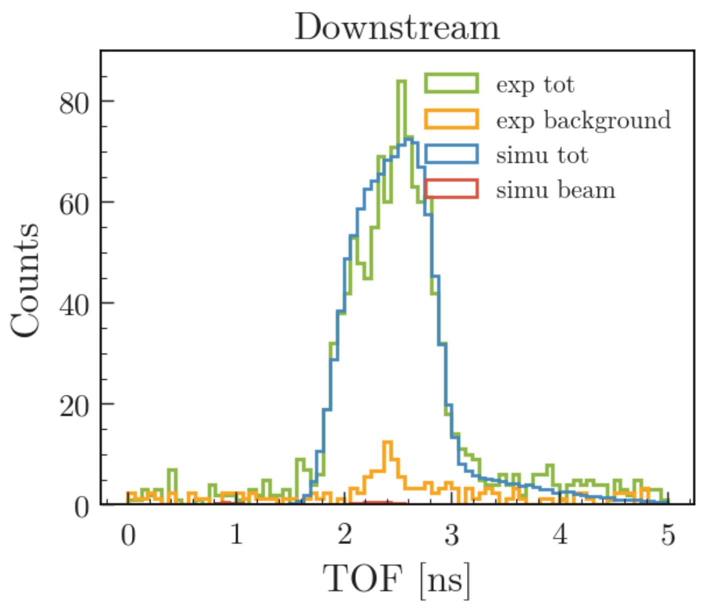
ϵ_{opt}



TIARA block detector: detection efficiency

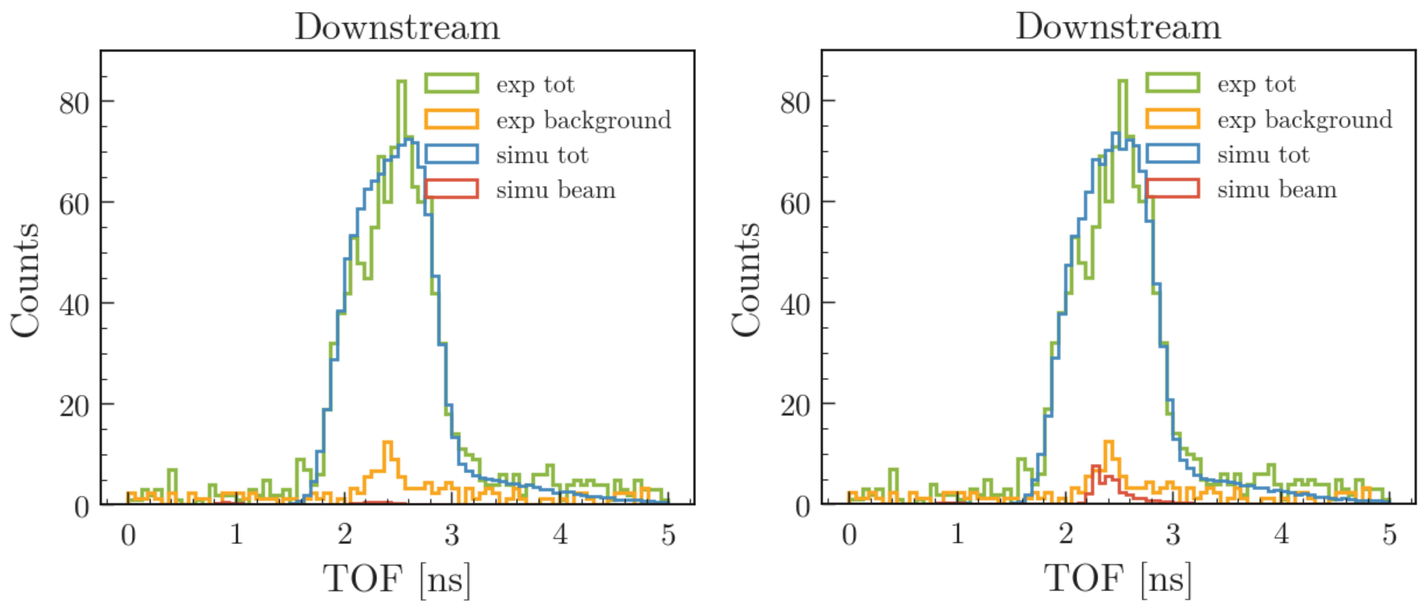
A. André
PhD thesis

Comparison experiment-simulation with detection efficiency taken into account:
detector at 13 cm from the beam axis



Interactions in the crystals do not justify the observed background

Comparison experiment-simulation with detection efficiency taken into account:
detector at 13 cm from the beam axis



Interactions in the crystals do not justify the observed background

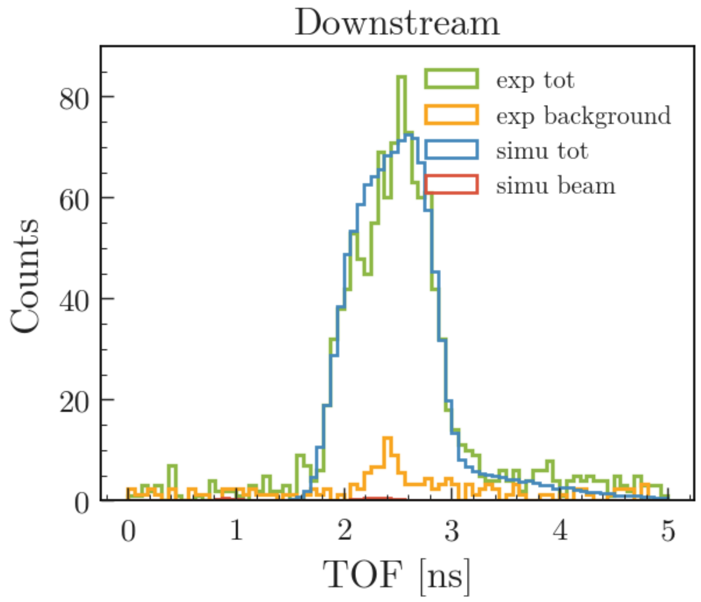
The background is mainly due to protons detected by the SiPM

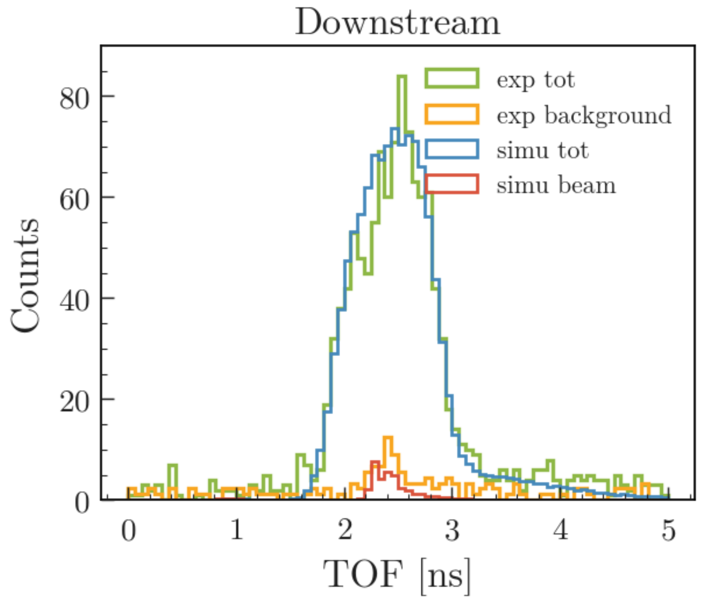
TIARA block detector: detection efficiency

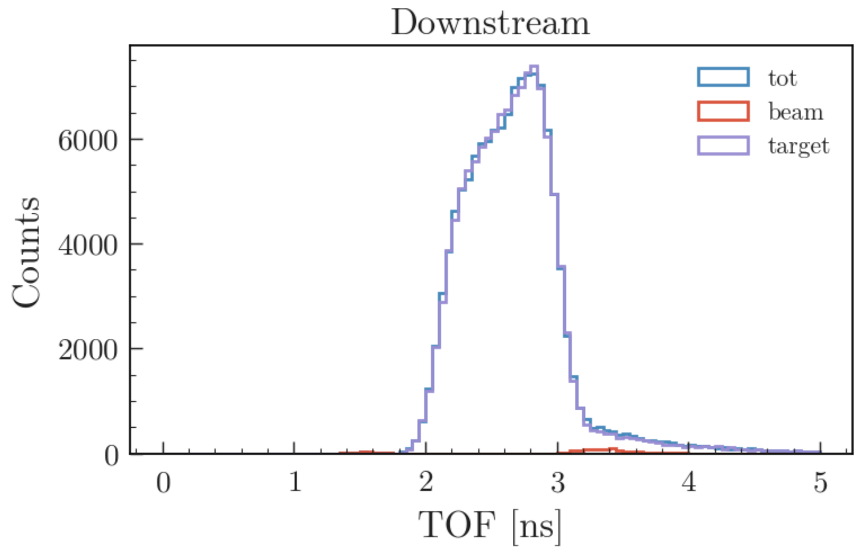
A. André
PhD thesis

Comparison experiment-simulation with detection efficiency taken into account:
detector at 13 cm from the beam axis

Simulation:
detector at 25 cm from the beam axis







Interactions in the crystals do not justify the observed background

The background is mainly due to protons detected by the SiPM

No background detected when the detector is moved away from the beam axis

Experimental validation of TIARA

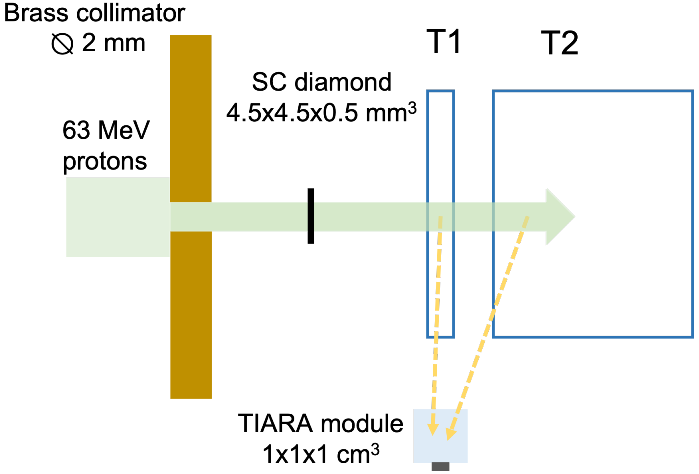
Measurement of proton range accuracy at MEDICYC **cyclotron**

Final test of 8-channel TIARA prototype at P1 **synchro-cyclotron**

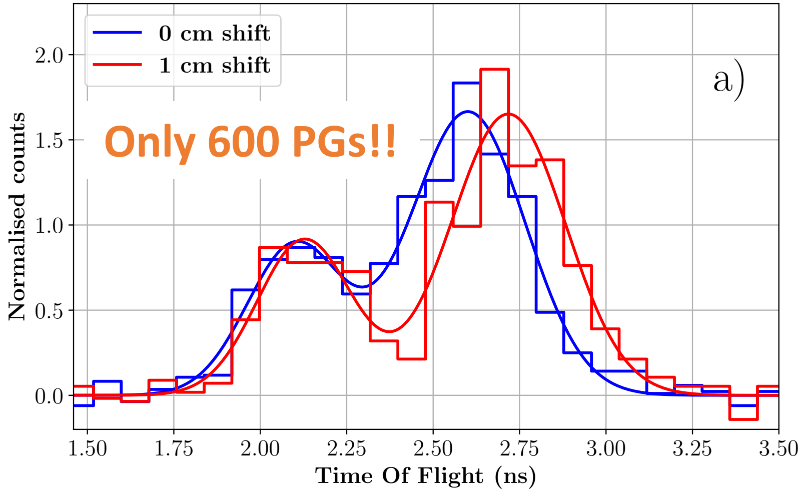
TIARA characterisation with protons and carbons at CNAO **synchrotron**

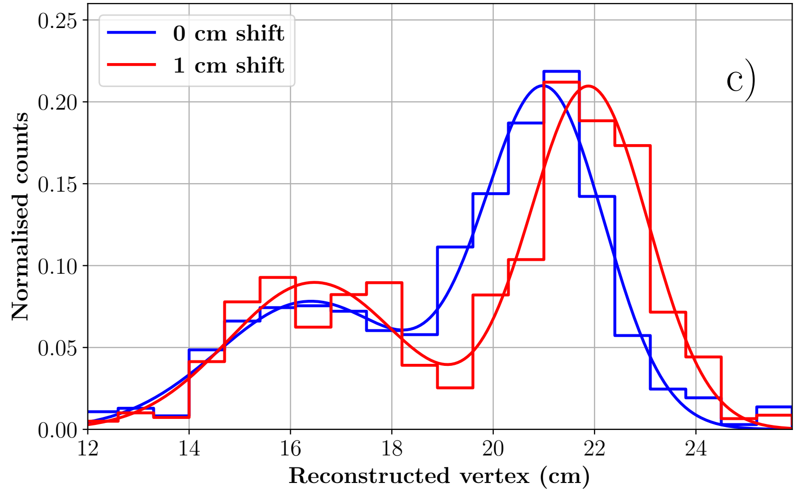
2021. Range accuracy with version v1 (63 MeV, SPR, cyclo)

M. Jacquet PhD thesis

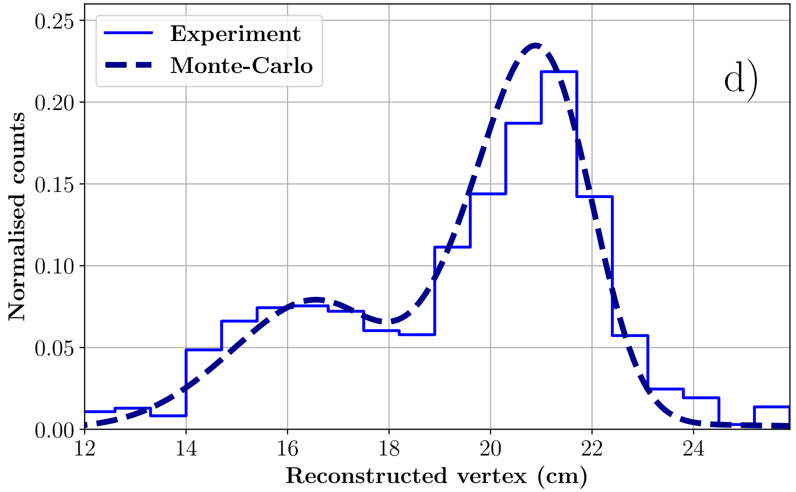


1) PG profiles from time to space domain with simplified reconstruction

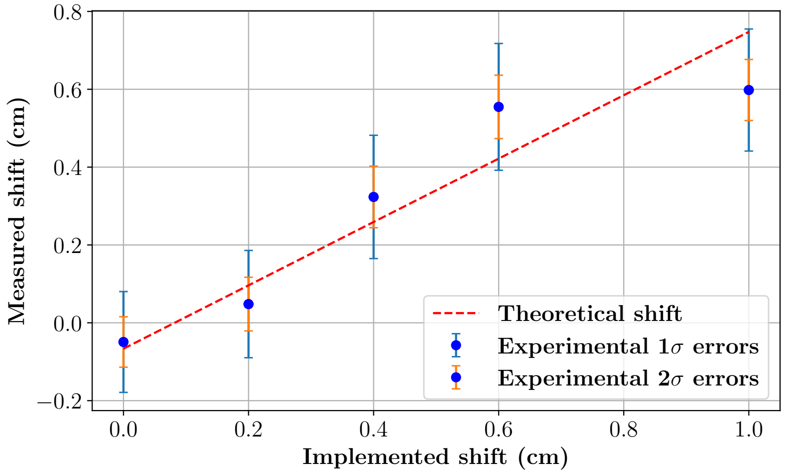




2) Comparison with reference conditions



2) Range shift sensitivity



@ 63 MeV, SPR

- Can measure a proton range shift of **4 mm at 2 sigma**
- Better than anticipated by MC simulations

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

2023. Range accuracy with version v5 (63 MeV, SPR, cyclo)

Antoine Lacassagne
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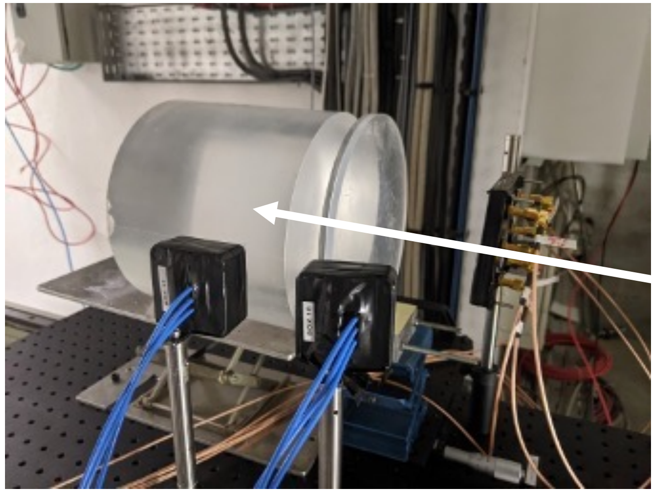
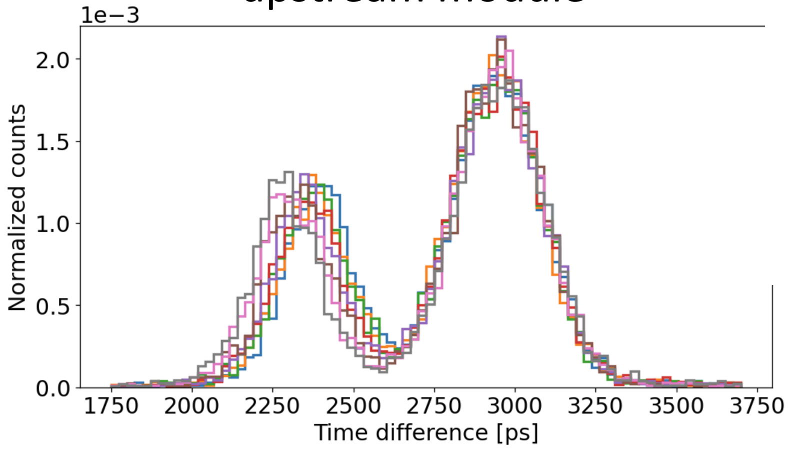
unicancer NICE

A. André
PhD thesis

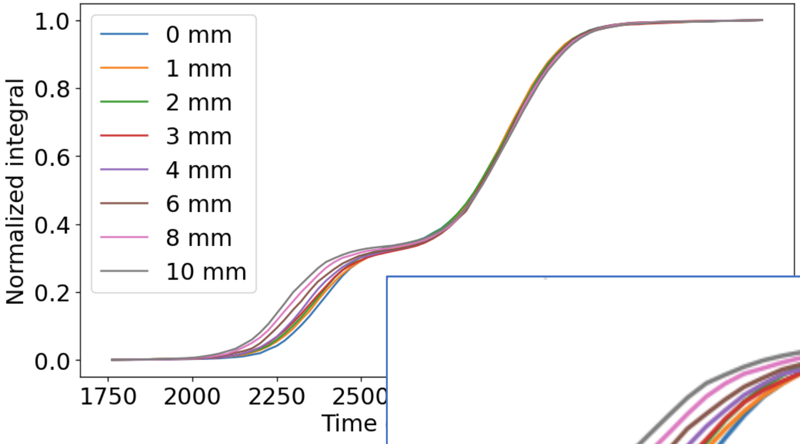
The thin target is translated from 0 to 10 mm in steps of 1 mm

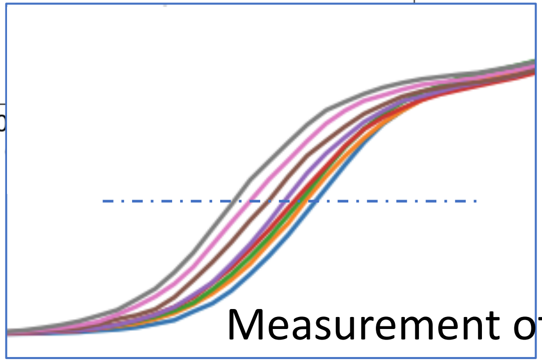


1. TOF distributions (~6600 PGs) upstream module



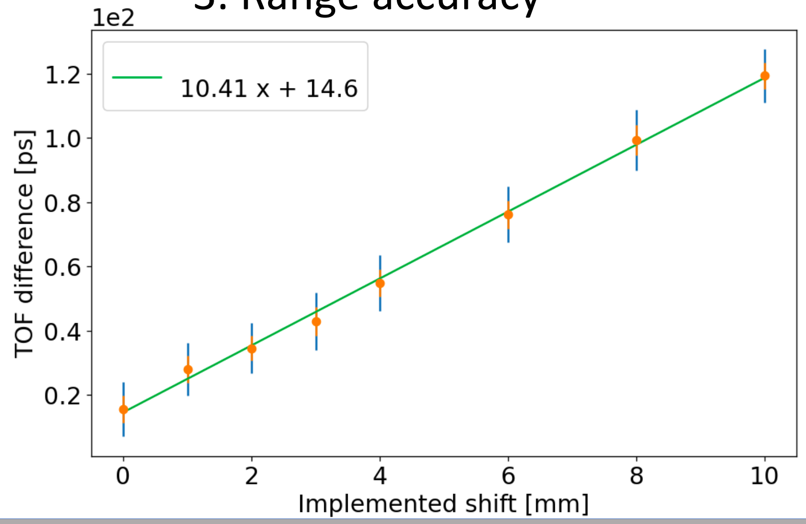
2. TOF integral distributions





Measurement of proton range shift

3. Range accuracy



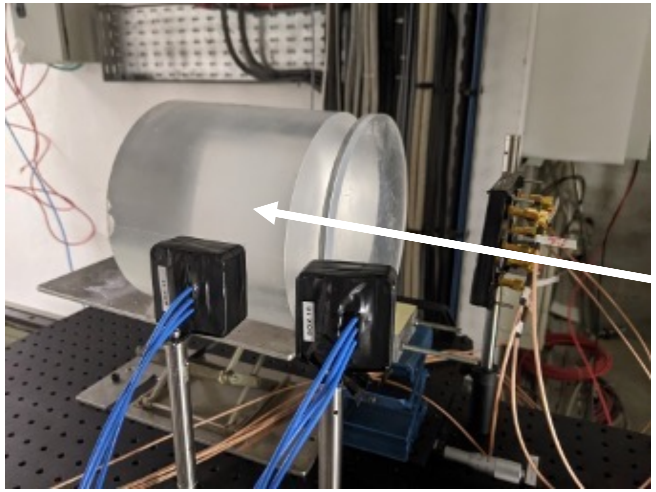
Experimental proton range accuracy:
1.65 mm at 2σ for 3000 PGs (~ 10^7 protons)

or 2.9 mm range accuracy at 2σ at the statistics of 2021 experiment

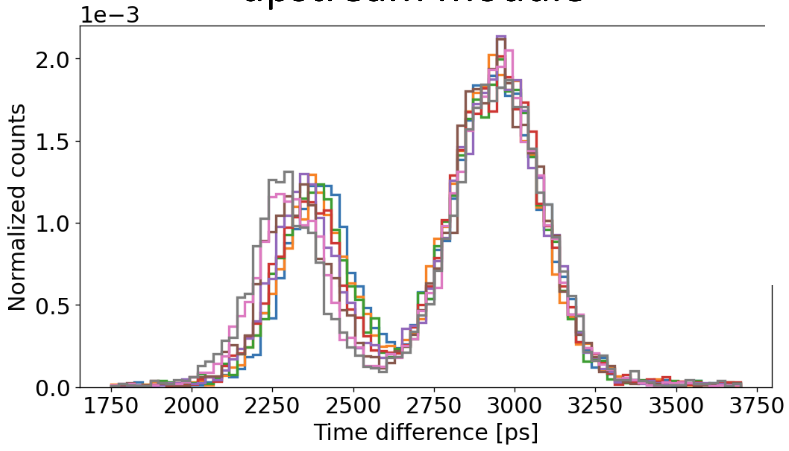
2023. Range accuracy with version v5 (63 MeV, SPR, cyclo)

A. André
PhD thesis

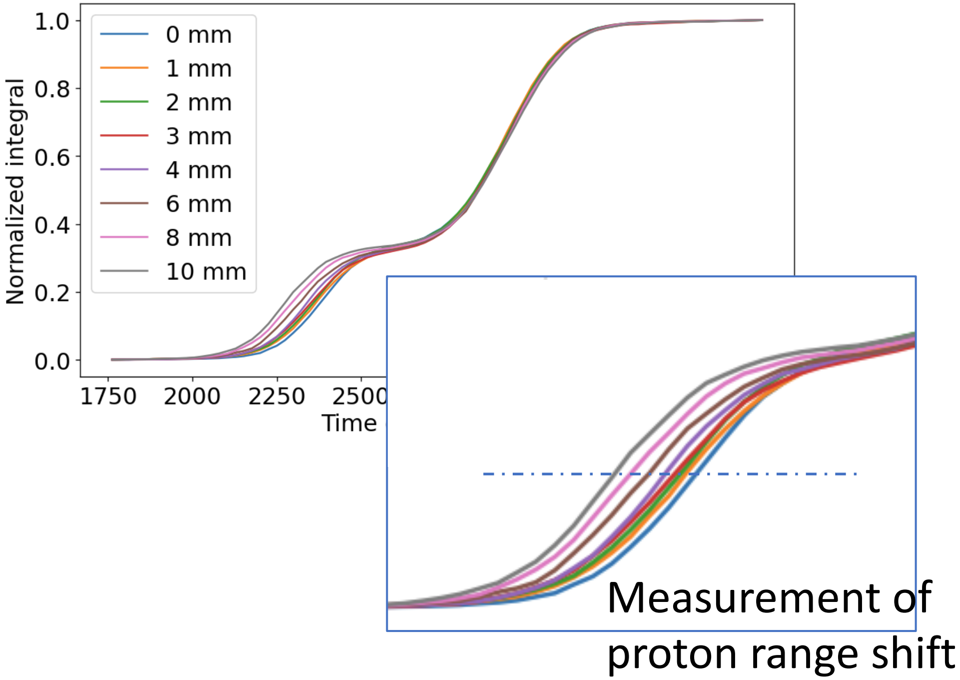
The thin target is translated
from 0 to 10 mm in steps of 1 mm



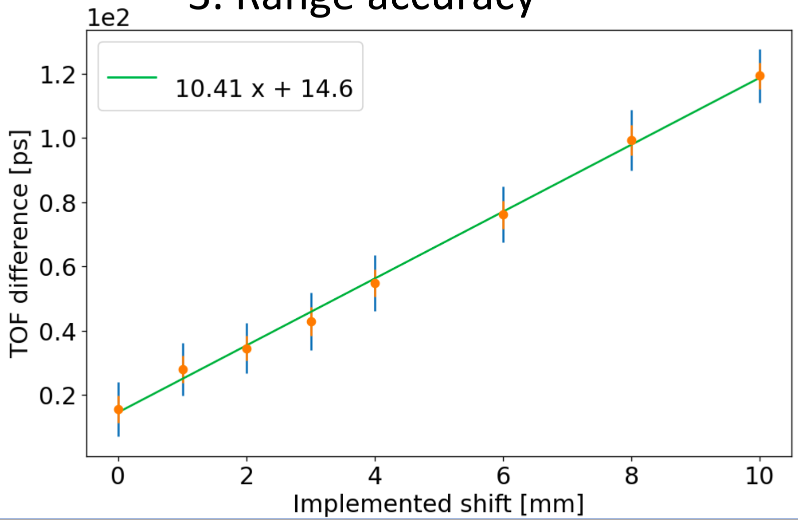
1. TOF distributions (~6600 PGs) upstream module



2. TOF integral distributions



3. Range accuracy



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

or 2.9 mm range accuracy at 2σ at the statistics of 2021 experiment

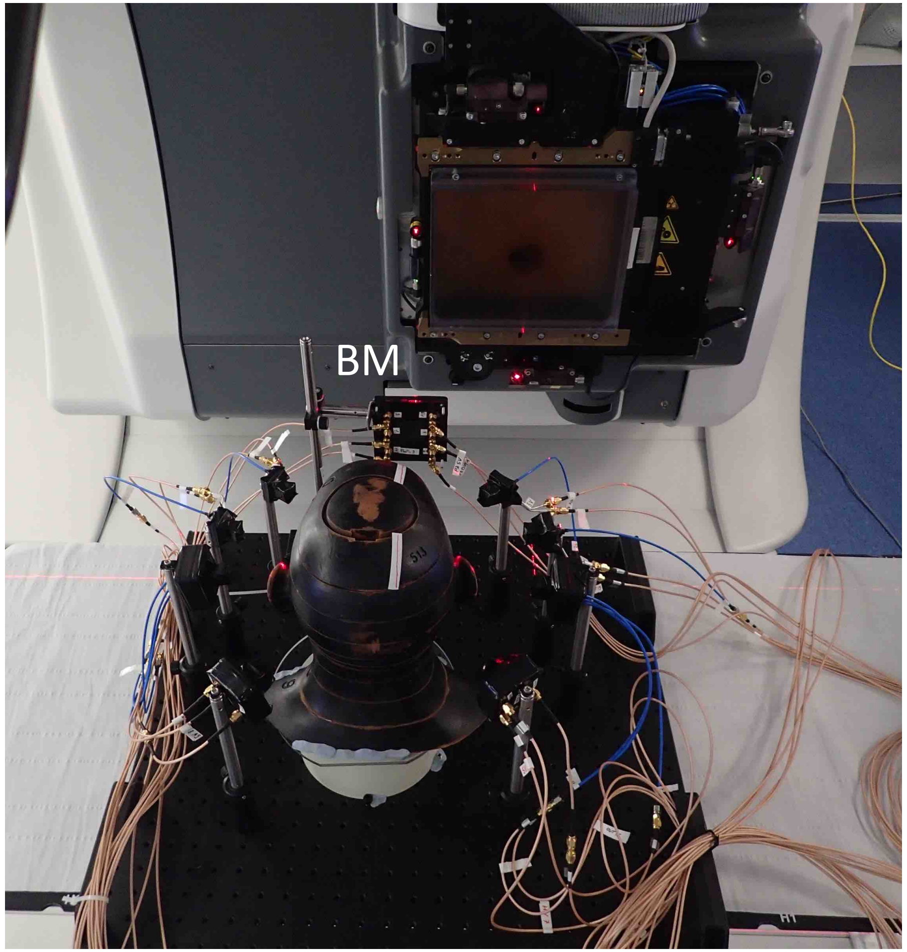
Initial MC prediction

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		

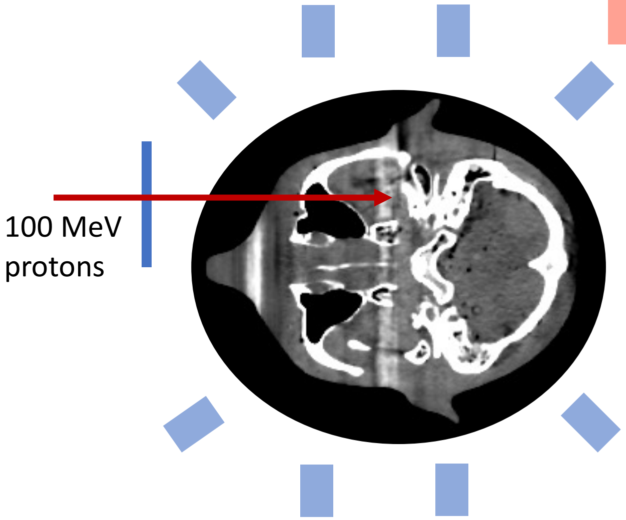
2024. Validation with version v5 (100 MeV, SPR, sync-cyclo)

A. André
PhD thesis
M. Pinson
postdoc

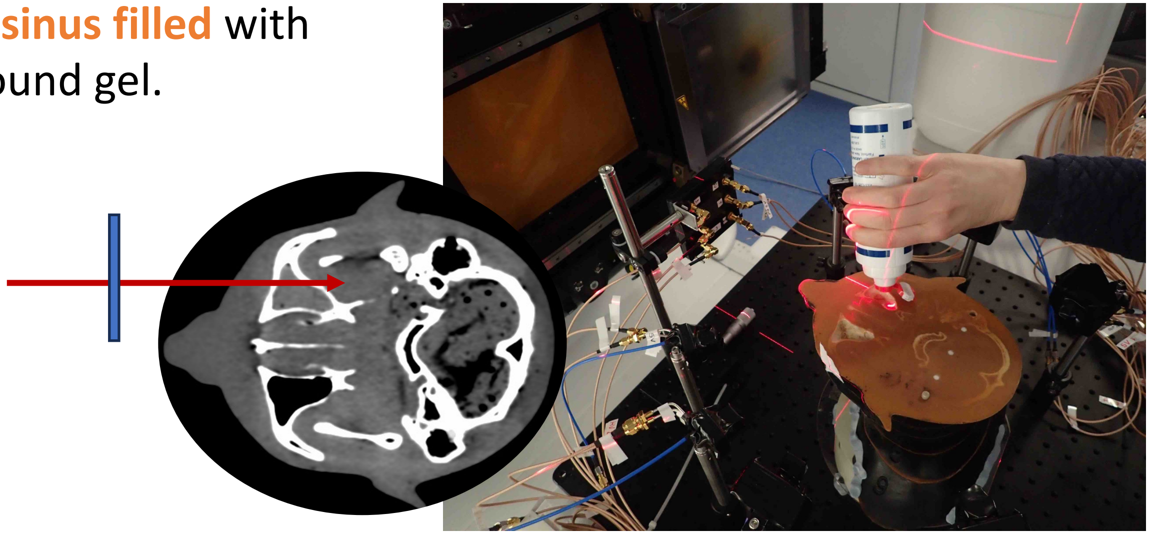
8 channels TIARA prototype



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



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



On-going analysis

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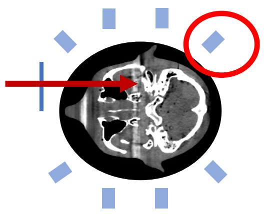
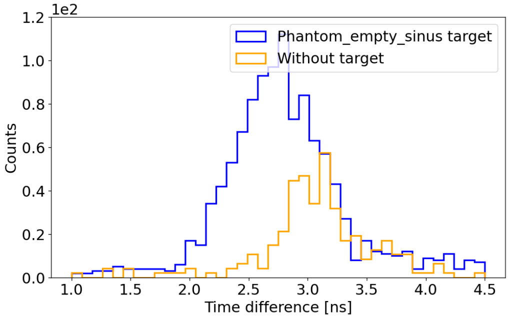
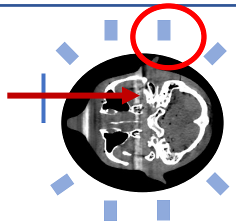
PhD thesis

Example of background analysis

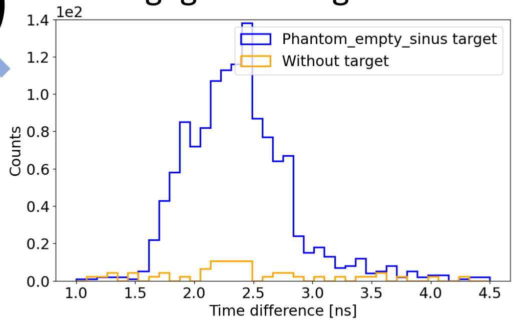


Worst case, downstream



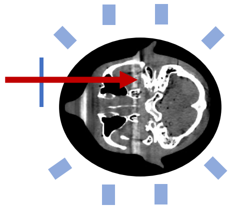


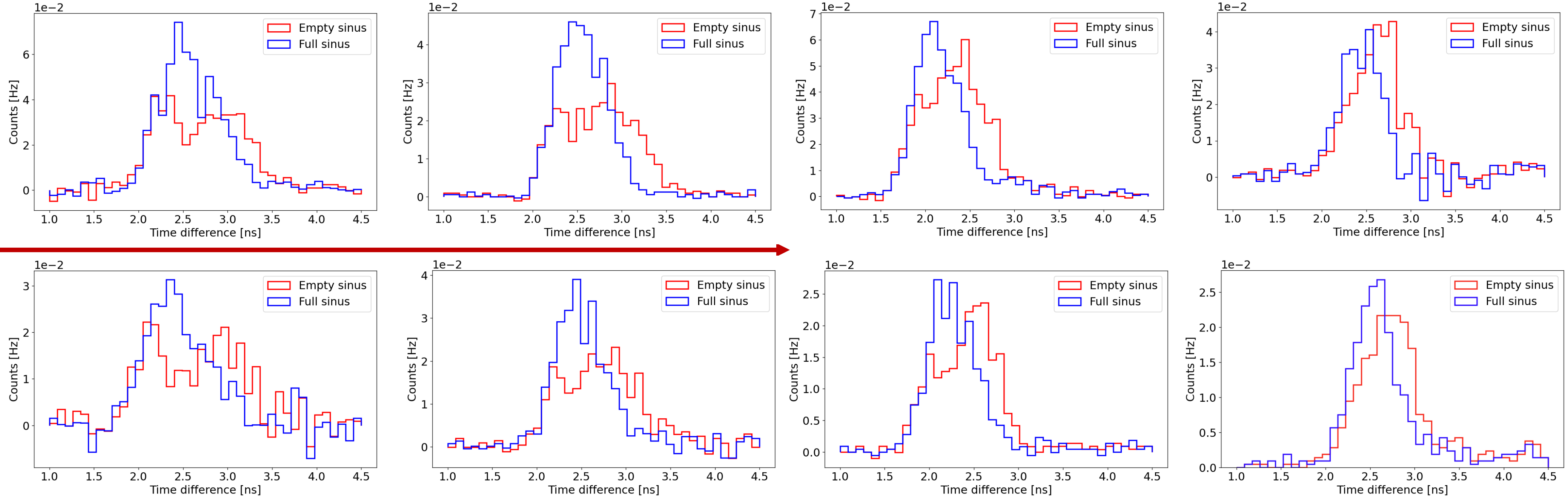
Other modules have mostly negligible background



All data after background subtraction: comparison sinus empty/filled

Between 500 and 1000 PGs per detector





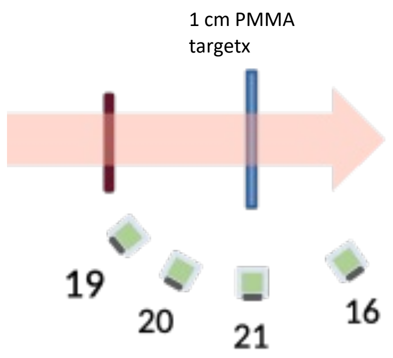
Beam direction

Protons from synchrotron (100 MeV, I = 6×10^6 p/s)

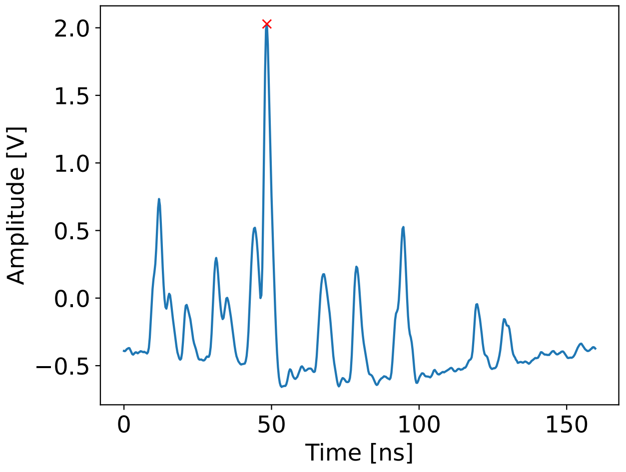
Preliminary

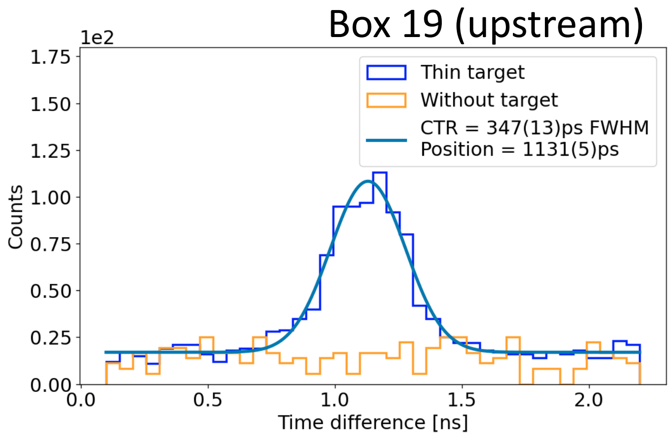
A. André
PhD thesis

Calibration



Signal from monitor not bunched at the gamma detector time-scale





Time resolution slightly degraded (148 ps rms) as this is not Single Proton Regime.

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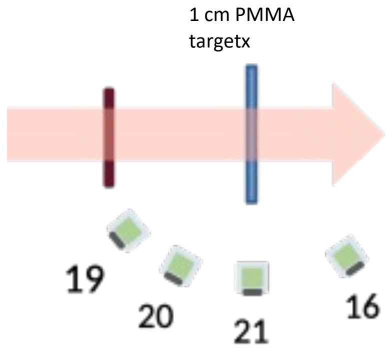

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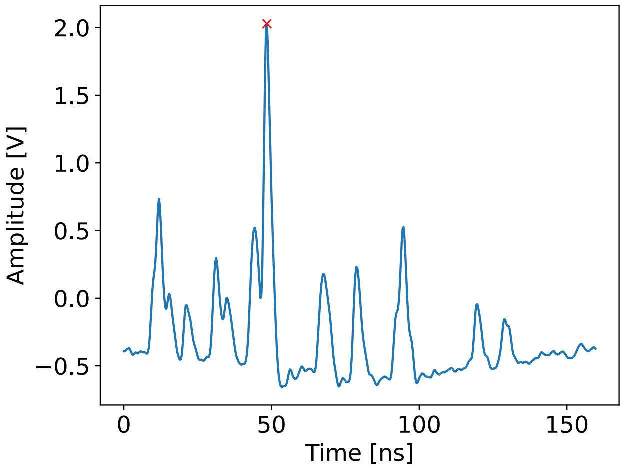
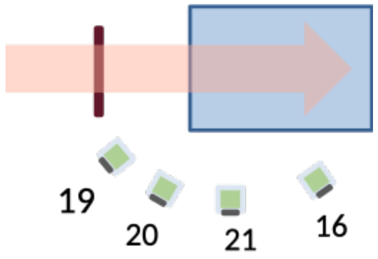
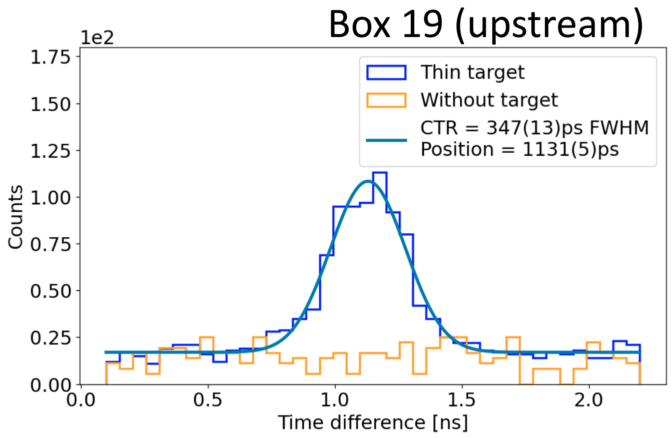


Measurement



- Negligible background with target/patient in place
- Evaluation of proton range measurement accuracy on-going

Protons from monitor stopped in the target



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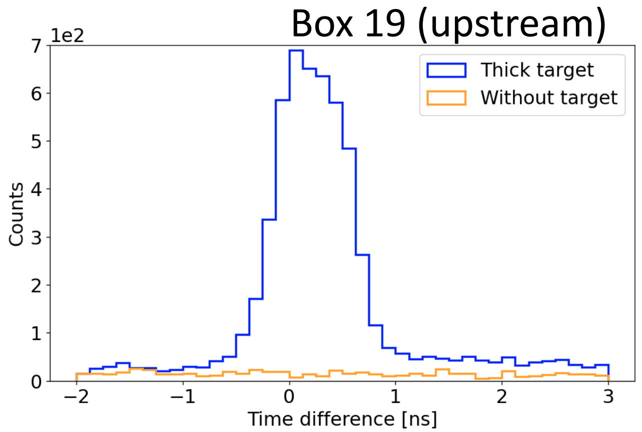
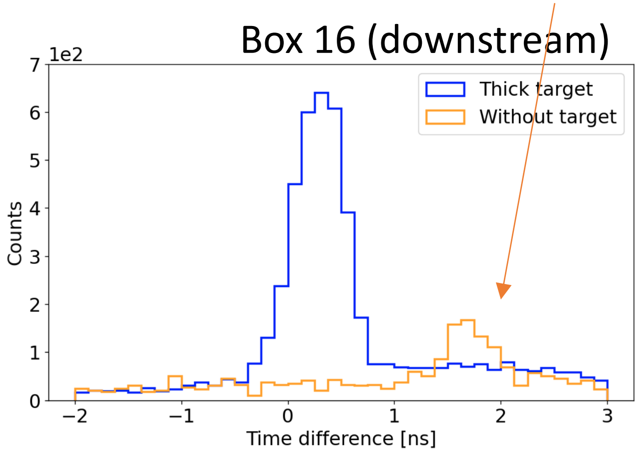


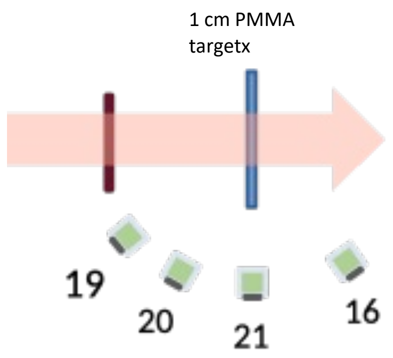


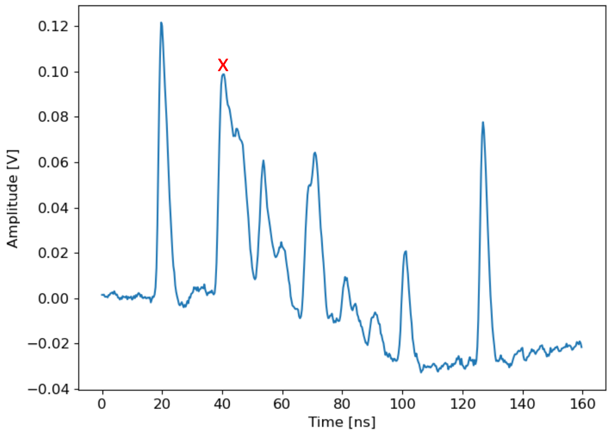
Carbon ions from synchrotron (200 MeV/u, I = 7.5 × 10^6 ions/s) Preliminary

M. Pinson postdoc

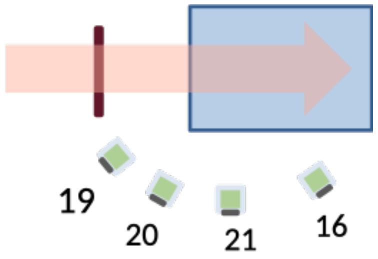
Calibration

Signal from monitor, not bunched





Measurement

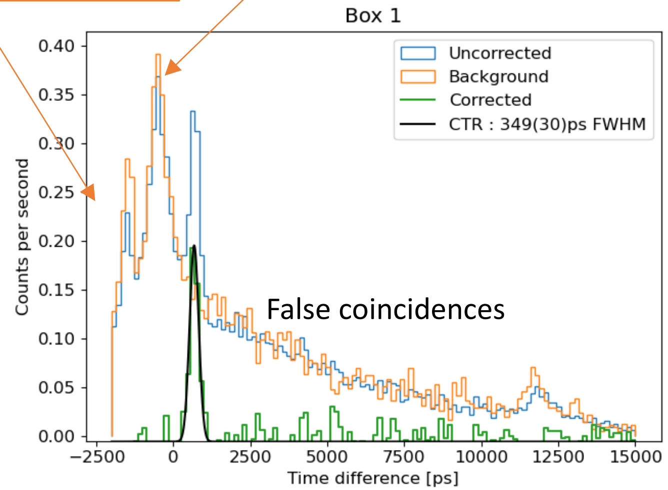


- Negligible background upstream
- Downstream modules not useful
- Evaluation of ion range measurement accuracy on-going

PG from monitor

Protons from monitor

Box 19 (upstream)

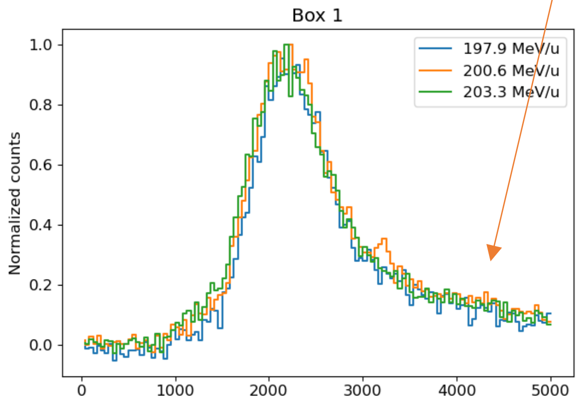


Same time resolution as protons (148 ps rms) at a clinically relevant intensity!

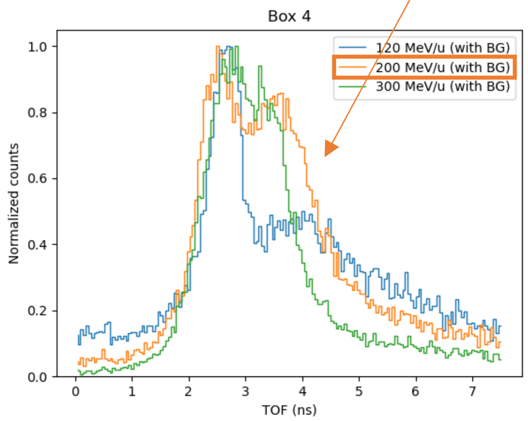
PGs from fragmentation tail

Protons from target

Box 19 (upstream)



Box 16 (downstream)



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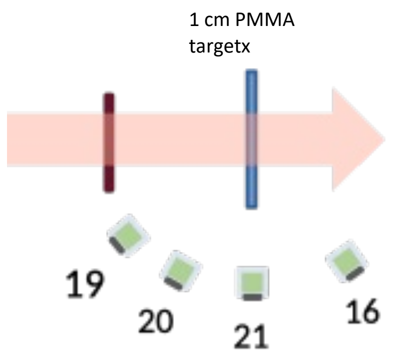
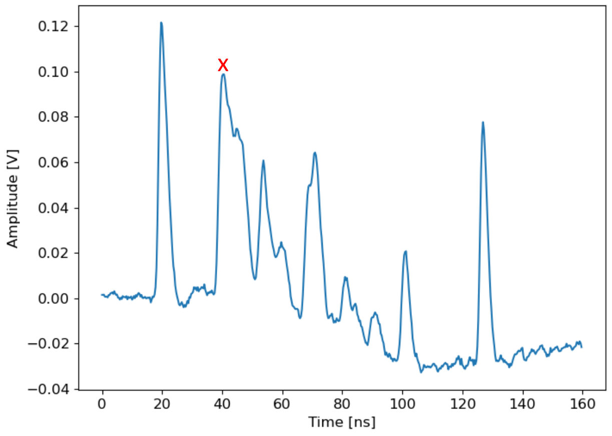
M. Pinson
postdoc

Calibration



Signal from monitor, not bunched



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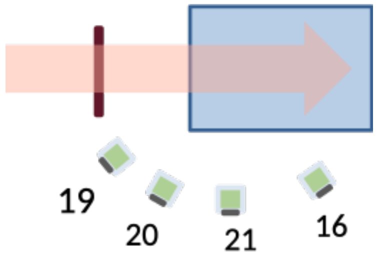

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PG from monitor

Protons from monitor

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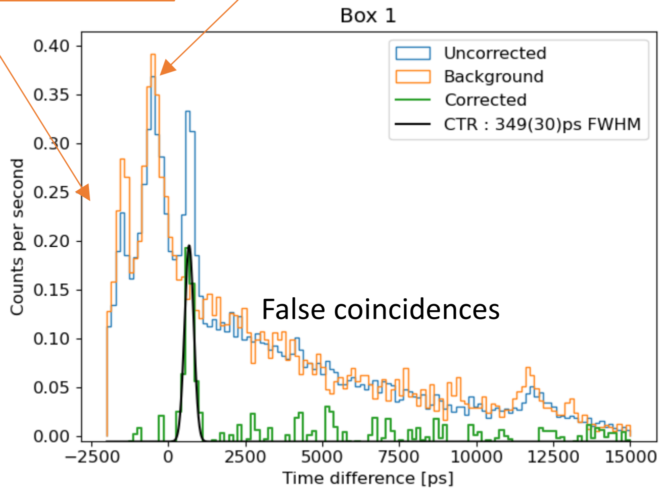

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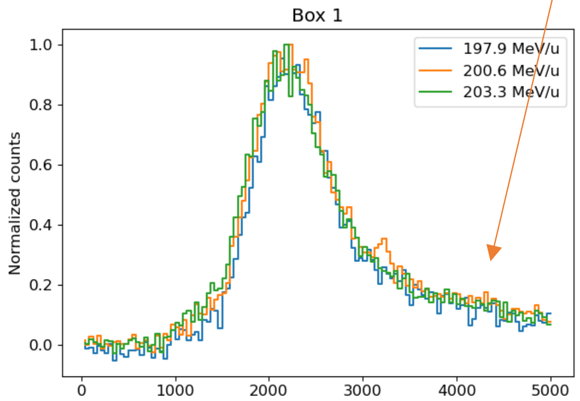
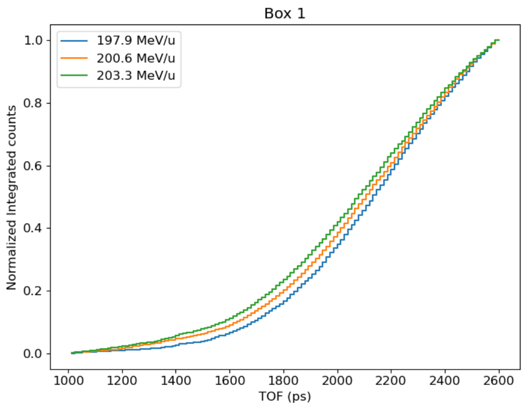


Range shift measurement



Conclusions (so far)

PGTI as a range monitoring technique

- ✓ Works with all common accelerators: cyclotron, synchro-cyclotron, synchrotron
- ✓ Proton range accuracy < 2 mm (2σ) for 3000 PGs, SPR and a simple target geometry
- ✓ 8-channels prototype developed and tested with complex anatomies (analysis on-going)
- ✓ Encouraging preliminary results for carbon ions

Performance evolution in SPR

Year	Experiment	#PGs	# protons	Energy (MeV)	Accuracy at 2σ
2020	TIARA, MC	3000	$\sim10^7$	100	3
2021	TIARA, experimental	600	$\ll10^7$	63	4
2023	TIARA, experimental	3000	$\sim10^7$	63	1.65

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Patient positioning ← → Treatment monitoring

SPR
PGTI reconstruction
Limited statistics
CTR ~100 ps RMS

Average Clinical Intensity
PGTI reconstruction
High statistics available (spot grouping possible)
CTR ~ ns RMS

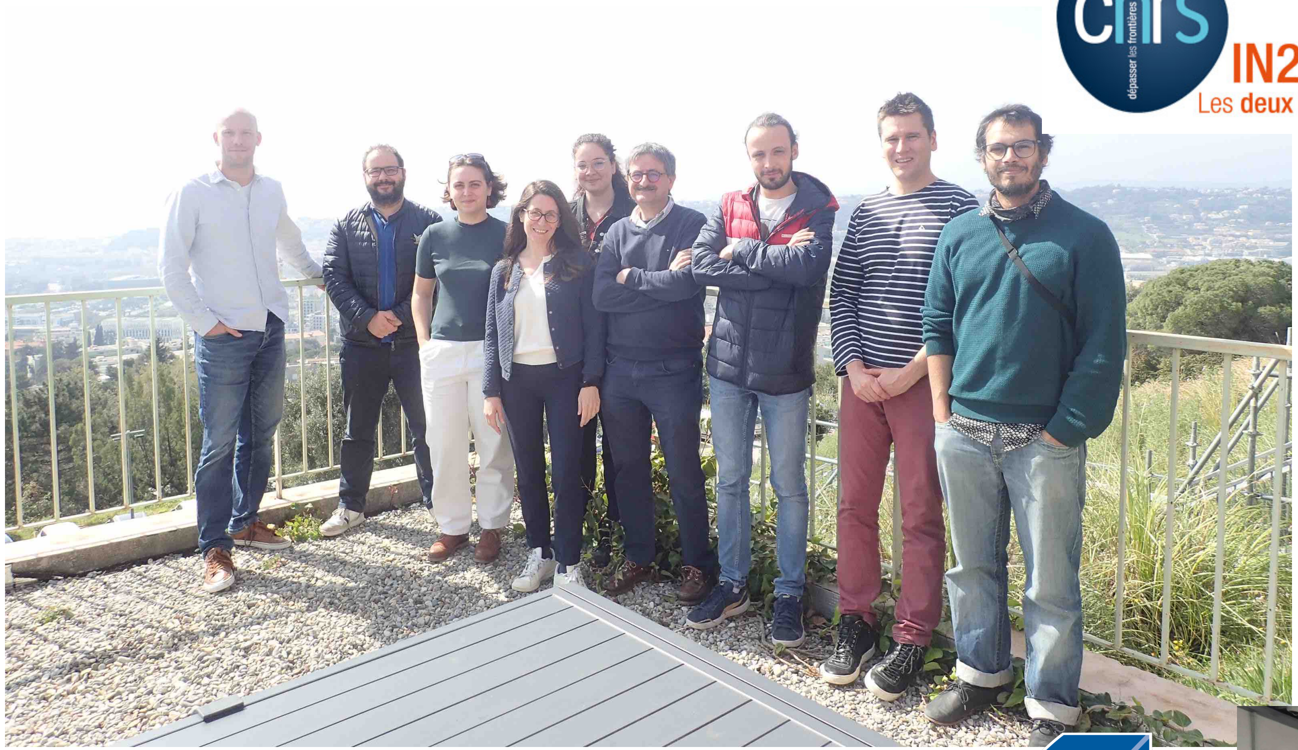
High Clinical Intensity
COG reconstruction
High statistics available
(spot grouping)

FLASH ?

→ Beam intensity

Acknowledgements and credits

The **TIARA Collaboration**



PGTI PROMPT GAMMA TIME IMAGING

LPSC GRENOBLE | MODANE

Antoine Lacassagne CENTRE DE LUTTE CONTRE LE CANCER unicancer NICE

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

CNRS IN2P3 Les deux infinis

CAL/IN2P3 COMEX for the allocated beam time
Petter Hofverberg (CAL), **Marco Pullia** (CNAO) and their teams for the nice reception
Some of the results have been obtained at CNAO experimental facility built in collaboration with INFN

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European Research Council (Established by the European Commission) — ERC Starting Grant (project 101040381)

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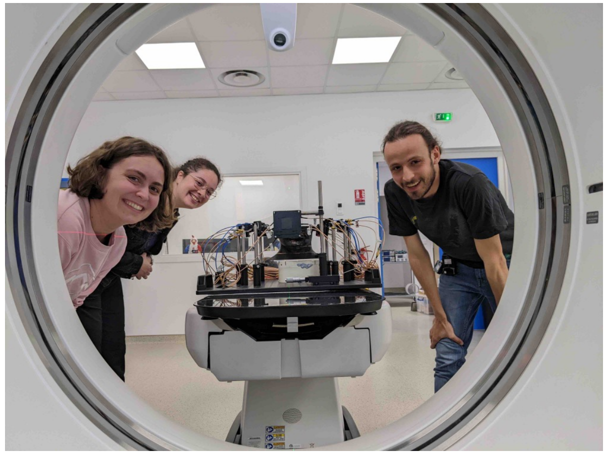

Positions available in the TIARA collaboration

2 years Post-doc position starting as soon as possible

Learning methods for dosimetry in hadrontherapy with Prompt-Gamma Time Imaging

https://www.cppm.in2p3.fr/web/en/jobs/jobs/index.html
Contact: Y. Boursier, CPPM, Marseille
(boursier@cppm.in2p3.fr)

PhD position starting October 2025

TOF-based proton imaging with TIARA

Contact: S. Marcatili, LPSC, Grenoble
(sara.marcatili@lpsc.in2p3.fr)