Development of a fast Cherenkov detector dedicated to Prompt Gamma Time Imaging

Maxime Jacquet
On the behalf of the TIARA collaboration

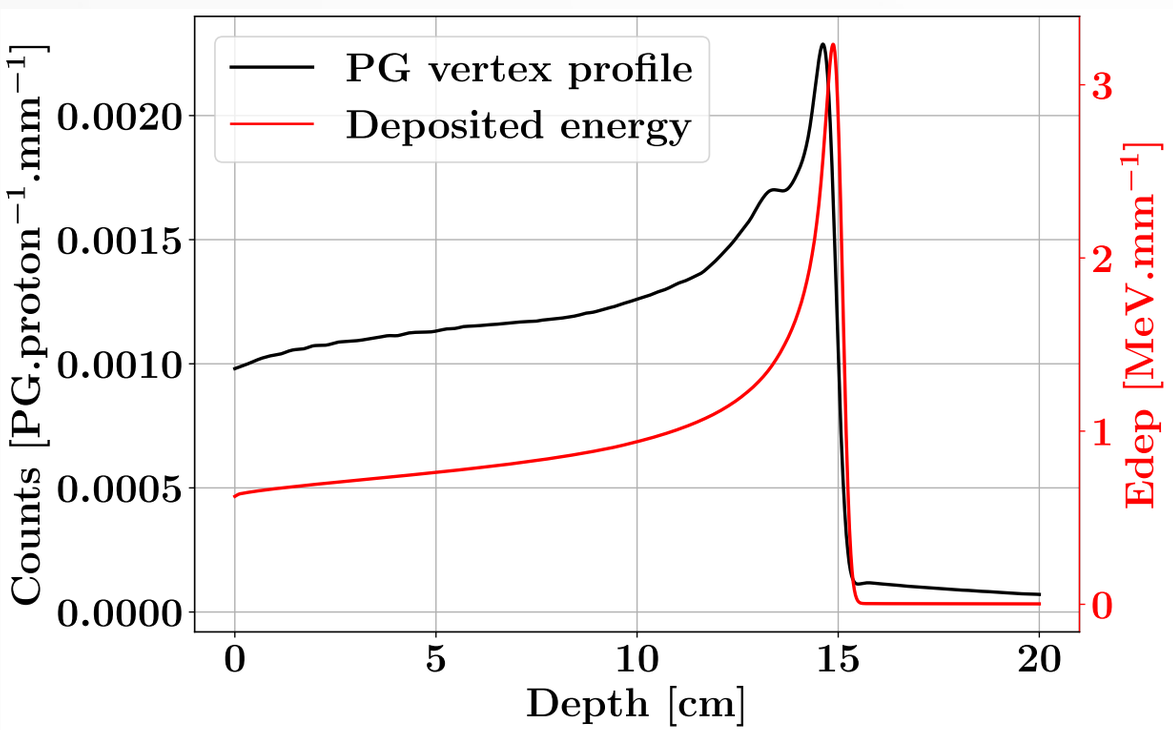
PG monitoring of the proton therapy

Proton therapy :

☺ **High ballistic precision**

☹ Uncertainties on the proton range

→ **PG monitoring**



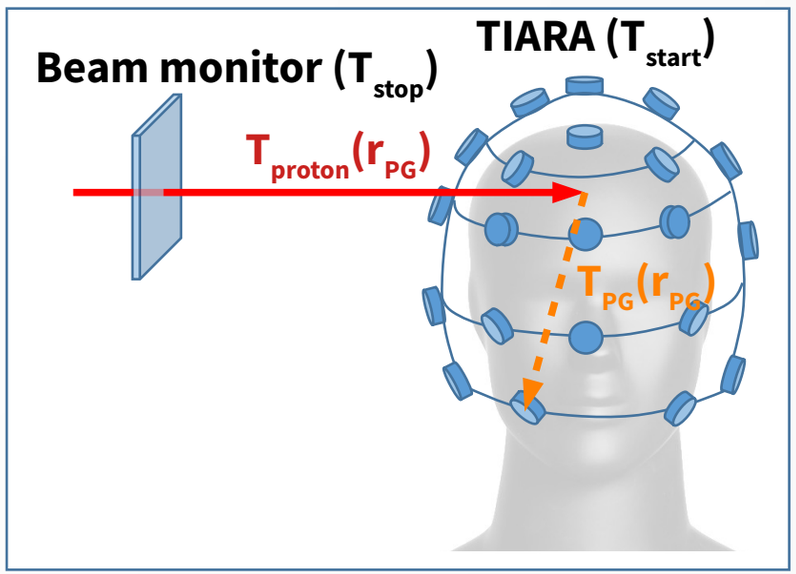
PG features :

- $1 < E_{PG} < 10$ MeV
- $\langle T_{PG} \rangle <$ **1 ps**
- **0.01 PG**.proton^{-1}.cm^{-1}
- **Spatially correlated with the proton range**

→ **Time-based PG monitoring**

Prompt Gamma Time Imaging (PGTI)

Proton range estimation from the exclusive measurement of particles Time-Of-Flight (TOF)



1) **Diamond-based beam monitor**

2) **T**ime of flight **I**maging **AR**r**A**y (**TIARA**)

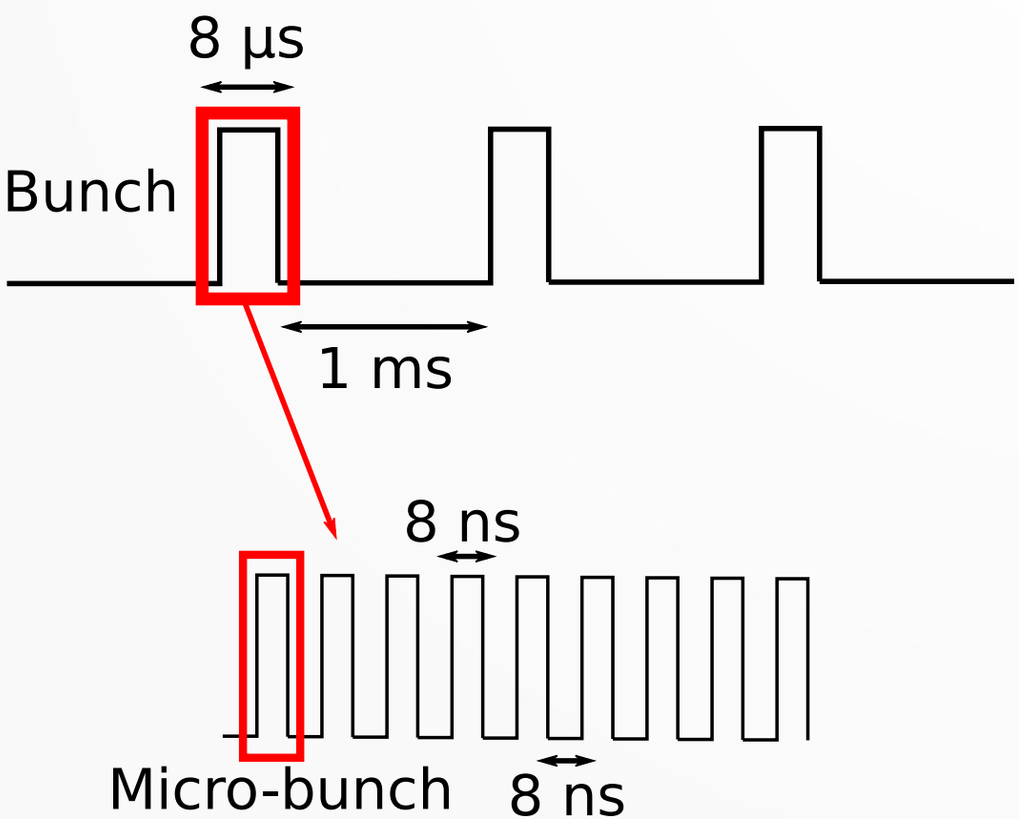
   - 30 ~ 1 cm^3 PbF_2 crystals read-out by SiPMs

Vertex reconstruction: Inverse problem resolution

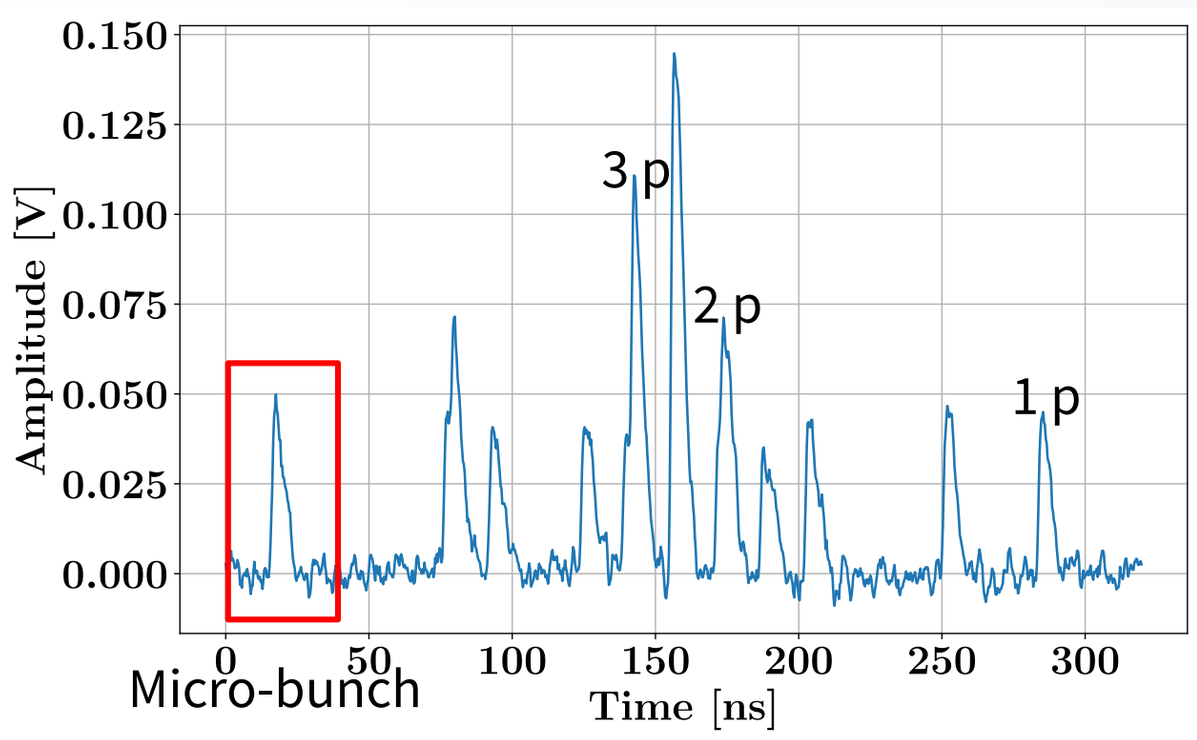
- $\mathrm{T_{Start}} - \mathrm{T_{Stop}} = \mathrm{T_{proton}}(\mathbf{r}_{\mathrm{PG}}) + \mathrm{T_{PG}}(\mathbf{r}_{\mathrm{PG}}, \mathbf{r}_{\mathrm{D}})$
- **Allows combining all PG detector responses**

Proton irradiation: S2C2 Proteus One

Time structure of the beam



Proton beam irradiation of the beam monitor



Proteus One operating modes

Hypothesis: **0.5%** of detection efficiency for 30 block detectors at 15 cm from the FOV center.

	Single Proton Regime (1p/μ-bunch)	Typical intensity (1600p/μ-bunch)	Maximum intensity (3×10^5p/μ-bunch)
Beam Monitor	Proton tagging	Micro-bunch tagging	-
TIARA block detector	1.1 kHz	1.7 MHz	311 MHz
CTR (FWHM)	235 ps	~ 2.35 ns	Event counting

Expected sensitivity for the different operating modes

MC Simulation of the method sensitivity with ~ 0.6% of TIARA detection efficiency

	Method	CTR (FWHM)	Number of protons	Nb of PGs	2σ sensitivity (mm)
Longitudinal shift	**PGTI**	**235 ps**	**10^7**	**3×10^3**	**3**
	PGTI		10^8	3×10^4	1
	PGTI	2.35 ns	10^9	3×10^5	2
	Center of Gravity	-	10^8	3×10^4	4
Lateral shift	Center of Gravity	-	10^8	3×10^4	2

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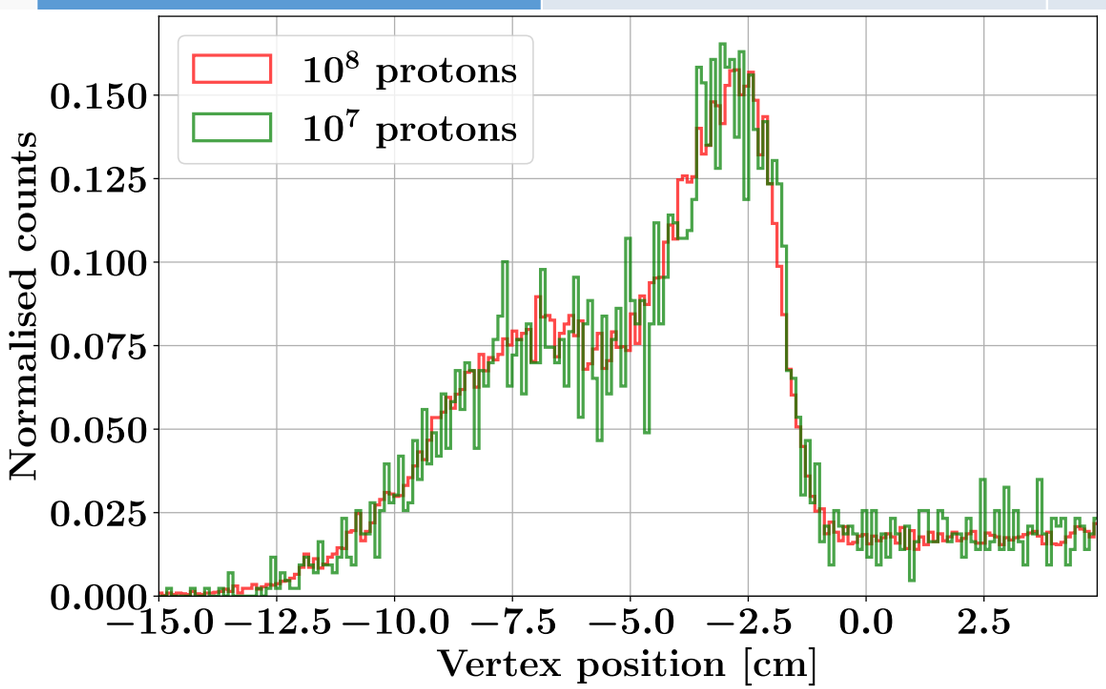

Single Proton Regime

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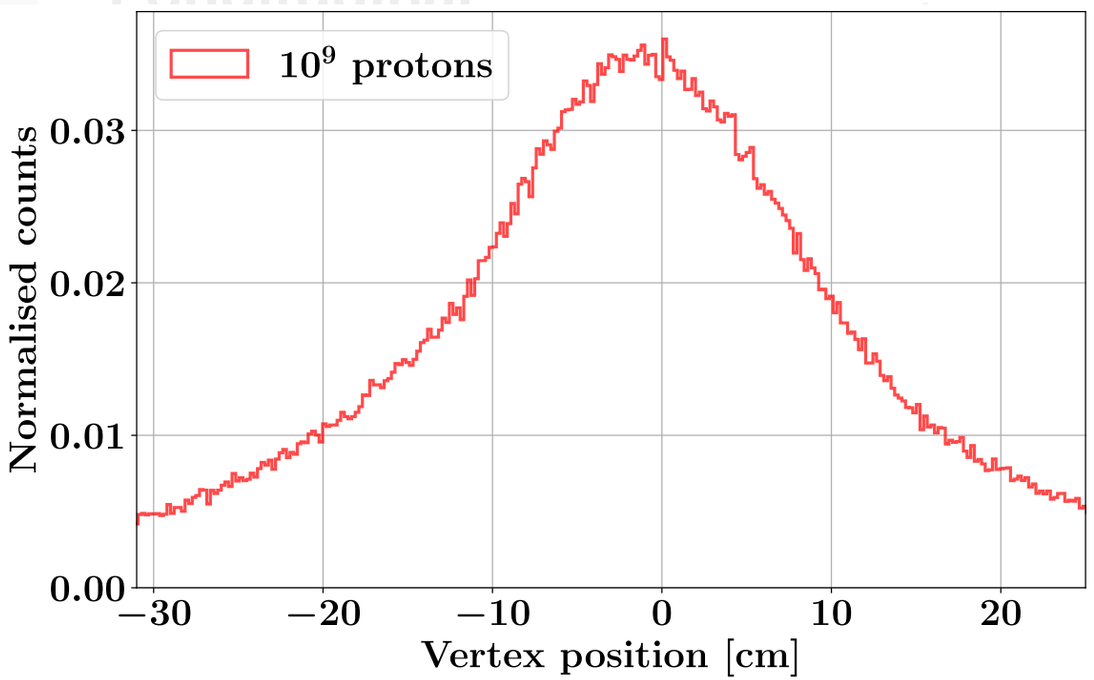

Nominal intensity :
Micro-bunch tagging

Expected sensitivity for the different operating modes

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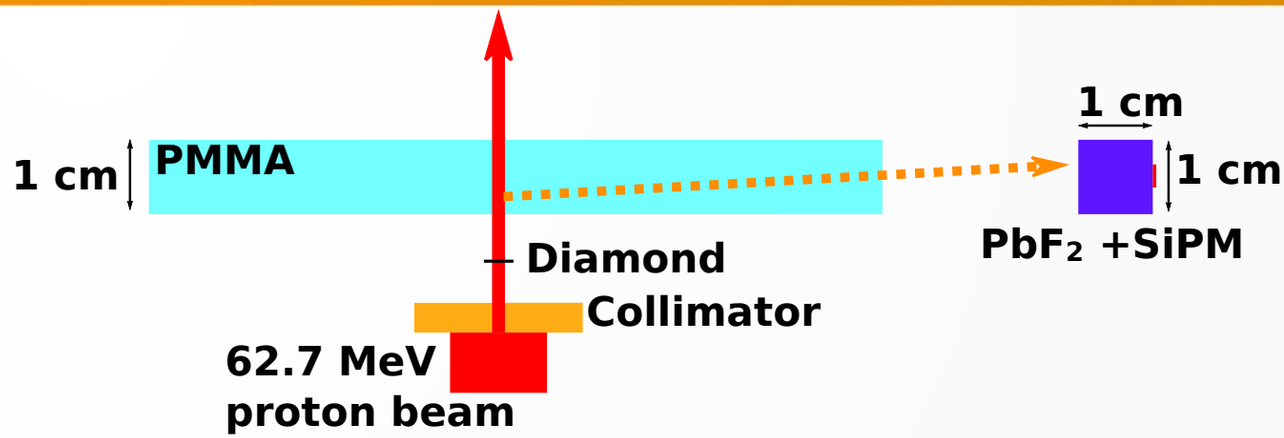
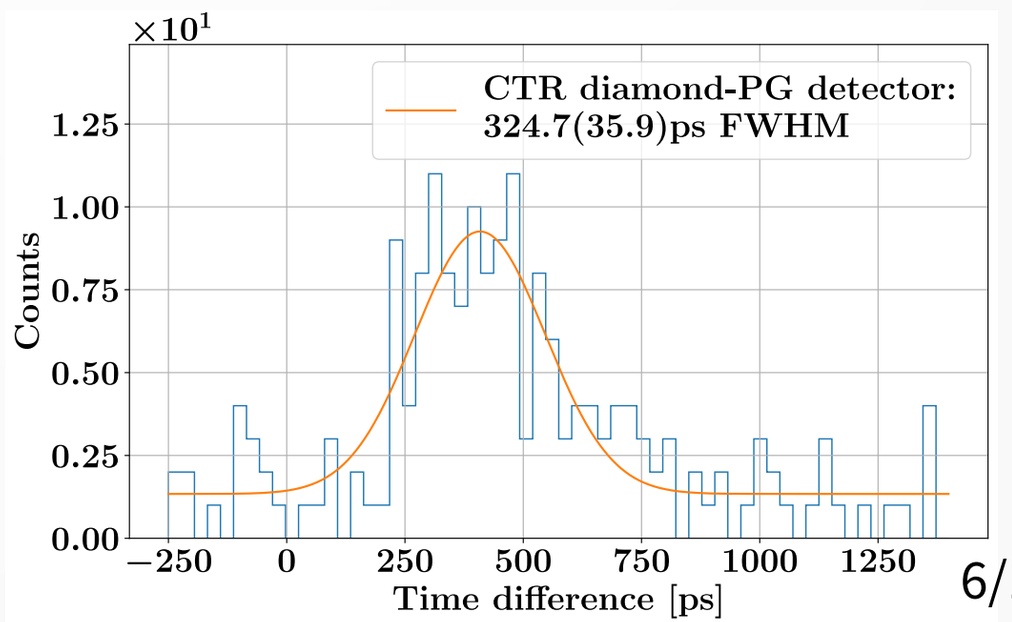
$\mathbf{r}_{\mathrm{COG}} = \frac{1}{N} \times \sum_{i=1}^{N_{Det}} \mathbf{r}_{\mathrm{PG}_i} \times n_i$			**Nominal intensity : Event counting**		
Longitudinal shift	Center of Gravity	-	10^8	3×10^4	4
Lateral shift	Center of Gravity	-	10^8	3×10^4	2

Gamma-proton CTR with 63 MeV protons



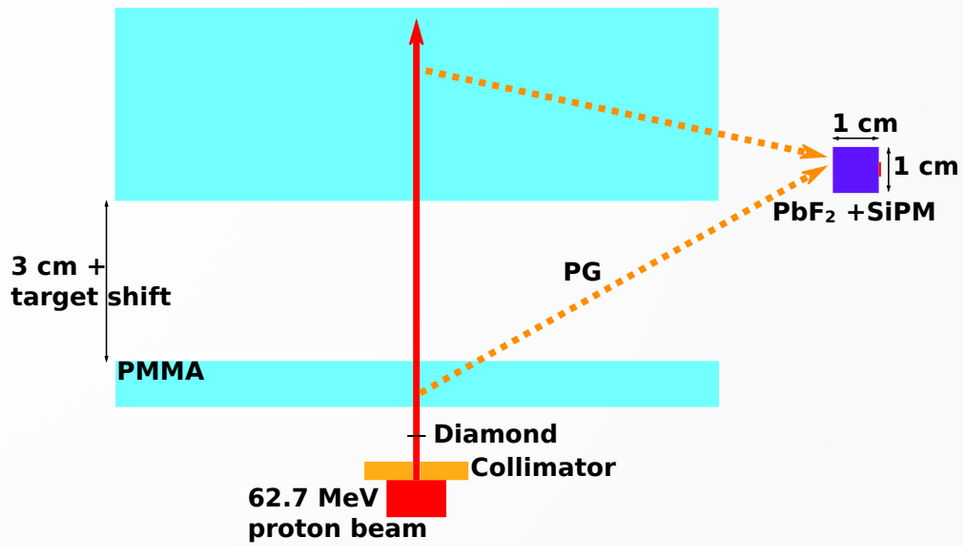
- **Single proton regime**
- Beam monitor :
  - 4.5×4.5 mm^2
  - Time resolution of ~ 160 ps FWHM
- 2 mm diameter collimated beam

CTR diamond-PG detector

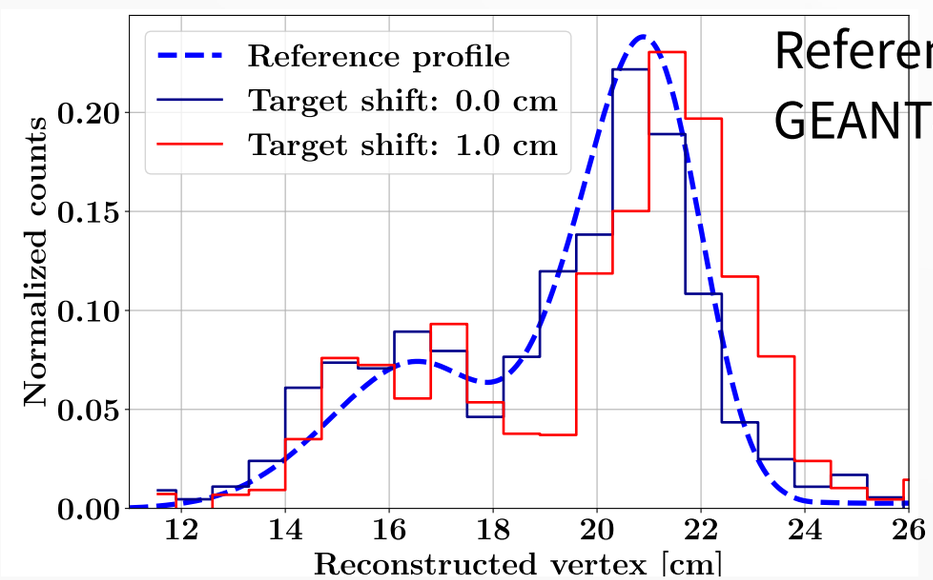


Experimental PGTI sensitivity

- Target shift within [0,1] cm
- **600 PG detected**

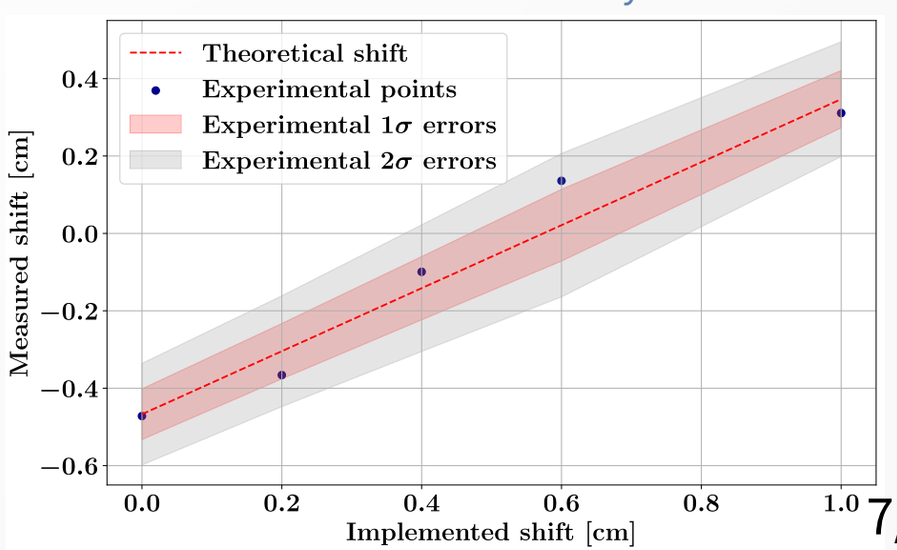


Distribution of the reconstructed PG vertices



Reference profile :
GEANT4 simulation

PGTI sensitivity

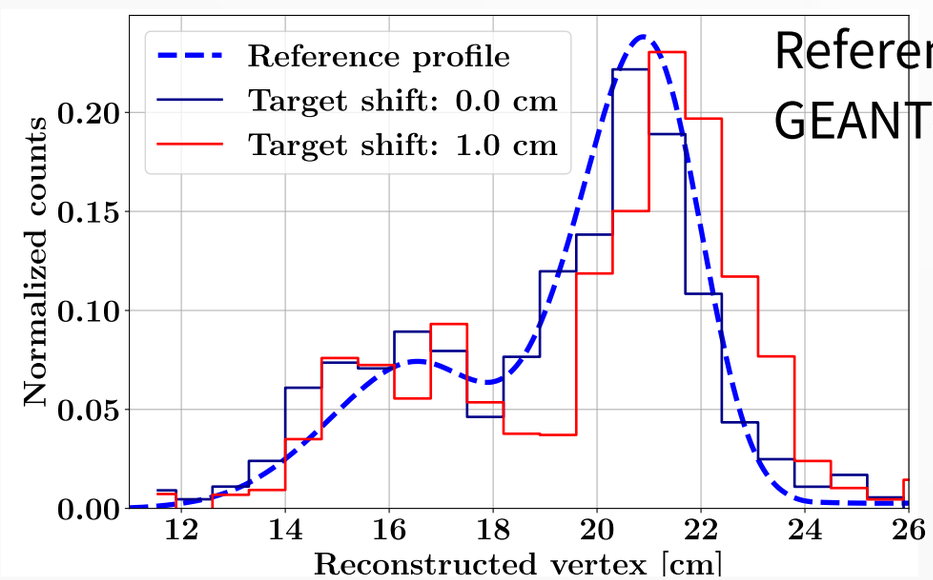


Experimental PGTI sensitivity

- Target shift within [0,1] cm
- **600 PG detected**

4 mm of sensitivity at 2σ with **only 600 PG** detected

Distribution of the reconstructed PG vertices



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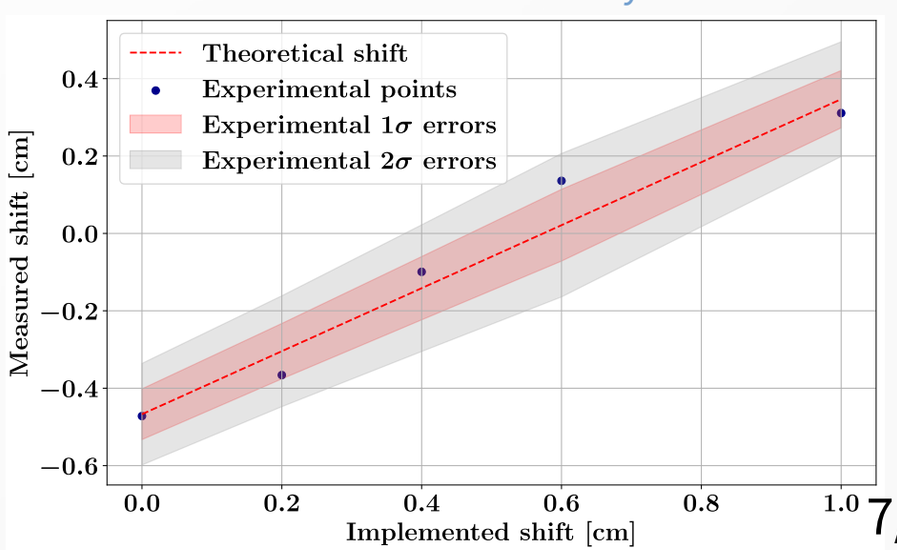

Summary of detection system performances

	Data type	Proton energy (MeV)	CTR (FWHM)	Number of protons	Nb of PGs	2σ sensitivity (mm)
Longitudinal shift	Simulation	100 MeV	235 ps	10^7	3×10^3	3
	Experiment	63 MeV	**324 ps**	-	**600**	**4**

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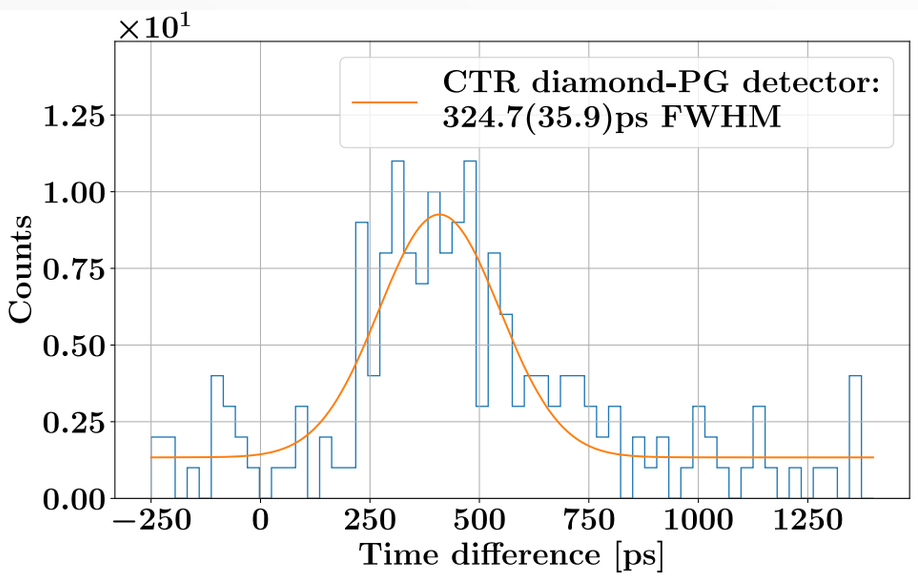
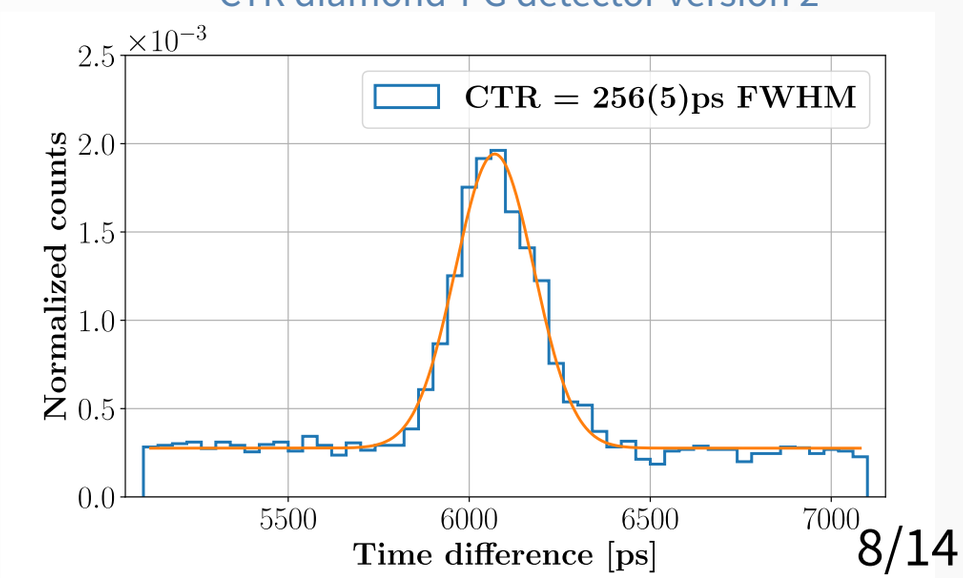
CTR diamond-PG detector version 1



Electronic read-out improvement

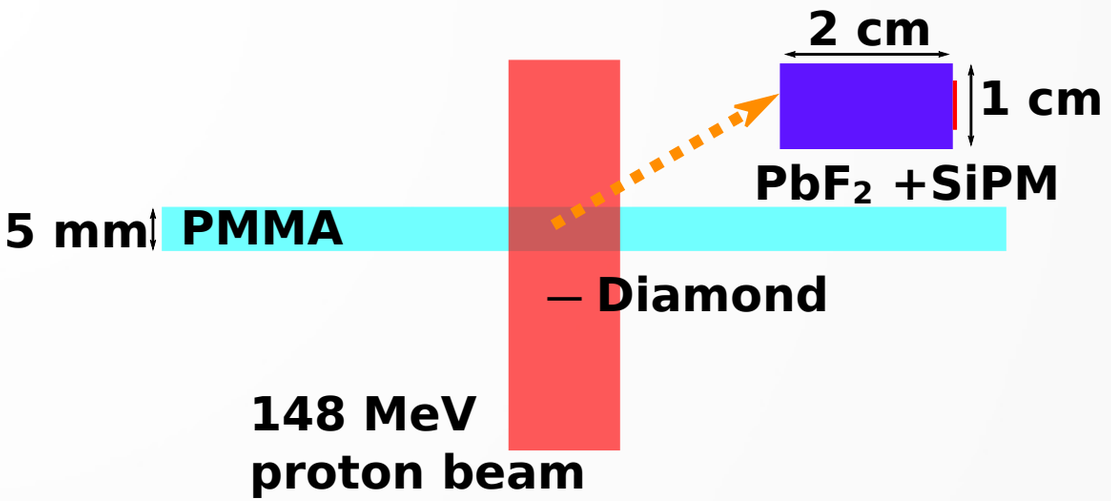
Cates et al 2018 Phys. Med. Biol.

CTR diamond-PG detector version 2

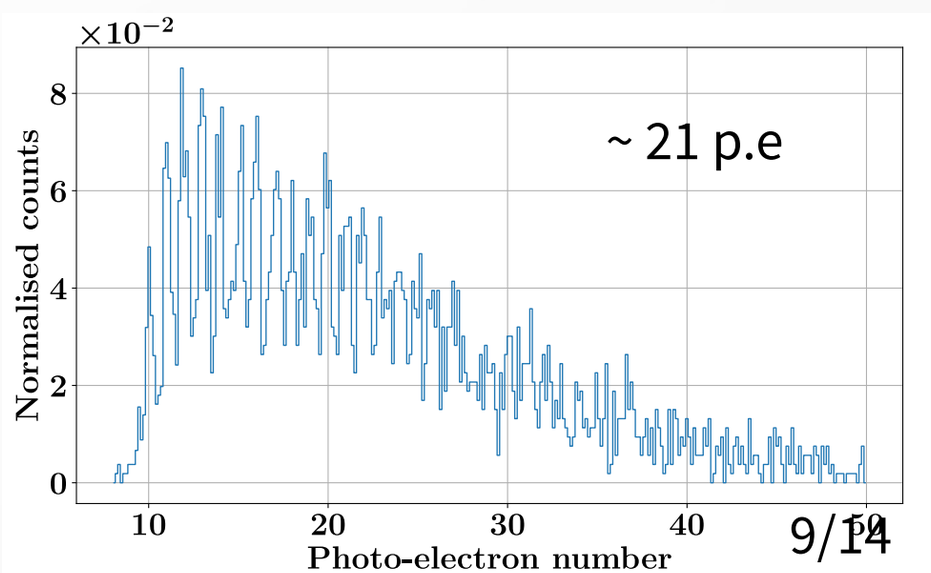


Gamma-proton CTR with 148 MeV protons

- **~ 4 protons/micro-bunch**
- Beam monitor
  - 4.5×4.5 mm^2
  - Time resolution of ~ 300 ps FWHM
- Gaussian beam of **4.2 mm σ width**



P.e spectrum



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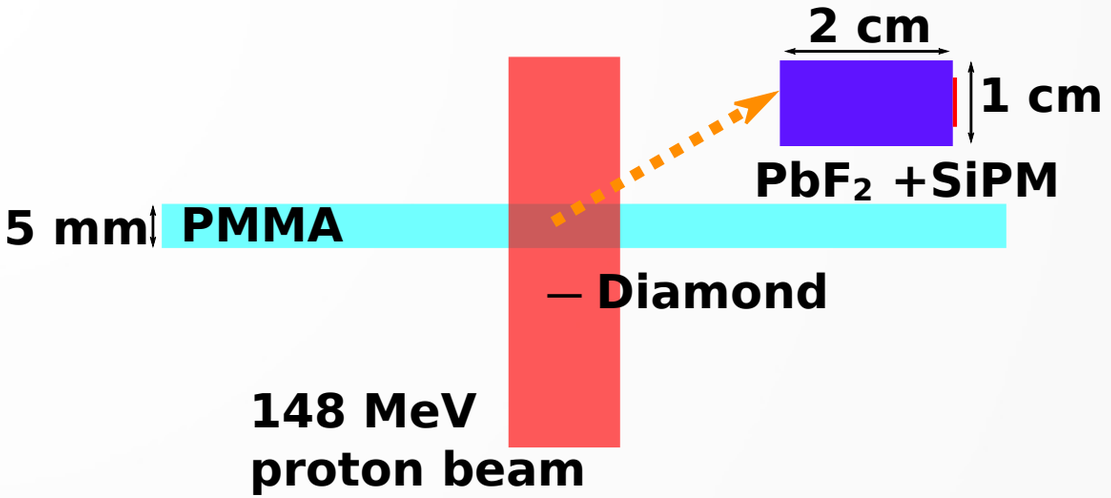
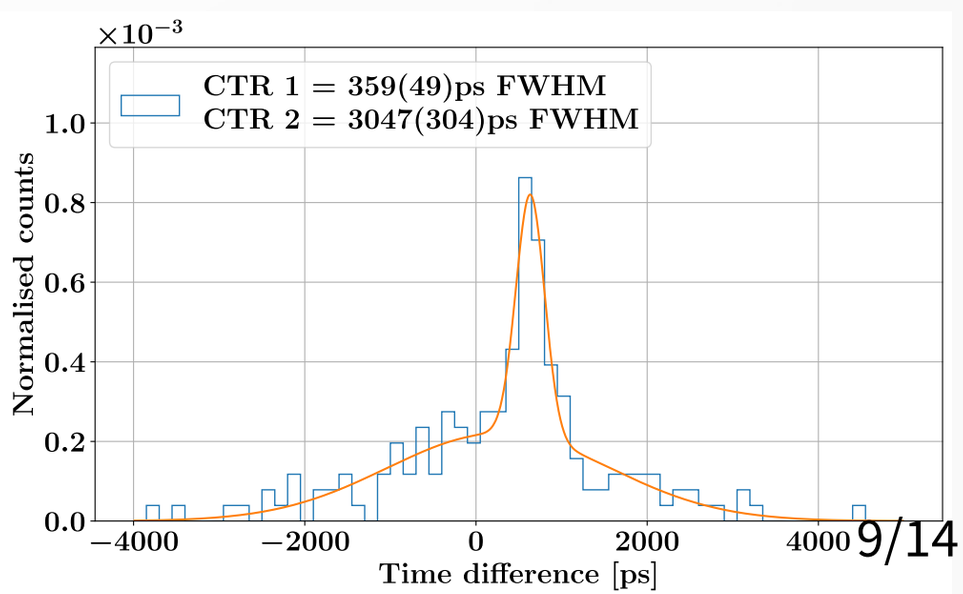


CTR diamond- PG detector



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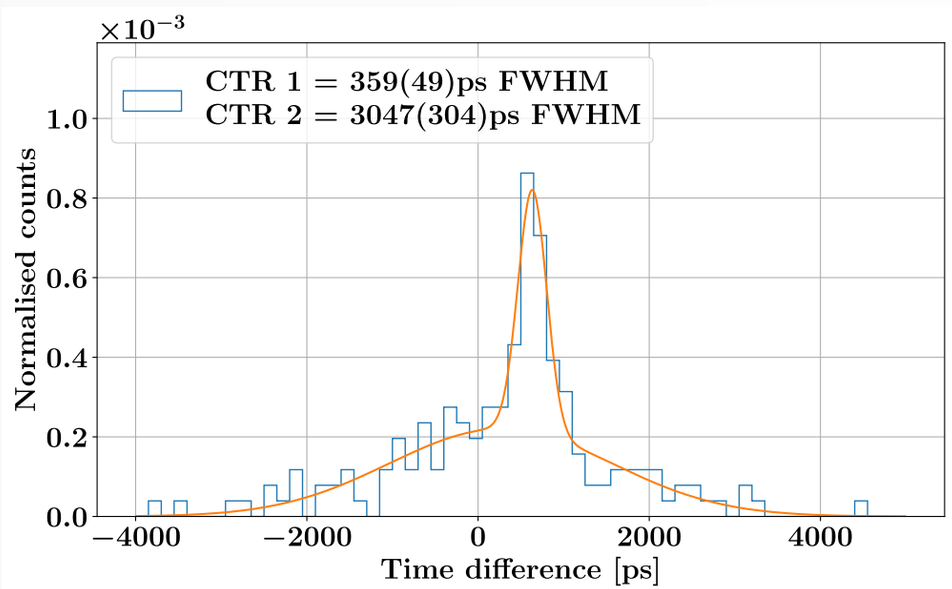

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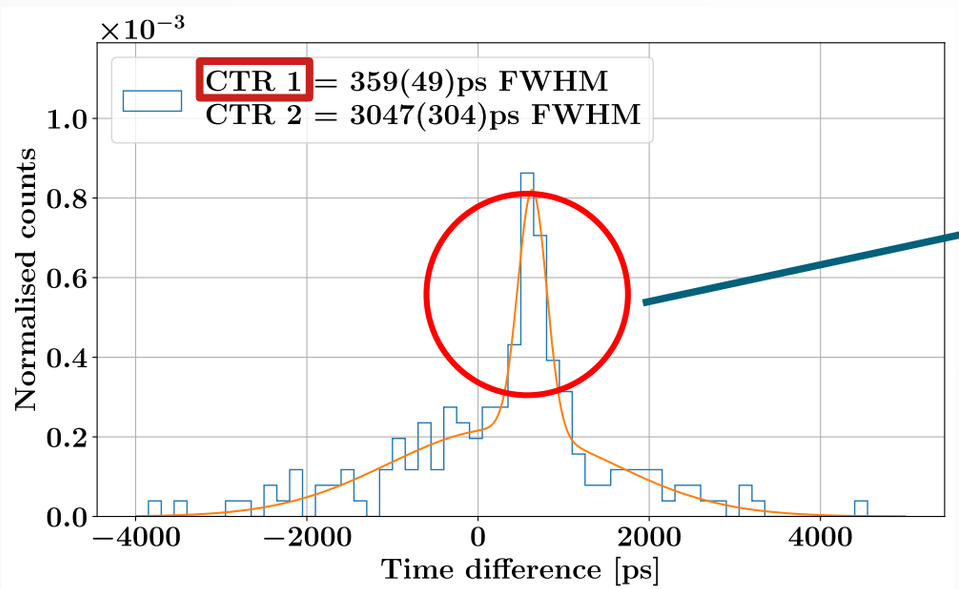

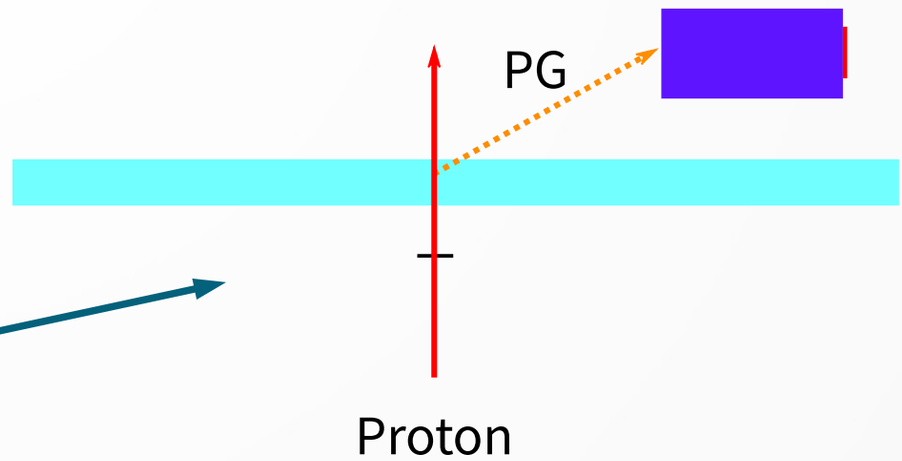

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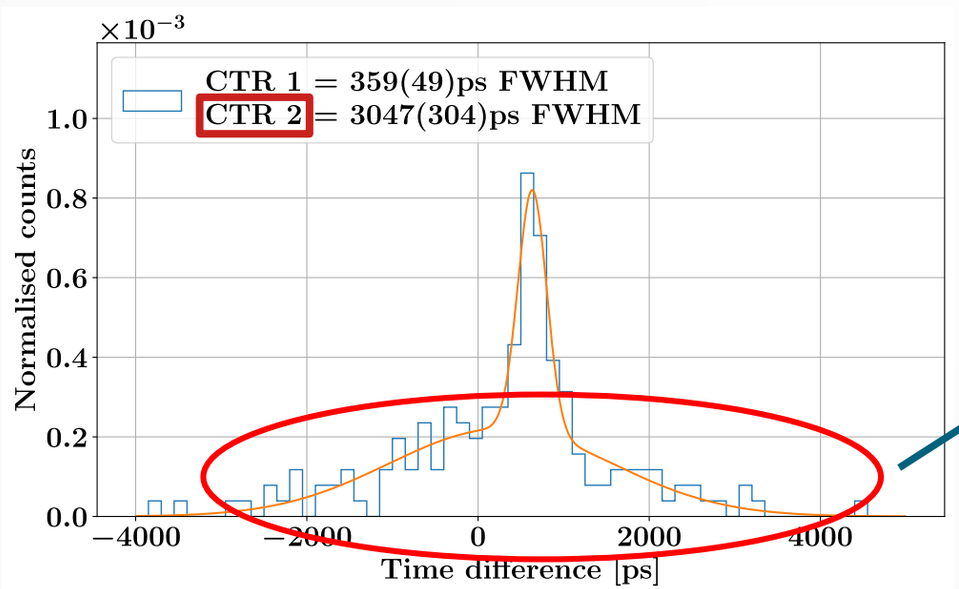

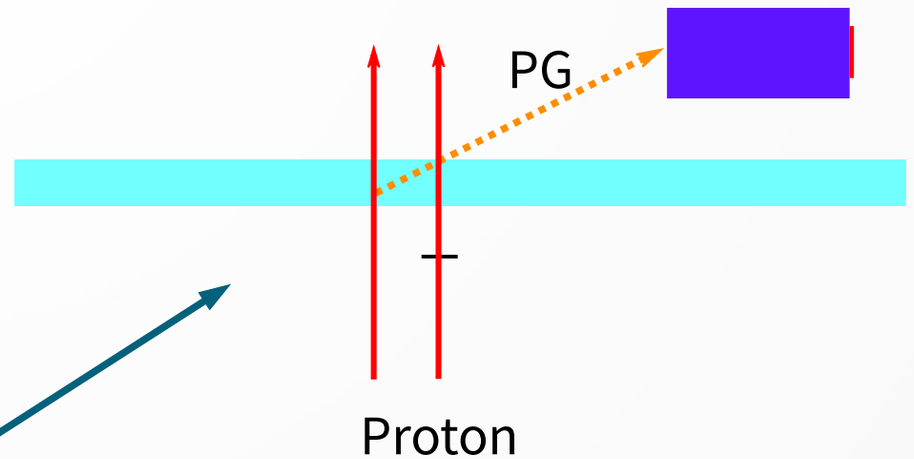

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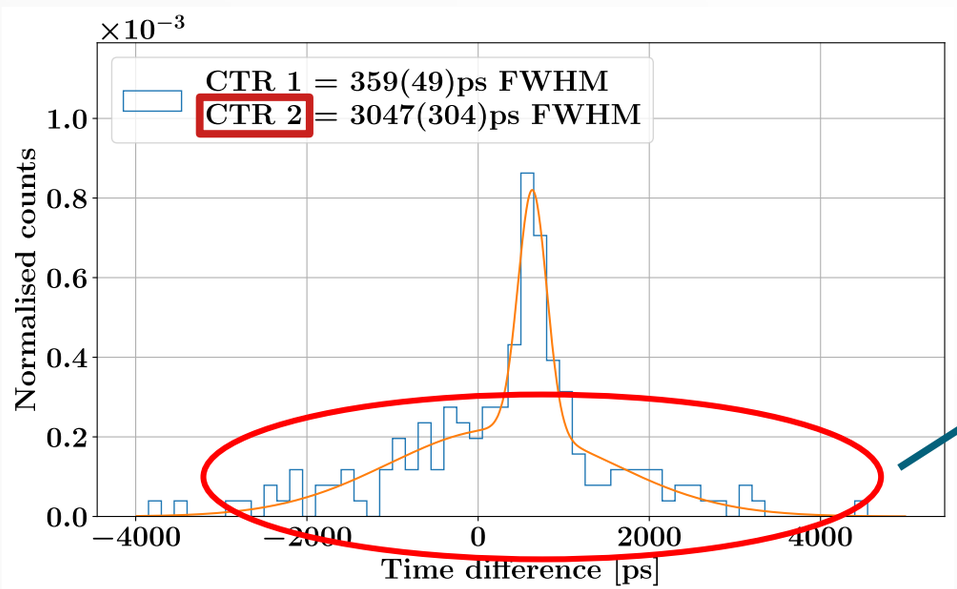
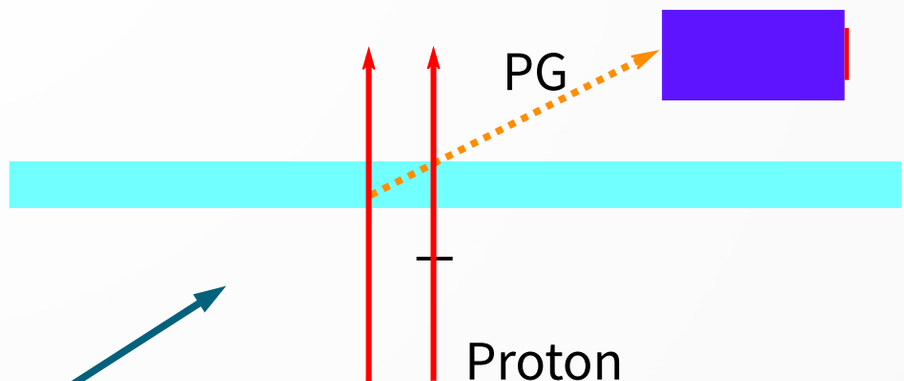
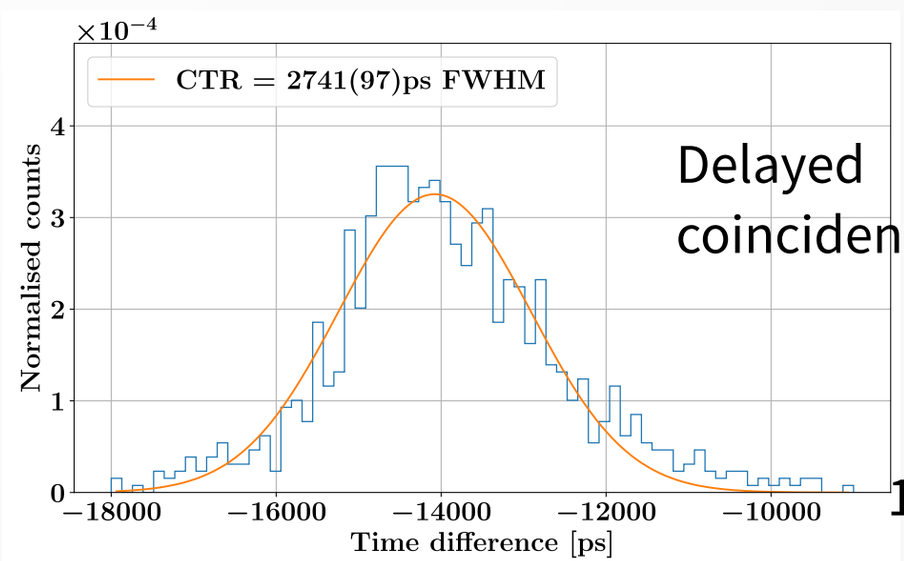




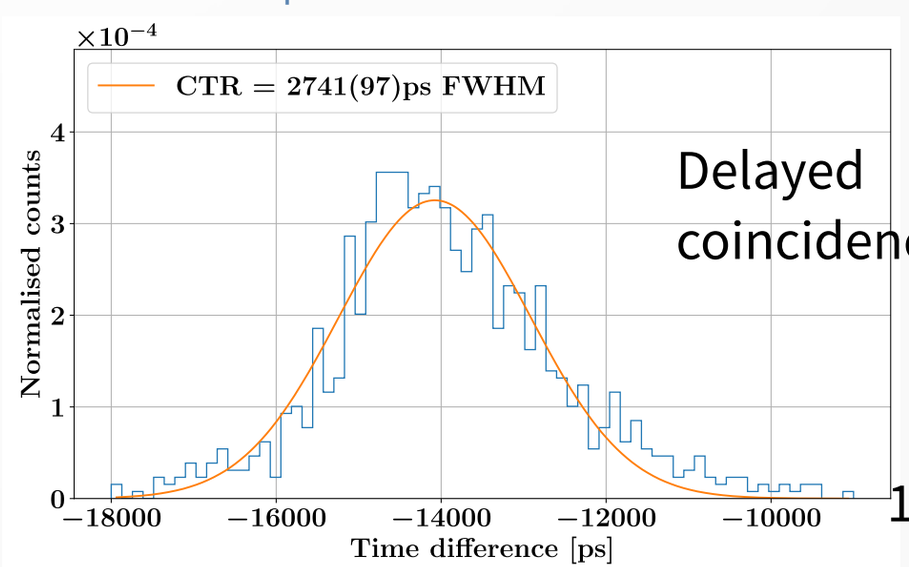
CTR proton bunch PG detector



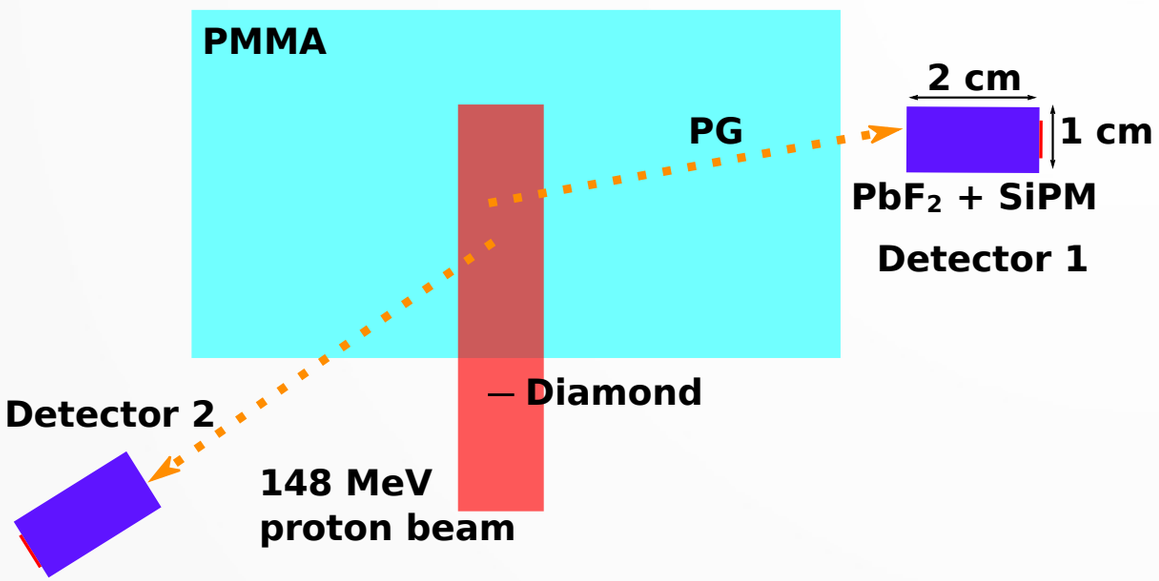
Gamma-proton CTR with 148 MeV protons

Micro-bunch tagging: ~ 2.7 ns FWHM of time resolution

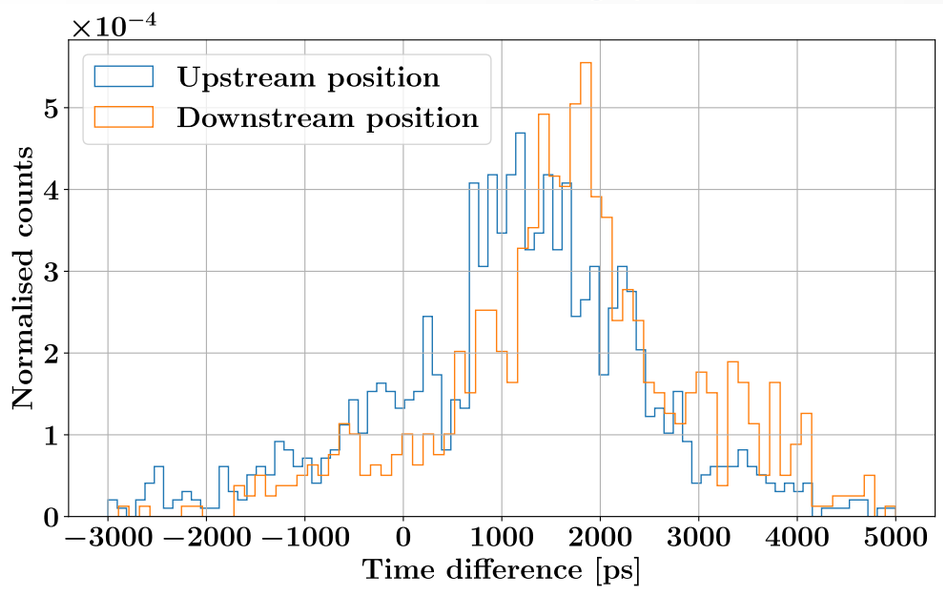
CTR proton bunch PG detector



PG Timing with 2 identical detectors in non symmetric positions



PG detectors PG timing spectrum



- A specific detector position biases the measured PG vertex profile
- TIARA modules are position sensitive

  → 3D coverage + combination of detector responses (**Prompt-Gamma Time Imaging**)

Proteus One operating modes: Results

	Single Proton Regime (1p/μ-bunch)	Typical intensity (1600p/μ-bunch)	Maximum intensity (3×10^5p/μ-bunch)
Beam Monitor	Proton tagging	Micro-bunch tagging	-
TIARA block detector	1.1 kHz	1.7 MHz	311 MHz
Targeted CTR (FWHM)	235 ps	~ 2.35 ns	Event counting (COG)
Experimental CTR (FWHM)	360 ps	2.7 ns	-
Simulation sensitivity	3 mm (10^7 protons)	2 mm (10^9 protons)	-

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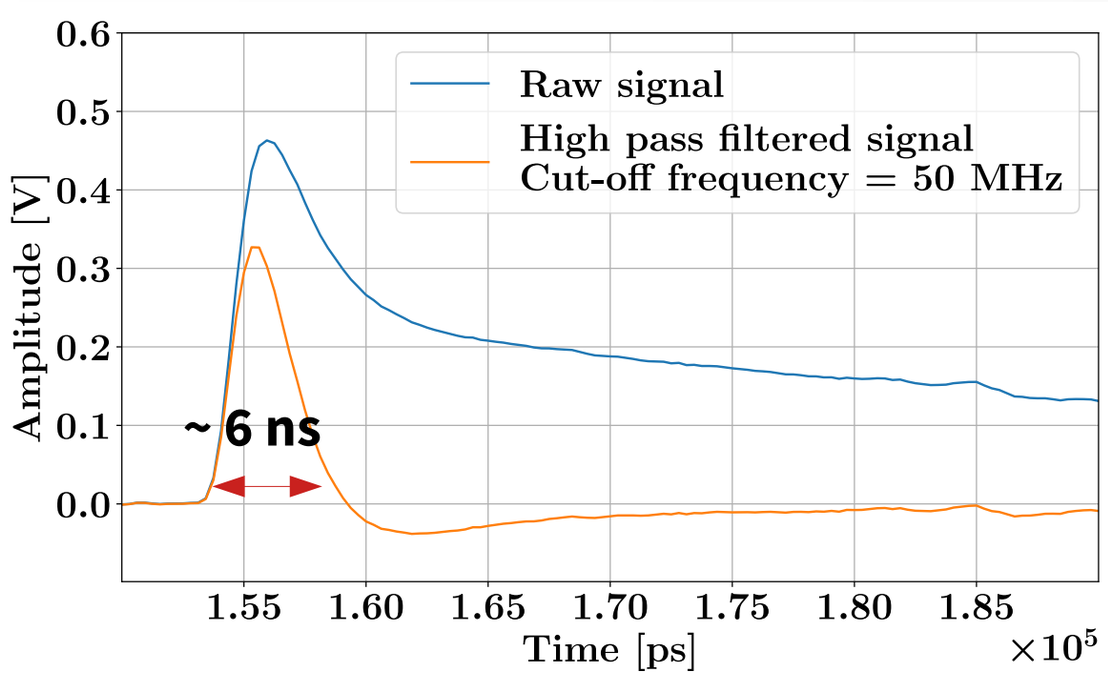
Simulation sensitivity	3 mm (10^7 protons)	2 mm (10^9 protons)	-

Event counting regime at 300 MHz : ~ one PG pulse every 3.3 ns

Intrinsic dead time of a Cherenkov-based PG detector

- Cherenkov emission physical time scale ~ **ps**
- **0.3 %** of triggered SiPM micro-cells per event
- ➔ Dead time mostly defined by the **signal shape**



TIARA block detector can already sustain a ~ **150 MHz PG detection rate**

Conclusion

- Development of a **reconstruction algorithm** to combine the response of multiple detectors.

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TIARA detection system	1.1 kHz	1.7 MHz	311 MHz
Experimental CTR (FWHM)	360 ps	2.7 ns	Event counting (COG)

- Creation of a high sensitivity PG detector
  - **4 mm sensitivity** on proton range with **600 PG detected** and 320 ps FWHM time resolution
  - **~ 360 ps FWHM** of CTR at clinical beam energy
  - **Ultra fast-timing acquisition** → Requirement to use a **reconstruction strategy**

References

- **Jacquet M** et al 2021 *Phys. Med. Biol.* **66** 135003
  A time-of-flight-based reconstruction for real-time prompt-gamma imaging in proton therapy
  https://doi.org/10.1088/1361-6560/ac03ca

- **Marcatili S** et al 2020 *Phys. Med. Biol.* **65** 245033

  Ultra-fast prompt gamma detection in single proton counting regime for range monitoring in particle therapy

  https://doi.org/10.1088/1361-6560/ab7a6c