Prompt Gamma Time Imaging: a novel technique for ion treatment monitoring

Sara Marcatili

on behalf of the PGTI collaboration

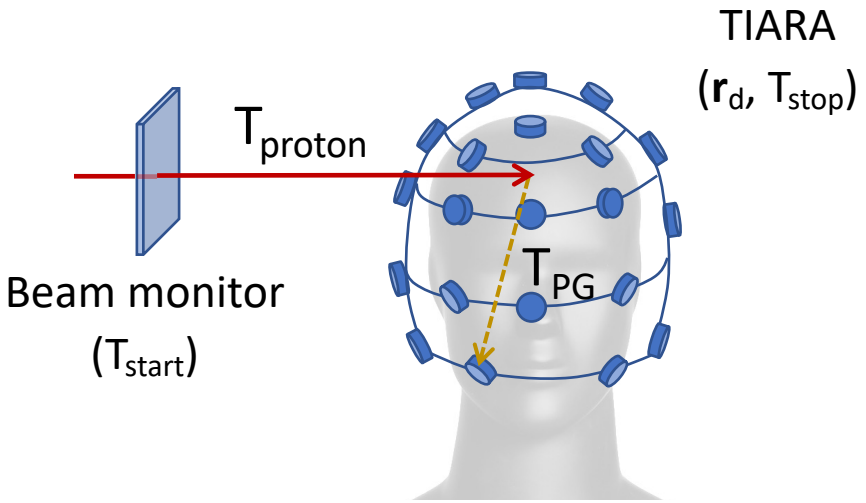
LPSC - Laboratory of Subatomic Physics and Cosmology

CNRS – National Centre of Scientific Research

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

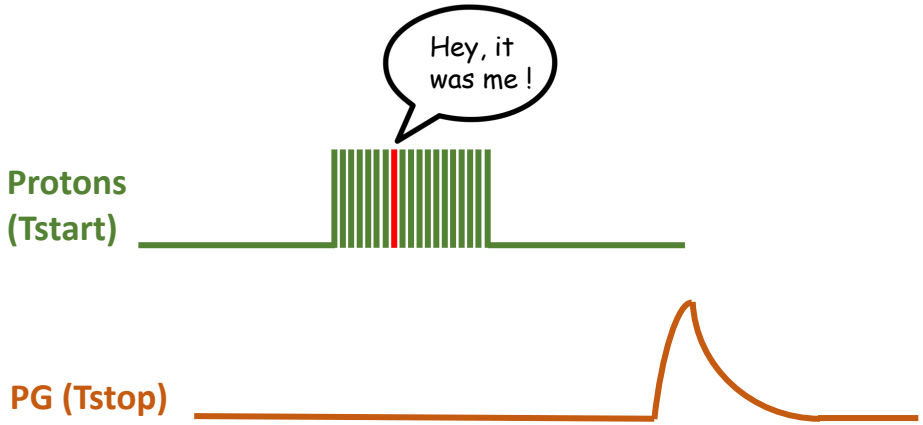
$$TOF = t_{stop} - t_{start} =$$
$$= T_{proton}(\mathbf{r}_v, v_p) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$

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

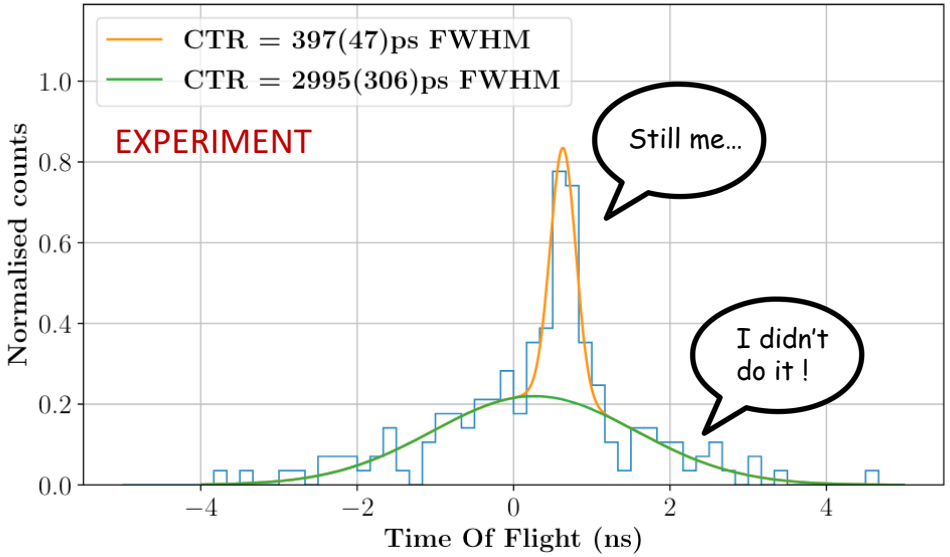
Allows combining the response of multiple detectors:
- to reach uniform sensitivity all over the ion range
- for IMPT compatibility

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

Reducing bunch-width related time uncertainties

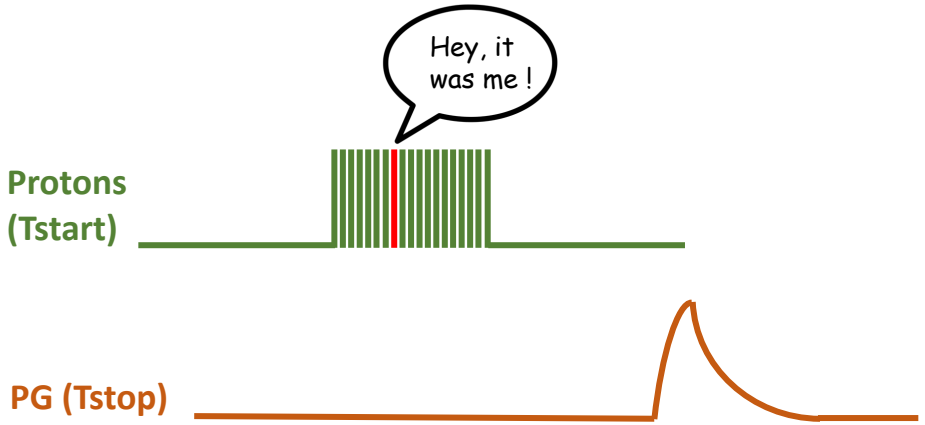


S2C2 synchro-cyclotron: 8 ns bunch width, 7 p/bunch, thin target

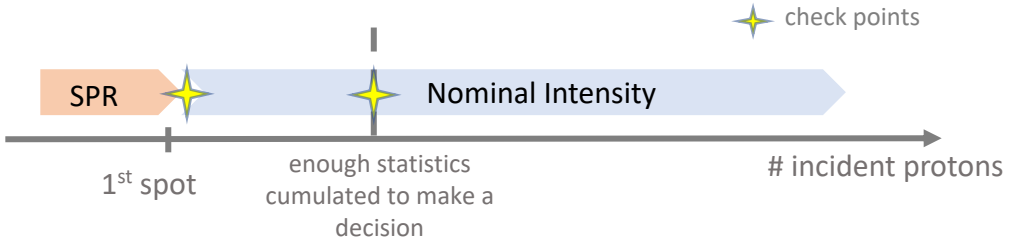


Jacquet et al. Scientific report (2023) 13:3609

Reducing bunch-width related time uncertainties



Proposed strategy.
lower the beam intensity to Single Proton Regime (SPR)



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

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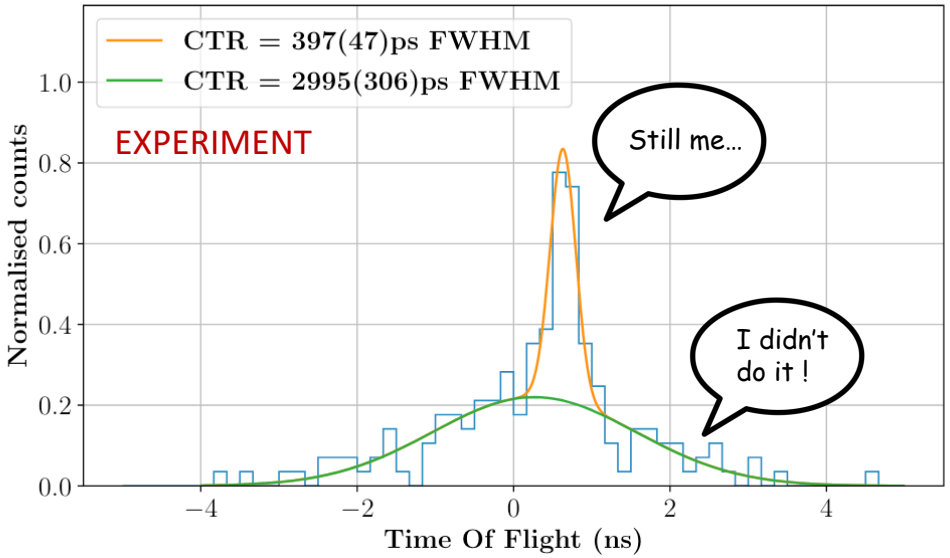

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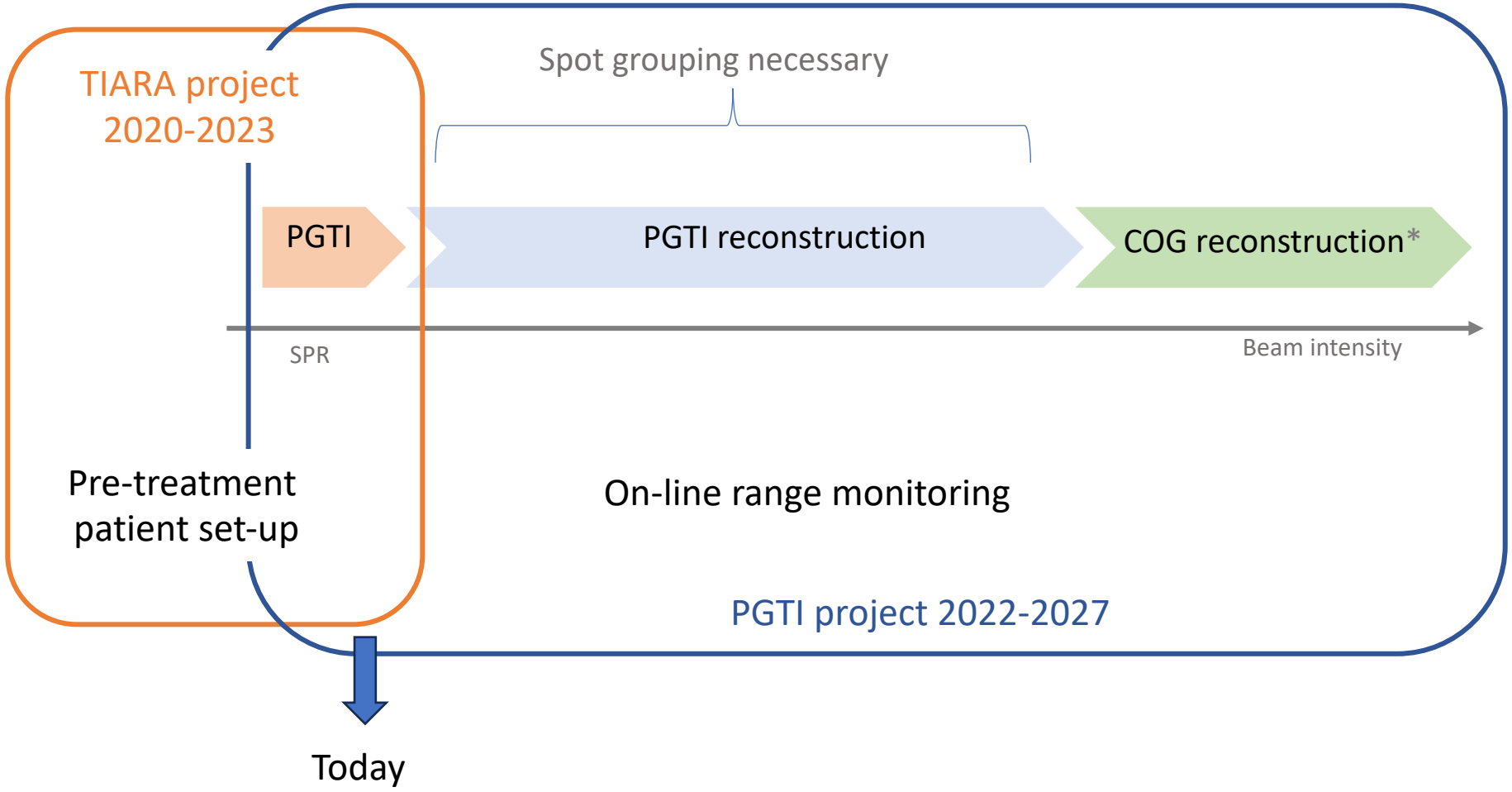
- SPR is the intensity allowing single proton tagging
- It depends on the accelerator time structure

		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

Project timeline



* For more info: https://arxiv.org/abs/2012.09275

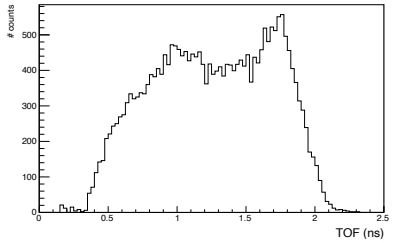
2020. Simplified PGTI reconstruction

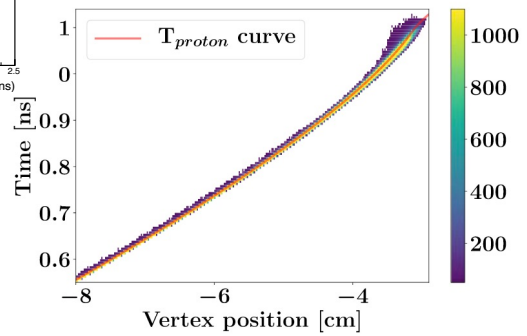
$$TOF = T_{proton}(\lambda, v) + T_{PG}(\lambda)$$

Experimental data

Trivial function

Preliminary MC in TPS conditions





Method

Non-iterative binary search for zeros to find the PG vertex distribution (λ)

Input data

- Patient's CT scan to calculate T_{proton}
- Detectors' position (centroids)

Features

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

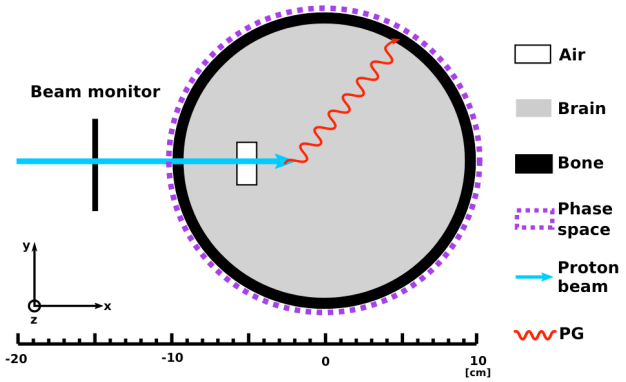
DOES NOT provide actual PG distribution in case of anatomical variation but **sensitive enough to detect a variation from TPS**

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

Simplified PGTI reconstruction: MC validation

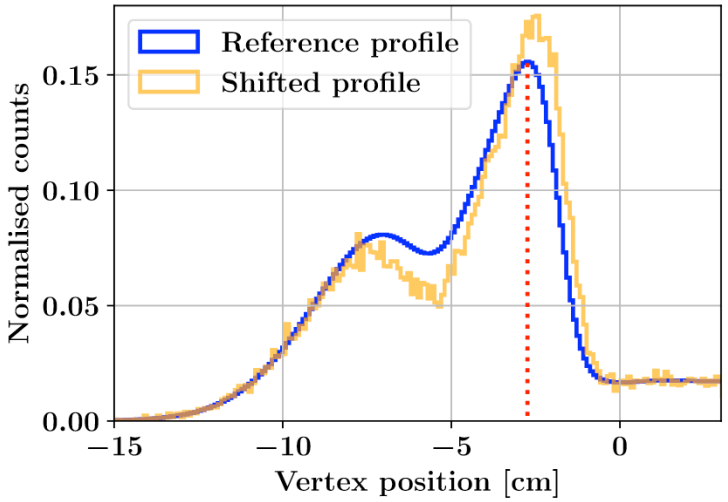
MC validation

- 100 MeV protons
- Air cavity of variable thickness
- 30 detection modules (1 cm³)
- 0.6% overall detection efficiency

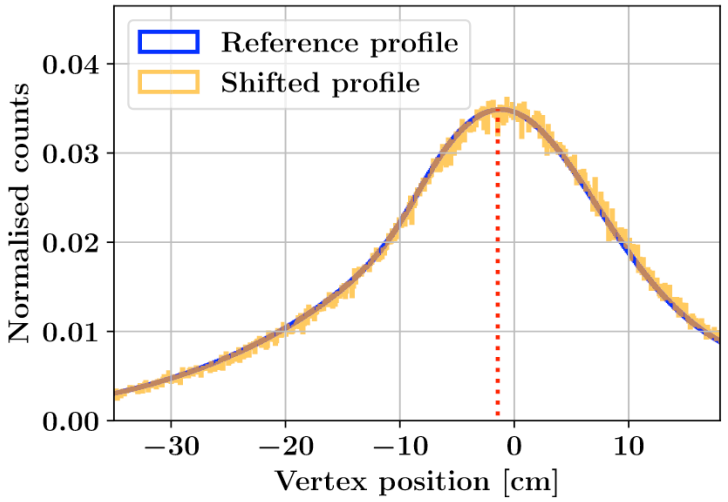


Sensitivity is a compromise between time resolution and proton statistics

SPR scenario: 10^8 protons, 100 ps rms



Nominal intensity: 10^9 protons, 1 ns rms



CTR (RMS)	# protons	# PG	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		
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;

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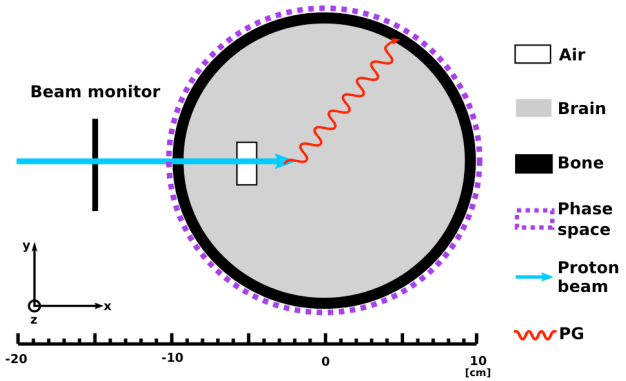

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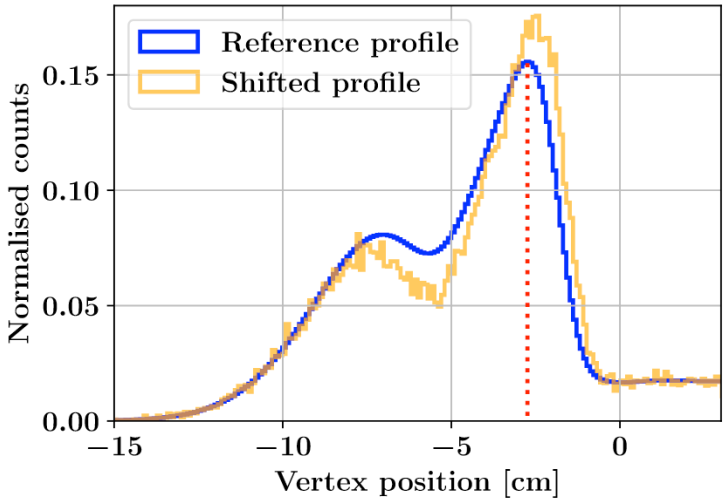

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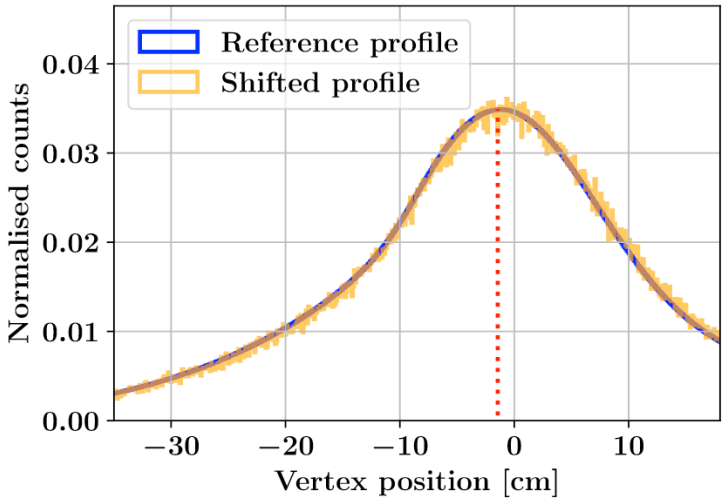

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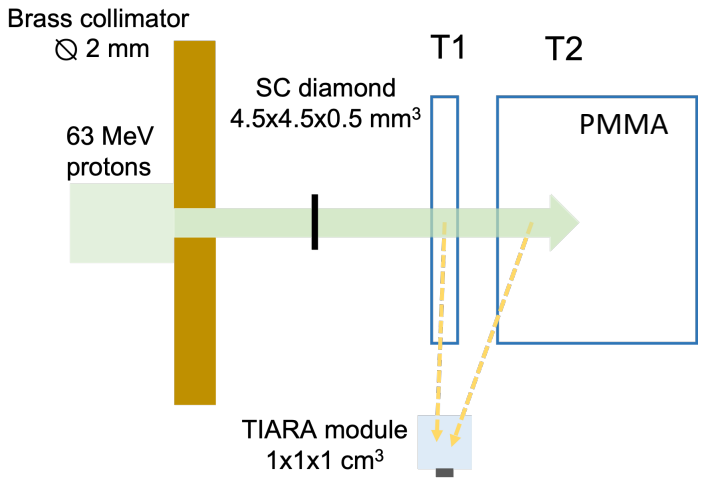
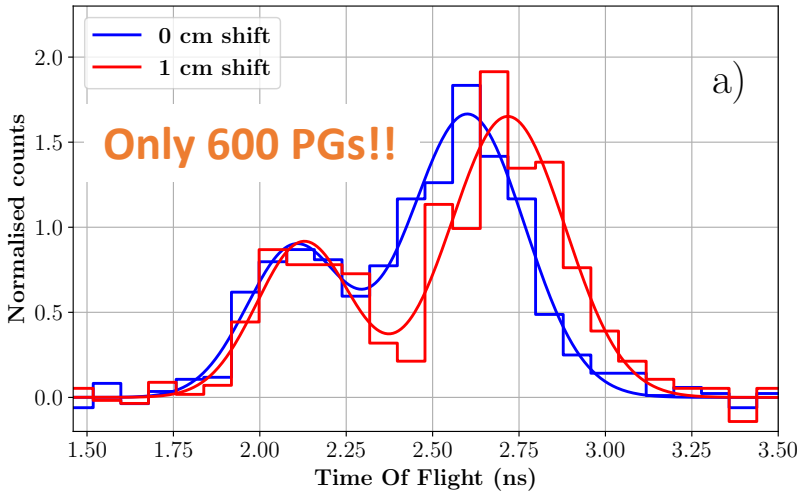
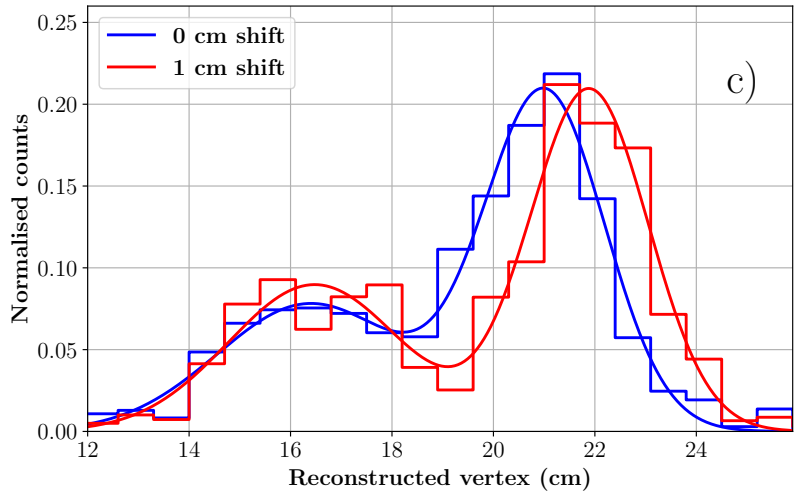
2022. Experimental validation with one module (63 MeV, SPR)

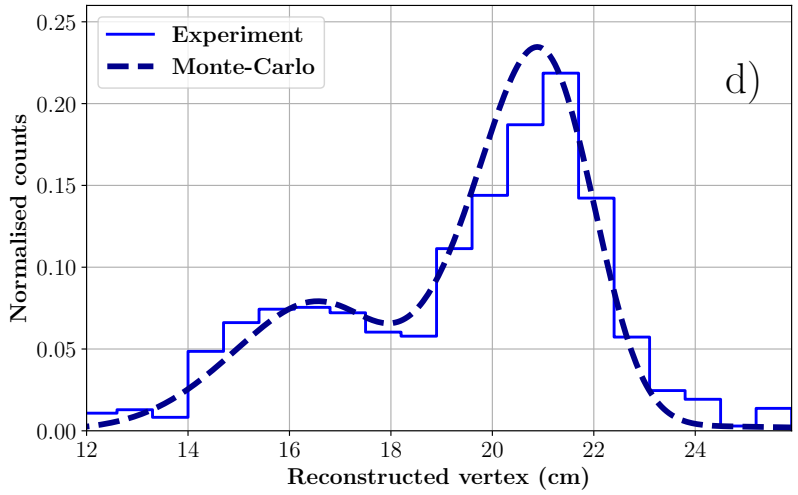


1) PG profiles: from time to space domain

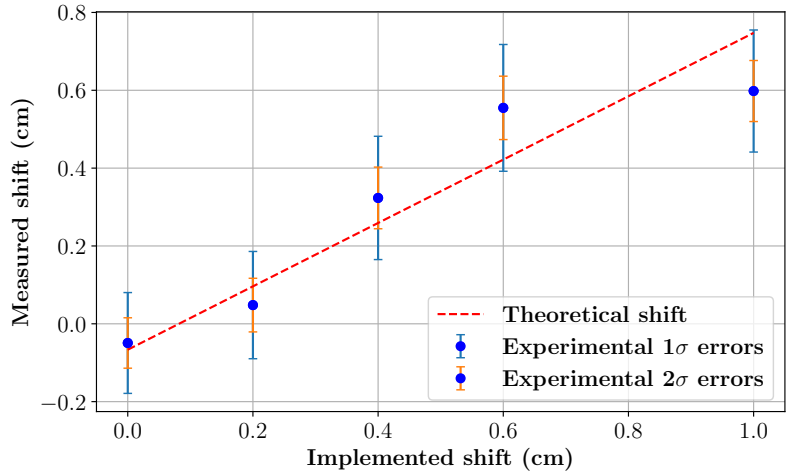




2) Comparison with reference conditions



2) Range shift sensitivity

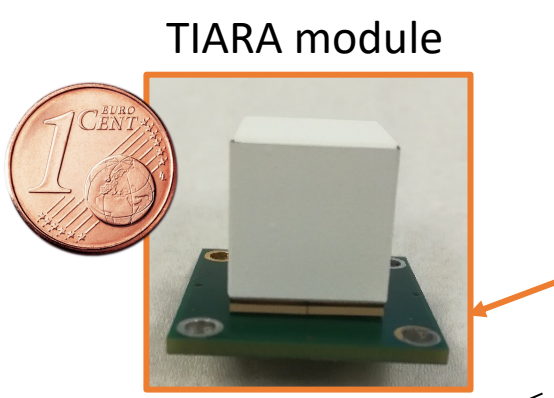


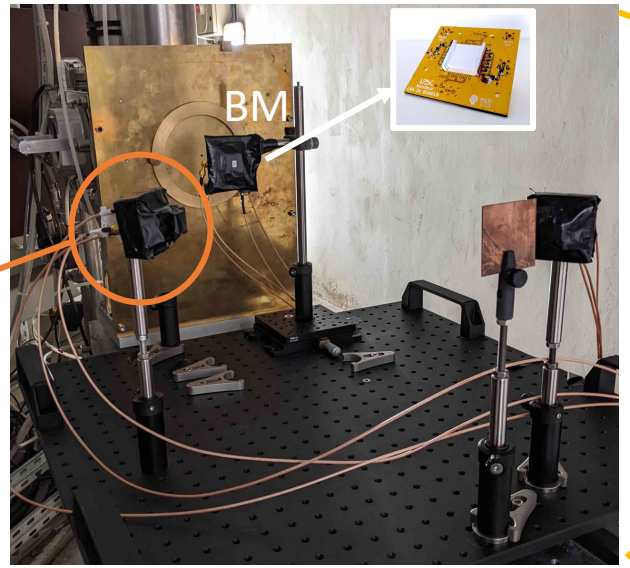
@ 63 MeV, SPR

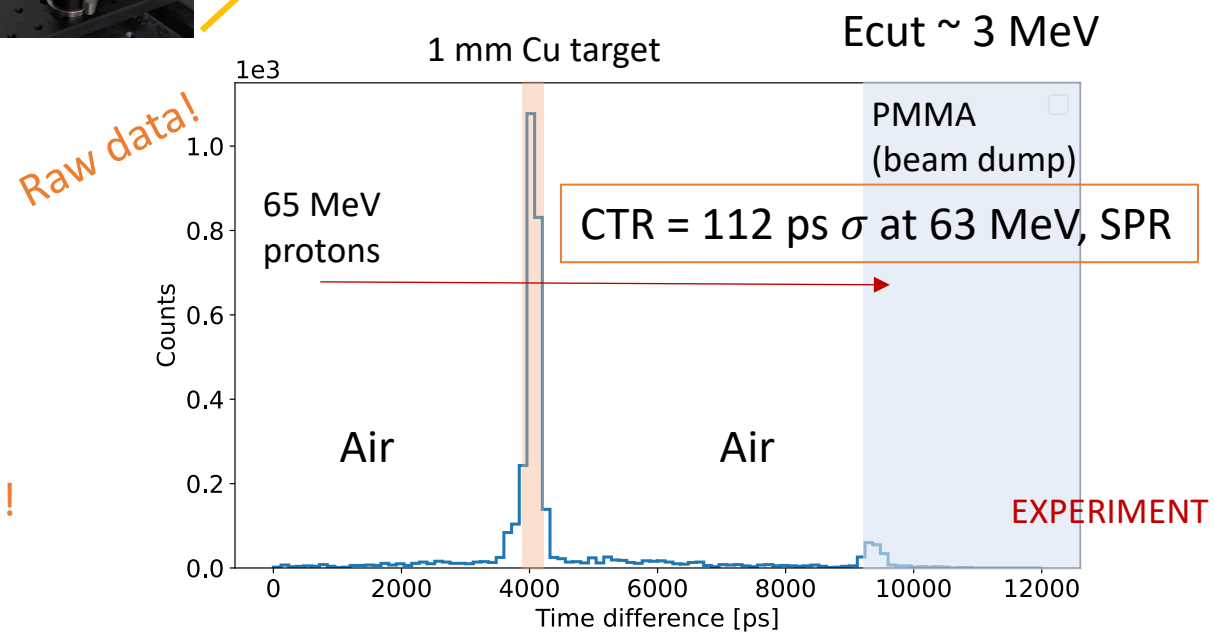
- Can measure a proton range shift of **4 mm at 2 sigma**
- Better than anticipated by MC simulations
- Obtained for a CTR= 137 ps σ (CTR=112 ps σ for current detector)

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

Gamma detector development





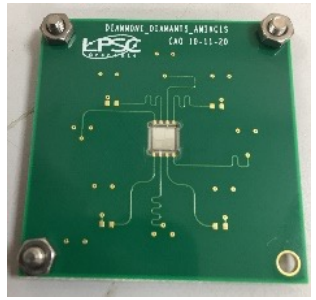


Cherenkov detectors (PbF_2) coupled to SiPMs

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

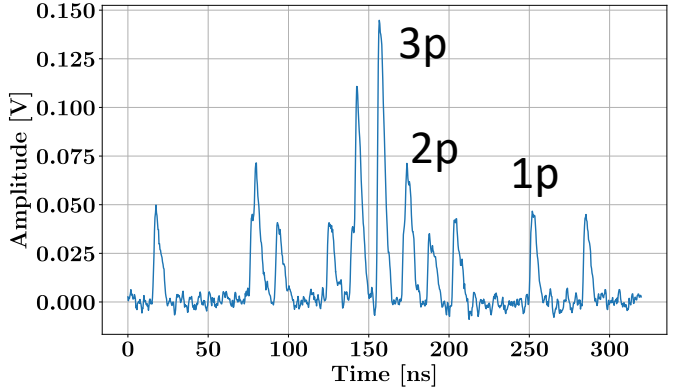
Beam monitor developments (c.f. Gallin-Martel's talk)

Single channel, single crystal diamond detector: 4.5 x 4.5 x 0.5 mm^2



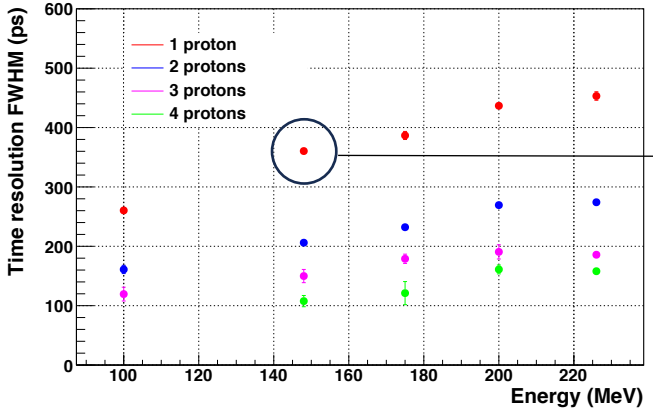
Beam size

Proton counting (at low intensity)



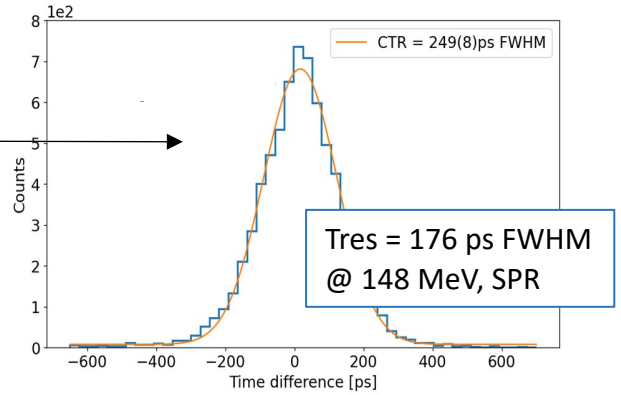
Time resolution (at low intensity)

With Cividec C2 amplifier



Proteus One, June 2021

With custom electronics from Clarys-UFT



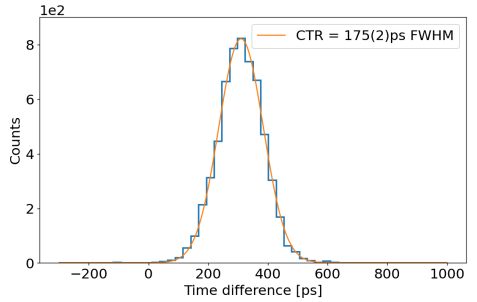
Tres = 176 ps FWHM @ 148 MeV, SPR

Proteus One, June 2023

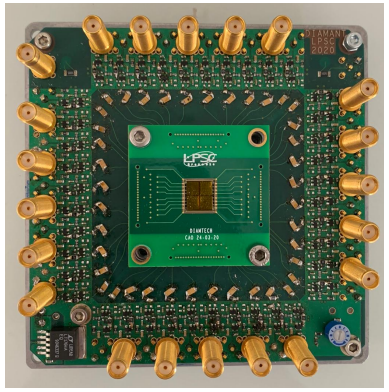
Plastic detector (preliminary version): 2x2 cm^2

Tres = 124 ps FWHM @ 148 MeV, SPR
Det. Eff. = 99.9%
Spatial Res. ~ 2 mm σ

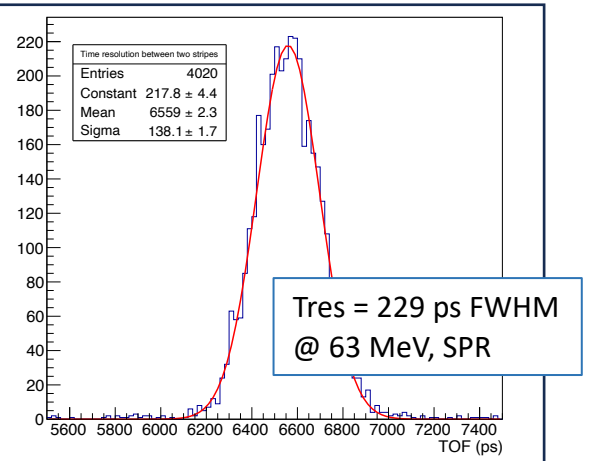
Beam size



Stripped detector: 9 x 9 x 0.5 mm^2, 1 mm pitch

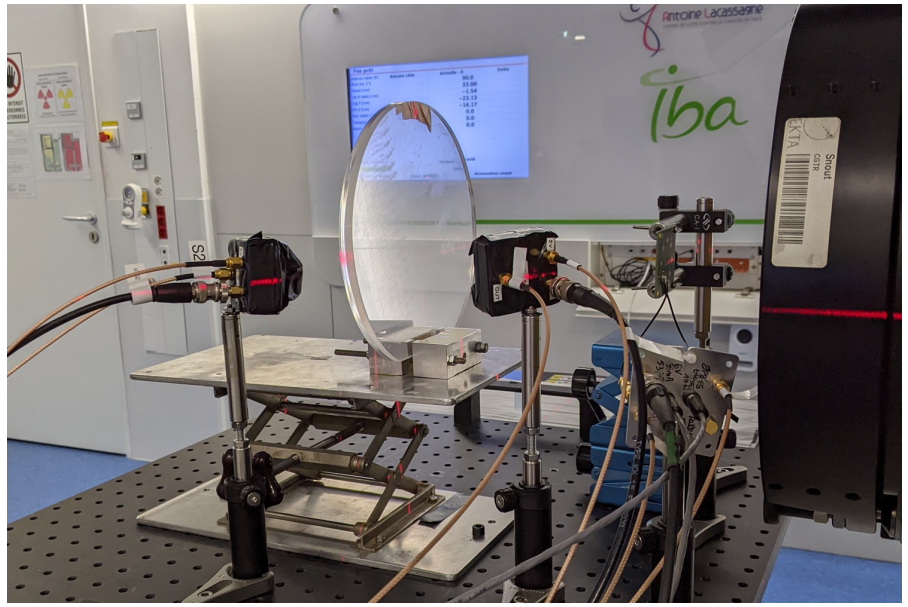


Clarys-UFT project



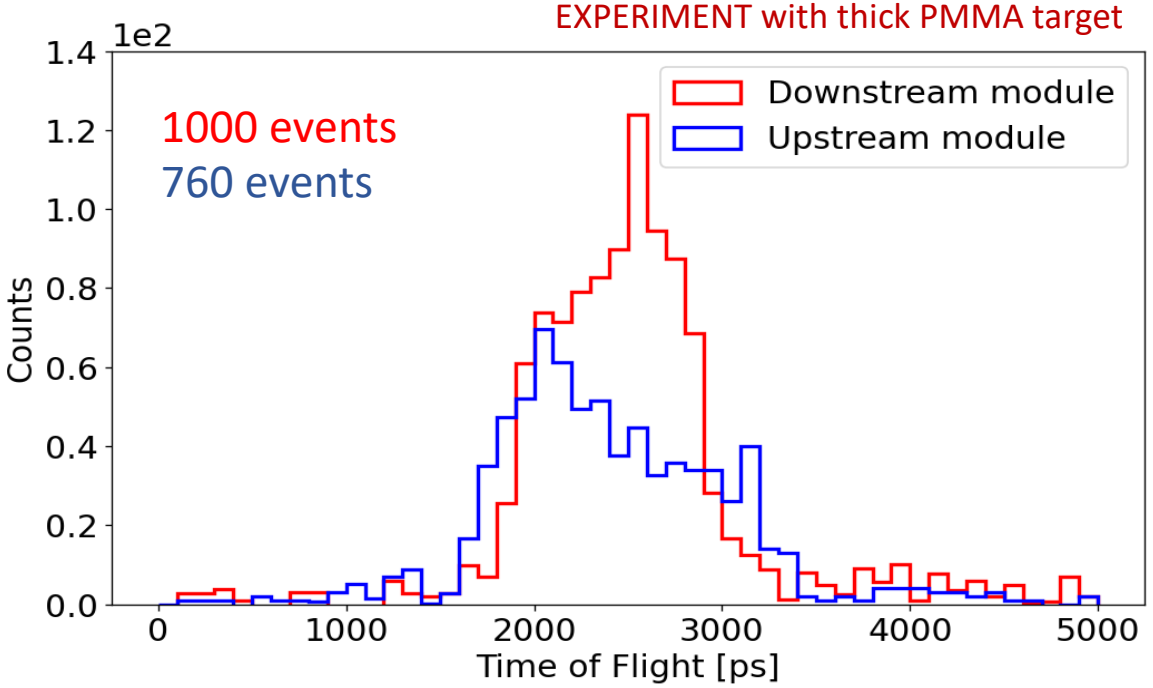
Tres = 229 ps FWHM @ 63 MeV, SPR

2023. Experimental validation with two modules at S2C2 (148 MeV, SPR)



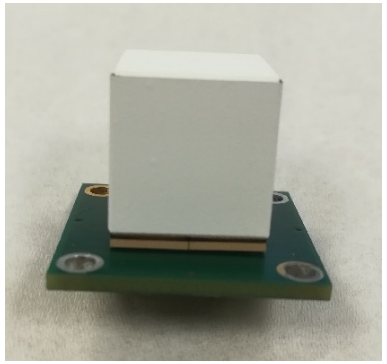
- **CTR = 124 ps RMS** measured with thin target
- PG TOF distributions measured with large target

EXPERIMENT with thick PMMA target



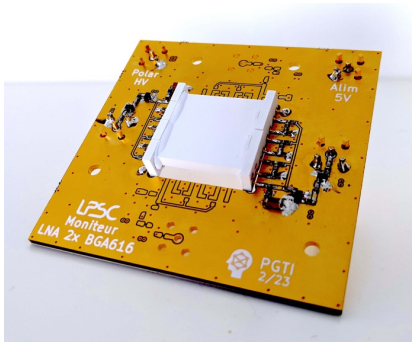
TIARA γ module

(1.5 cm)^3 PbF_2 coupled to SiPMs



Beam monitor for SPR

~ 4cm^2 plastic detector



- **Negligible background**
- Low statistic acquisition ~ 10^7 incident protons
- Uniform sensitivity all over the range expected

PGTI reconstruction: alternating approach

Courtesy of A. Cherni. To be submitted to PMB

$$T(\lambda) = T_p(\lambda, v) + T_{PG}(\lambda)$$
$$= \int_0^{\lambda} \frac{1}{v(s)} ds + \frac{1}{c} ||x(\lambda) - d||$$

✗ Inverse (ill/well)-posed multi-variable problem

$$(t \sim \mathrm{N}(\mathbf{T}(\lambda, \mathbf{v}), \sigma^2)), \quad \underset{\lambda \in \mathbb{R}^N, \mathbf{v} \in \mathbb{R}^N}{\text{minimize}} \underbrace{\frac{1}{2\sigma^2} \| t - \mathbf{T}(\lambda, \mathbf{v}) \|^2}_{\text{Cost function}} \quad (1)$$

λ = PG vertex distribution **v** = proton speed

Alternating method to establish Proton speed (**v**) and PG yield (**λ**)

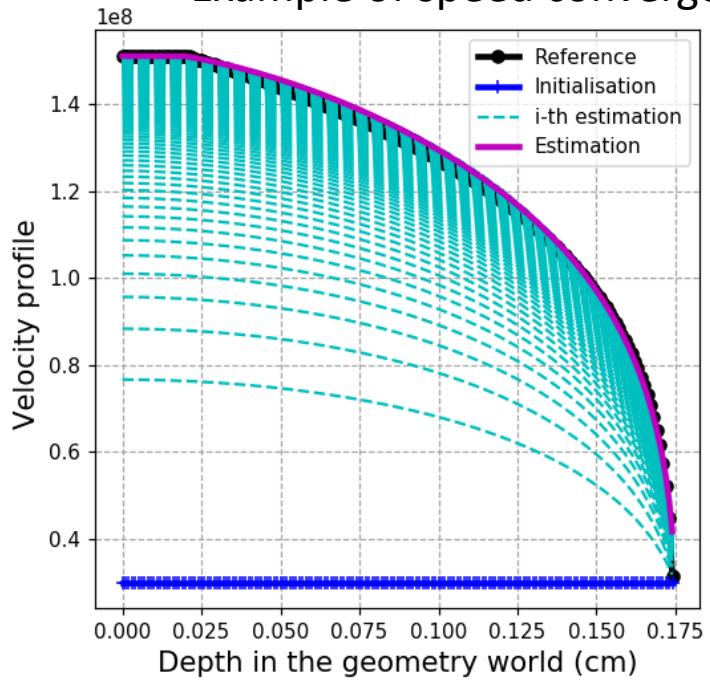
- Step 1: Fix **v** and resolve problem (1) according to λ

$$\underset{\lambda \in \mathbb{R}^N}{\text{minimize}} \frac{1}{2\sigma^2} \| t - \mathbf{T}(\lambda) \|^2 \quad (1.a)$$

- Step 2: Fix λ and resolve problem (1) according to **v**

$$\underset{\mathbf{v} \in \mathbb{R}^N}{\text{minimize}} \frac{1}{2\sigma^2} \| t - \mathbf{T}(\mathbf{v}) \|^2 \quad (1.b)$$

Example of speed convergence



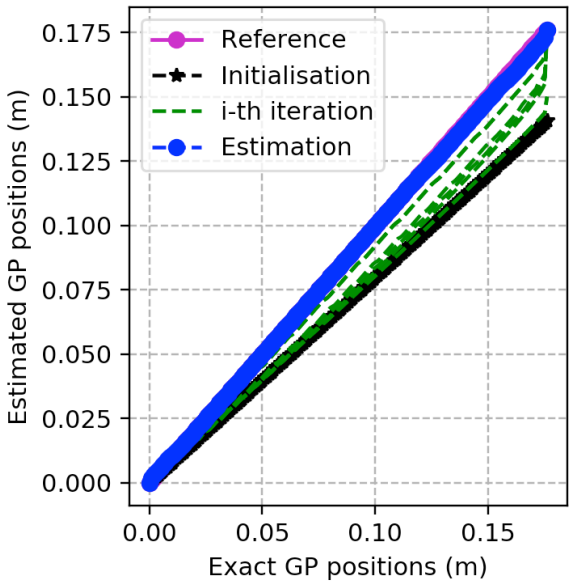
Does not require any a priori knowledge of the proton speed (or time), but using a close guess speeds-up convergence

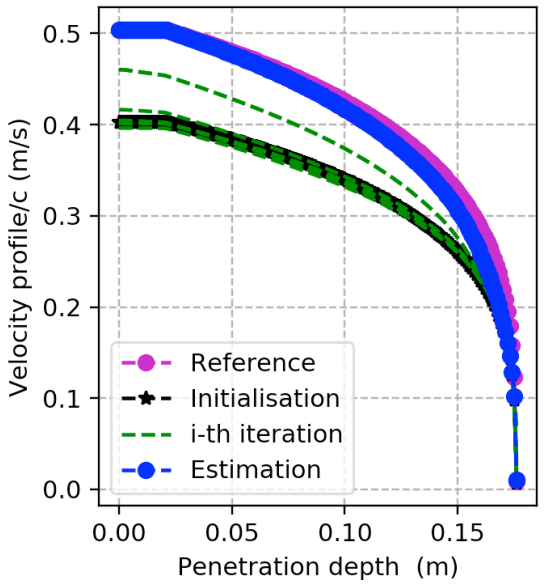
PGTI reconstruction: alternating approach

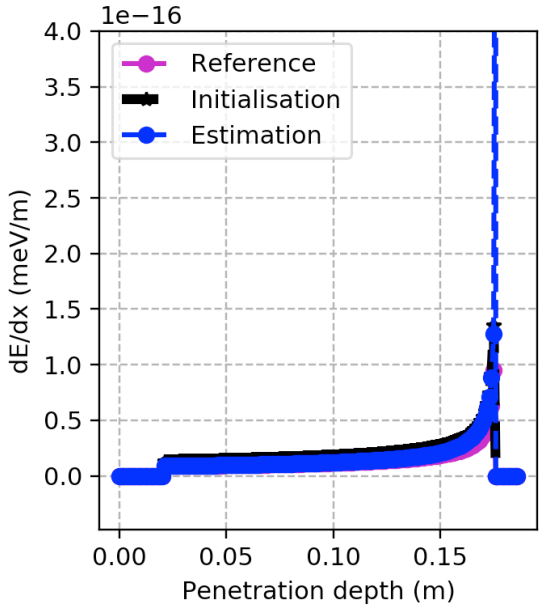
Courtesy of A. Cherni. To be submitted to PMB

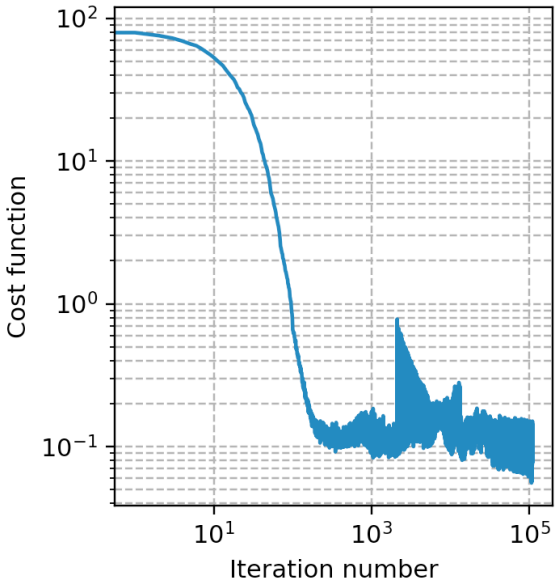
SIMULATIONS

Example: 148 MeV protons impinging on a water sphere









We can use directly the dE/dx to assess the proton range.
But for this, we need a uniform sampling of the PG TOF.

=> paves the way to online dosimetry

Preliminary results

Conclusions and perspectives

1. We are developing a new approach to PG imaging with the following characteristics

- Very high sensitivity (statistically significant information within a single spot in SPR)
- Capable of measuring proton beam deviations in any direction thanks to 3D coverage (IMPT)
- Direct determination of dE/dx with uniform sensitivity

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

Future needs for the project

- Tests at nominal intensity with 8 module prototype (first test scheduled November 2023)
- The technique/detector performances ultimately depend on the accelerator time structure
  => Need to test with protons from synchrotrons
- Test the PGTI technique with carbon ions

Acknowledgements and credits

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PGTI collaboration

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CAL
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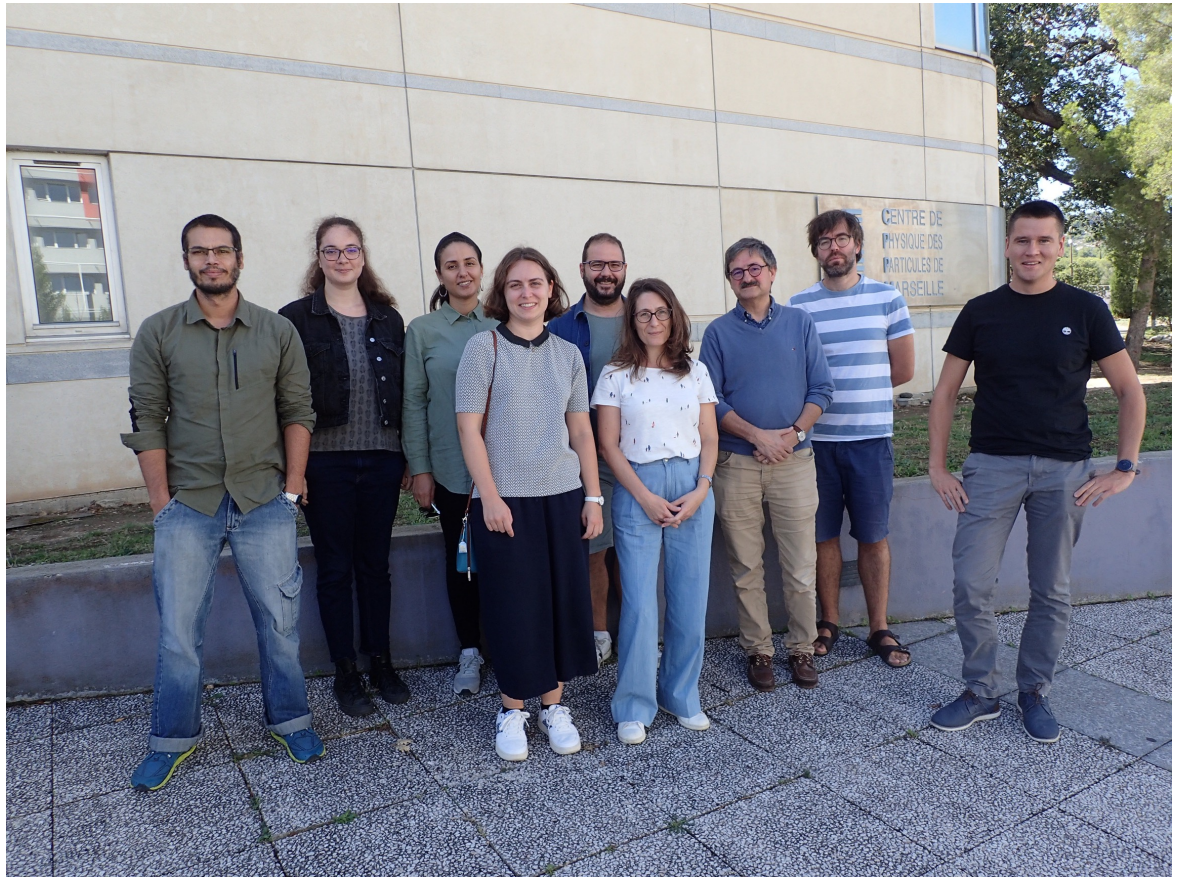
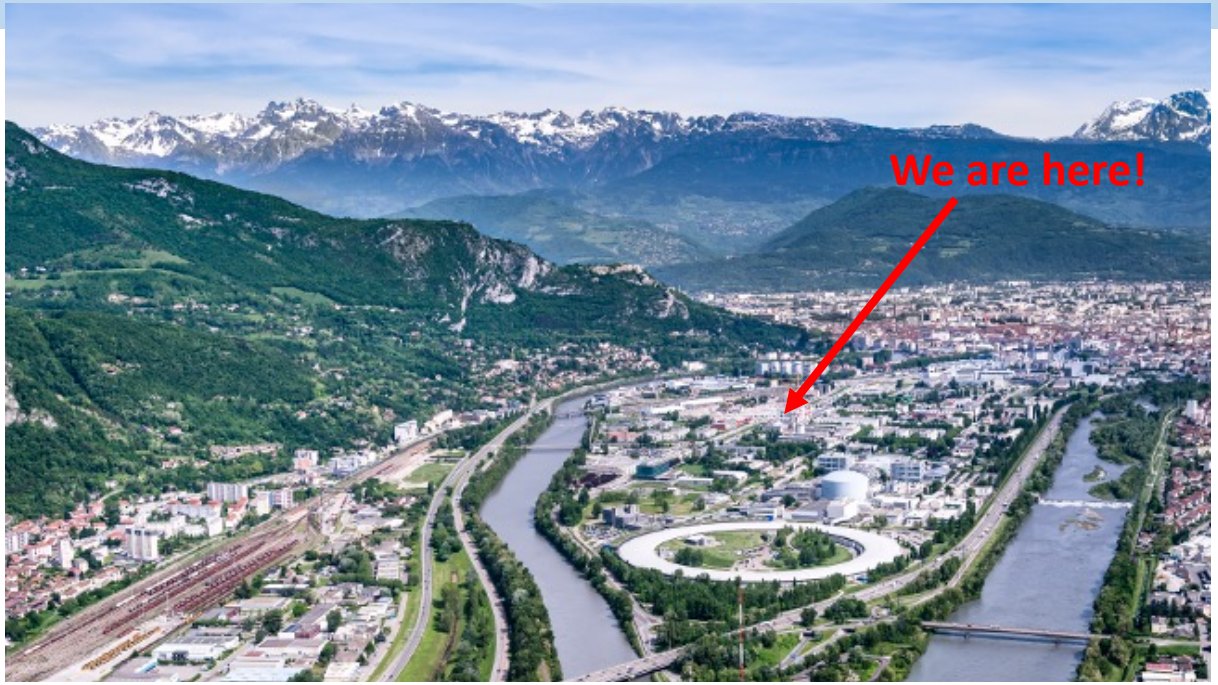


Two positions available in the PGTI project

Postdoc fellow (2-years)
Monte Carlo simulation and data reconstruction
Start date: asap
https://inspirehep.net/jobs/2705316

Research engineer/postdoc (2-years)
Development of a fast digital TDC
Start date: asap
https://euraxess.ec.europa.eu/jobs/94746



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Why we do need to reconstruct the PG vertex

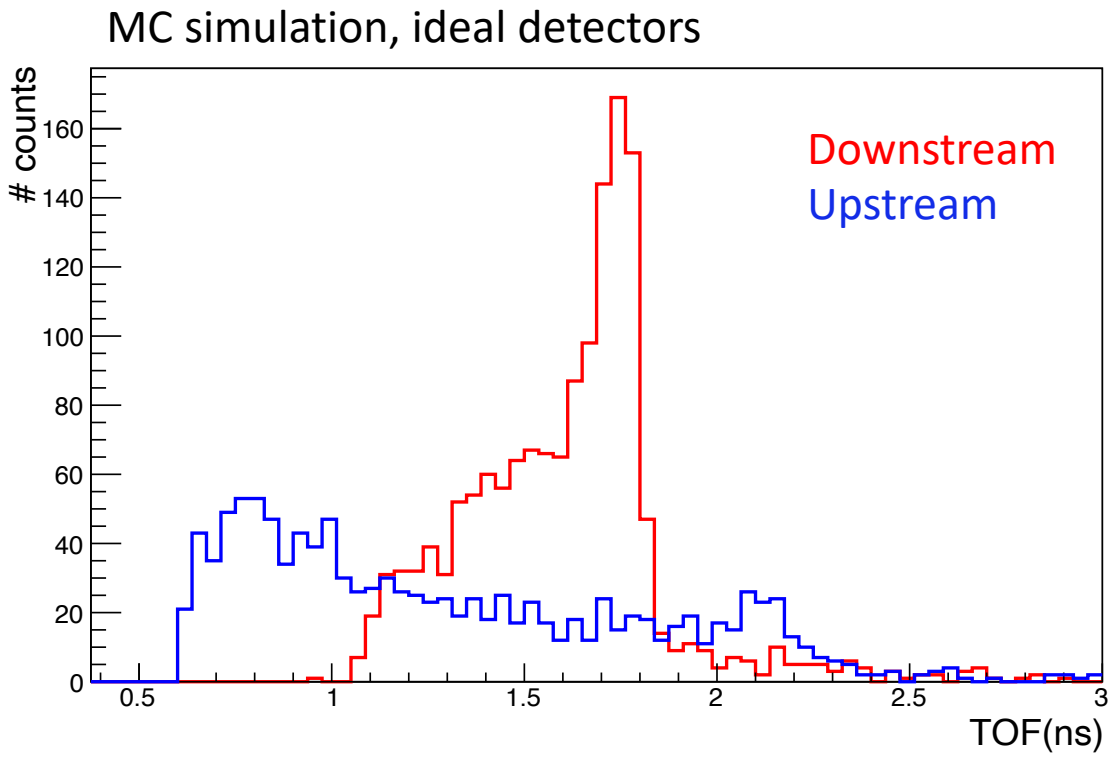


Fig. The two TOF distributions are produced by the same proton beam, but they extend on different time ranges as the PG TOF contribution depends on the detector position.

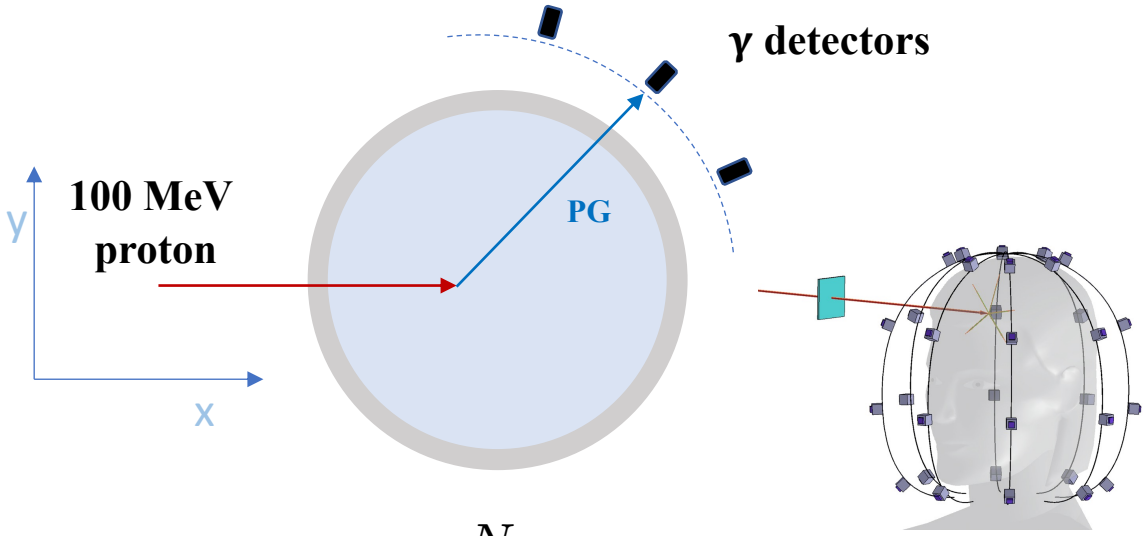
TOF distributions from detectors placed at different angles **cannot be summed up in the time domain**.

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

PGTI reconstruction allows to combine the response of multiple detectors.

Measurement of lateral beam displacement with TIARA and COG



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

N = total number of PG detected

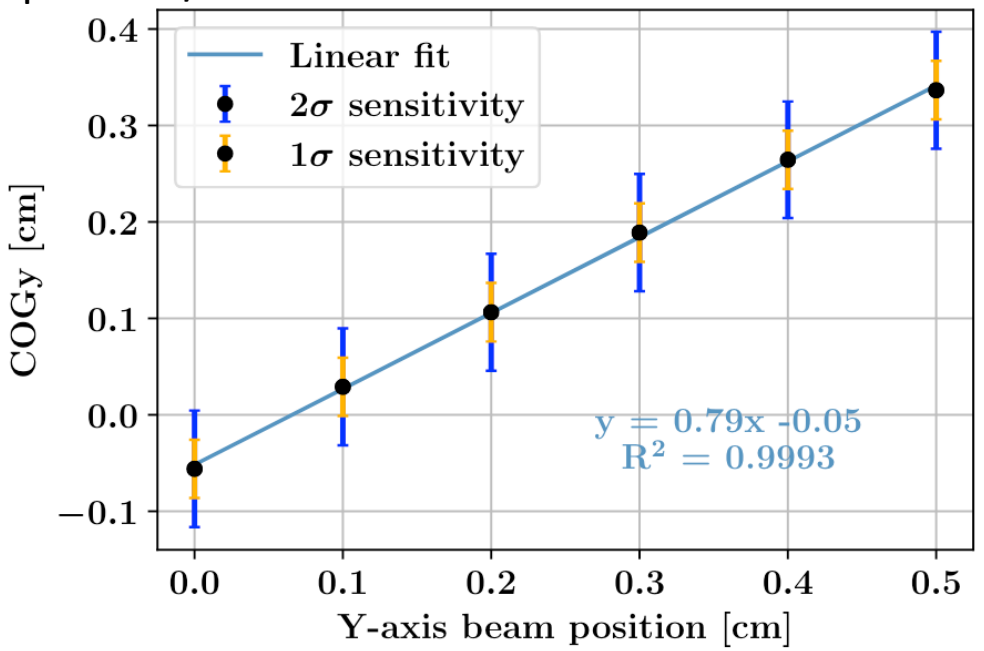
n_i = number of PG detected in module i

Y_i = x coordinated of gamma detector

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

10^8 protons / ~30000 PGs

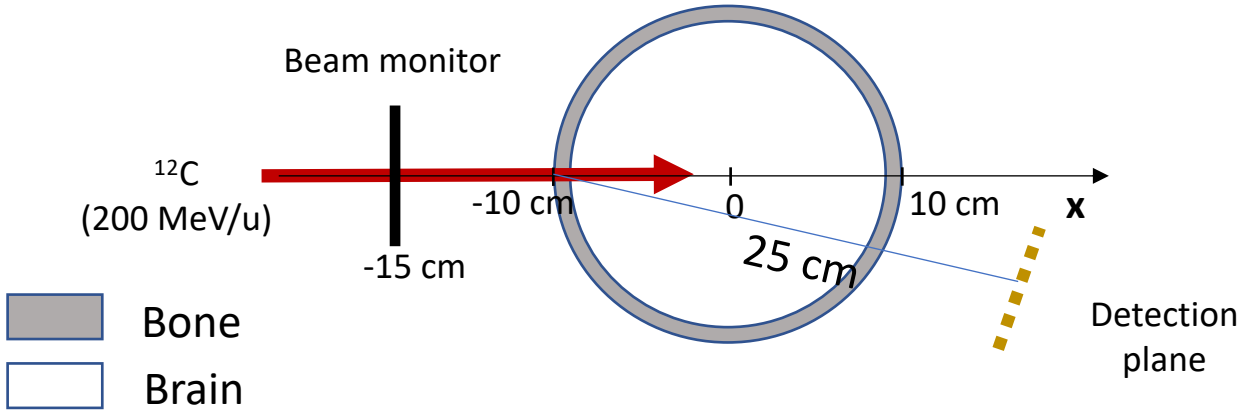
SIMULATION



Possible to distinguish a lateral beam displacement of **2 mm at 2 sigma**

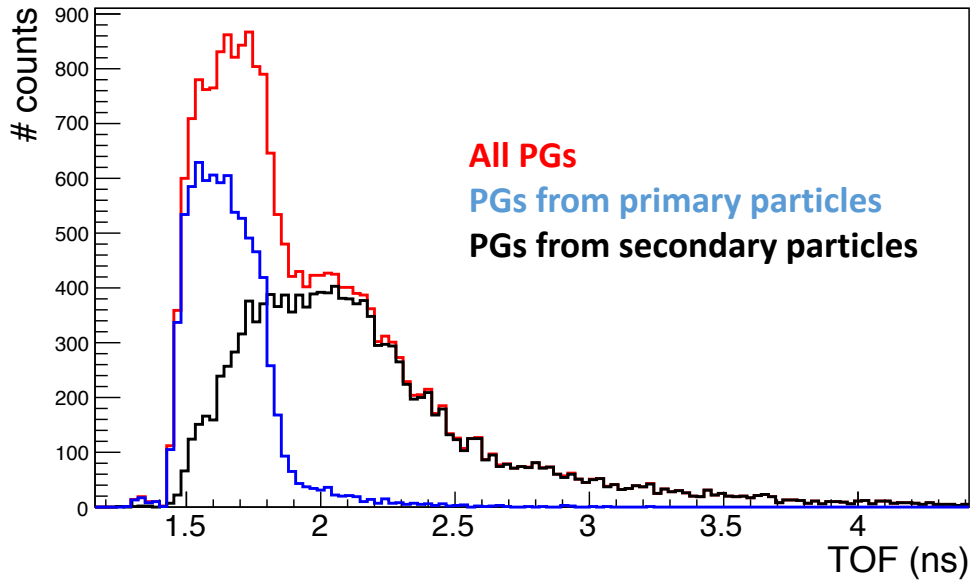
- **3D info:** multiple detectors allow a full angular coverage to measure deviations in any direction.
- Could be **compatible with IMPT**

PG TOF detection with Carbon ions (Monte Carlo)



Very preliminary

PG Time-Of-Flight



PG profile