Development and characterization of a fast detector dedicated to time-of-flight gamma imaging in proton therapy

Adélie ANDRÉ

Supervised by Sara MARCATILI and Marie-Laure GALLIN-MARTEL

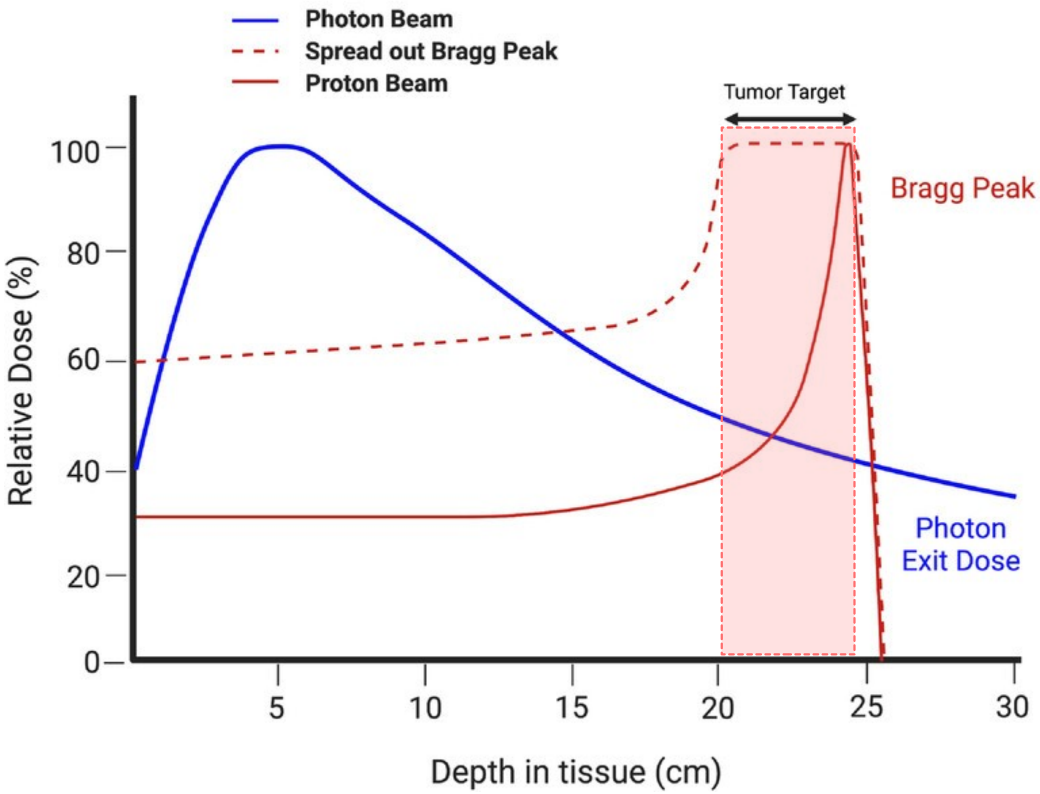
Nuclear Physics and Medical Applications team (PNAM)

Context – Proton therapy

Dose (1Gy = 1J/kg)

- High ballistic precision of the dose deposition (Bragg peak)

- Less dose deposition in surrounding healthy tissue



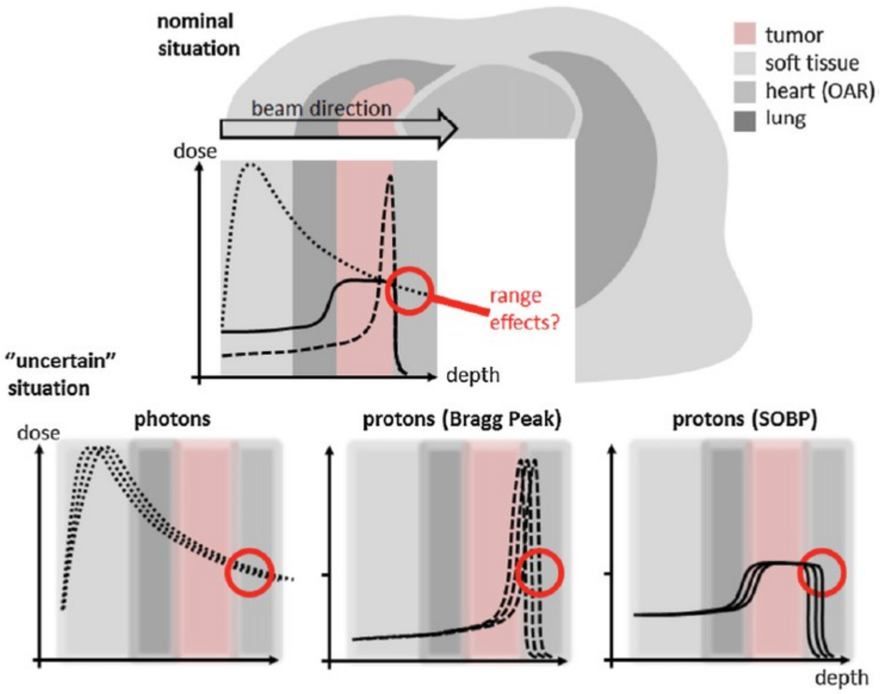
Context – Proton therapy

Limitations:

- Uncertainties induce high healthy tissues overdosing or tumor underdosing compared to conventional radiotherapy

- Safety margins (~1 cm)
- Protontherapy potential not fully exploited

→ On-line proton range verification is highly desirable to assure the correct dose delivery



A.C. Knopf et al.
Phys. Med. Biol. 2013

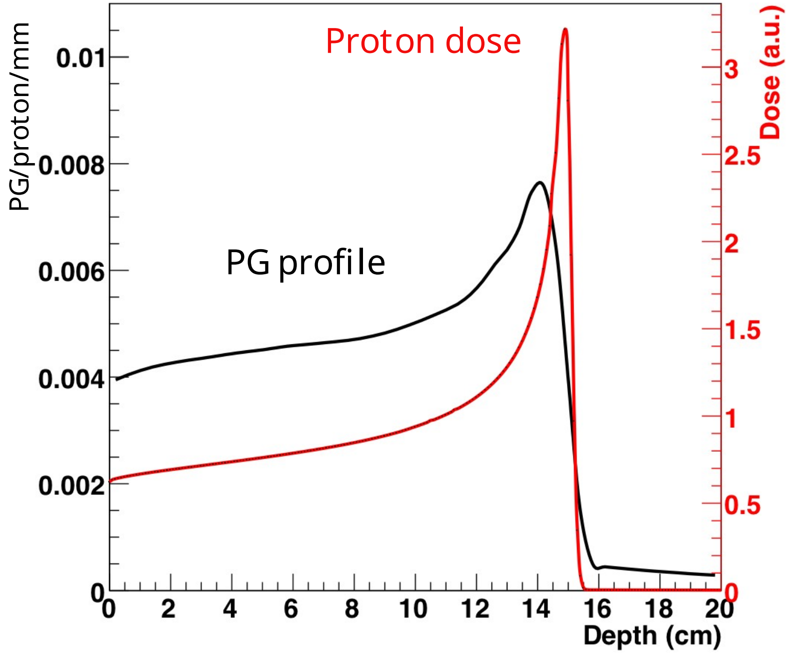
Context – Prompt Gammas in proton therapy

- Primary beam stops inside the patient
- Real time control by secondary radiations detection

Prompt Gamma (PG)

0 < E < 10 MeV
Emission within < 1 ps
Production rate ~ 1% /cm /p

→ requires the development of a dedicated detection system

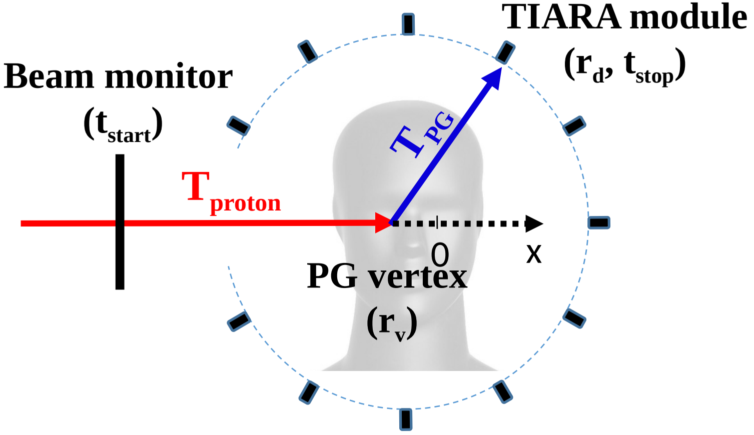


Correlation between the dose deposition and the PG emission profiles

Reconstruction of the proton range through time-of-flight (TOF) measurement.

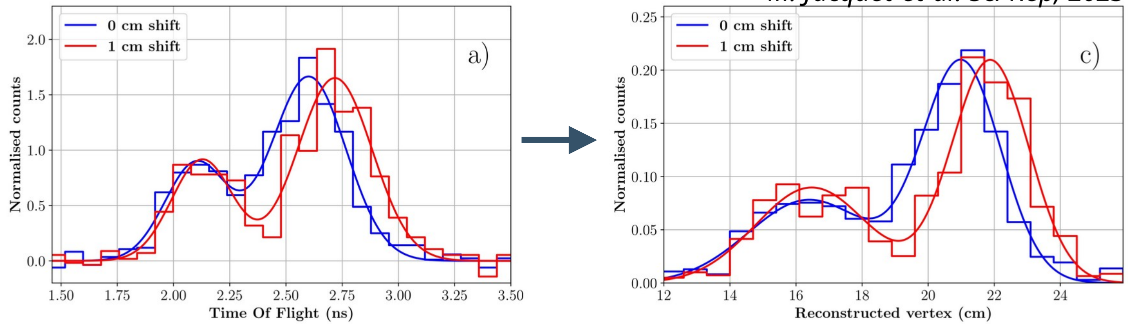
M. Jacquet et al. Sci Rep, 2023

TIARA = TOF Imaging ARrAy



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

A reconstruct algorithm of PG distribution is under development in our collaboration (CPPM Marseille)

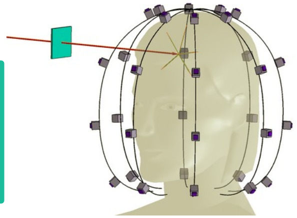


TOF profile **Spatial profile reconstructed**

TOF depends on both the position of the TIARA module (r_d) and the PG emission vertex position (r_v).

Spatial reconstruction needed to combine TIARA modules:
→ **more statistics**
→ **3D sensibility**

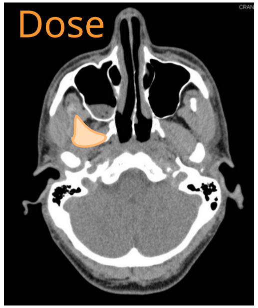
Final detection system
~ 30 TIARA modules



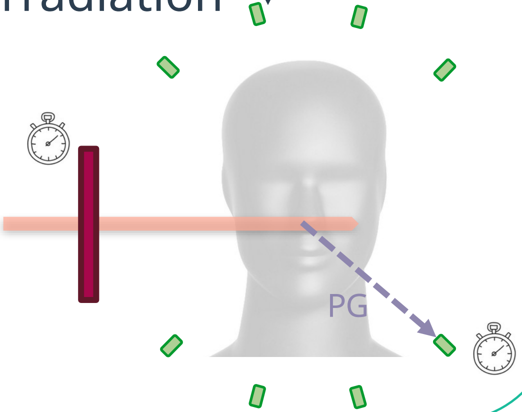
PGTI objective

Clinical treatment

Treatment plan



Irradiation



Monte Carlo simulations

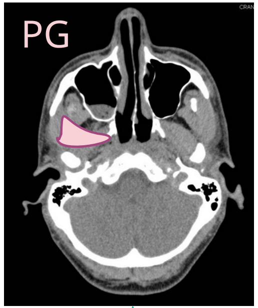
- ☐ PG emission
- ☐ Detector response

PG measurement

- ☐ Fast detection system (beam monitor + PG module)
- ☐ Spatial reconstruction

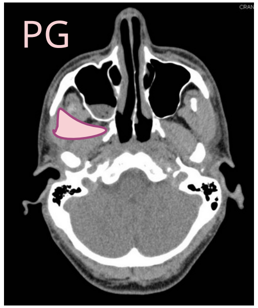
PGTI verification

Computed



Comparison

Measured



TIARA collaboration

Centre Antoine Lacassagne (CAL)	Laboratoire de Physique Subatomique et Cosmologie (LPSC)	Centre de Physique des Particules de Marseille (CPPM)
Clinical expertise and proton beam facilities	Detector development	Development of the reconstruction algorithm

Medicyc (63MeV)

ProteusOne (100-225MeV)

My PhD

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

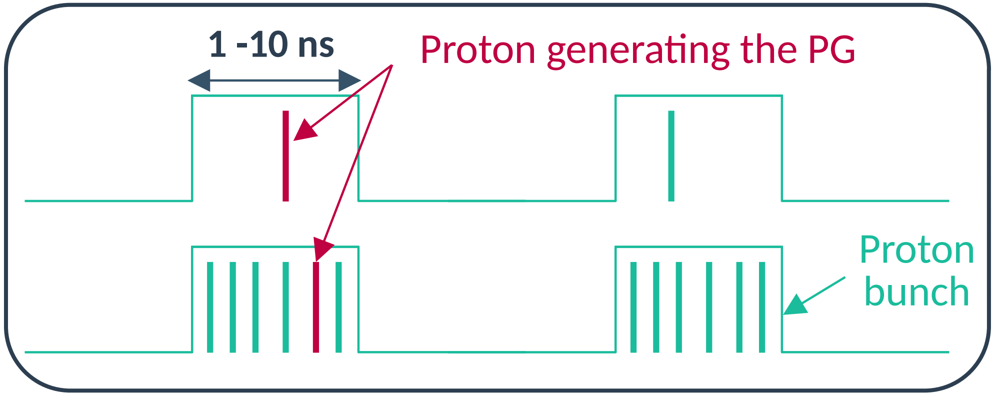
Context – PGTI regimes

Two possible regimes:

- **single proton regime** (for patient positioning),

- **nominal intensity** (during the whole treatment)

Clinical proton beam structure



Jacquet et al. Phys Med Biol, 2021

Measured parameter	CTR (FWHM)	Nb. Of protons	Nb. Of PGs	Sensitivity mm (at 2 σ)	Regime
Longitudinal shift	235 ps	10^7	3×10^3	3	Single proton regime
	235 ps	10^8	3×10^4	1	
	2.35 ns	10^9	3×10^5	2	Nominal intensity
Lateral shift	-	10^8	3×10^4	2	

Sensitivity estimation based on Monte Carlo simulation of a 100 MeV proton beam and 0.6% detection efficiency

PGTI **sensitivity** depends on events **statistic** and the system **Coincidence Time Resolution (CTR)**

A detection system of 235 ps FWHM CTR is required

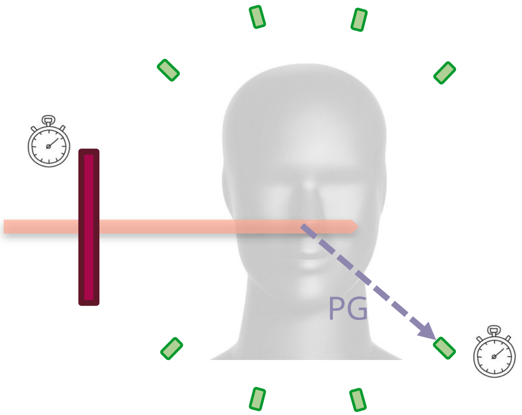
PhD objectives

- Development of a first prototype of the detection system composed of a beam monitor and 8 PG modules

- Characterization under clinical proton beam (Single Proton Regime + Nominal intensity)

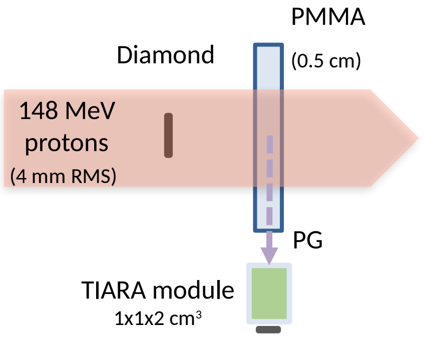
Summary

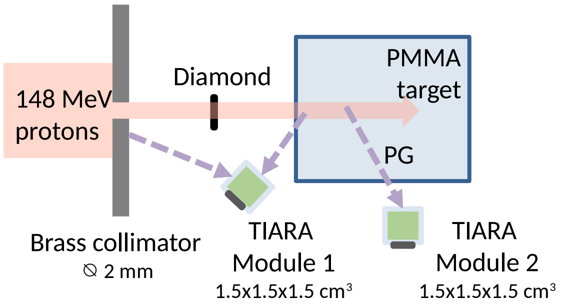
- Beam monitor development and characterization
- TIARA module development and characterization
- PGTI measurement:
    - Experimental TOF measurement
    - Background analysis based on Monte Carlo simulations
- Conclusion and perspectives



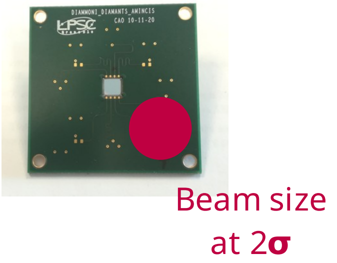
Beam monitor – Motivations

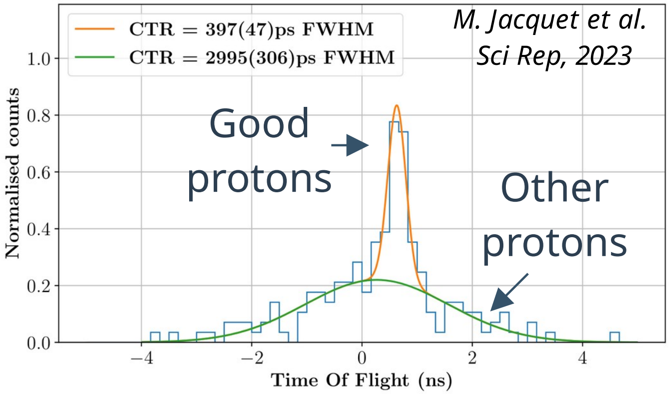
Setup realized for TOF measurement at CAL



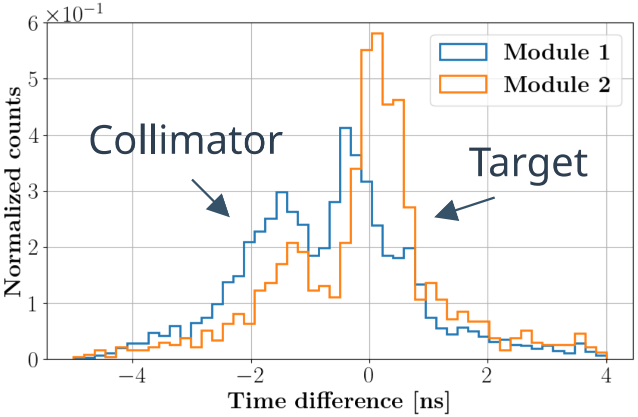


4.5 x 4.5 mm² diamond





TOF spectrum obtaind with a diamond beam monitor and no collimator

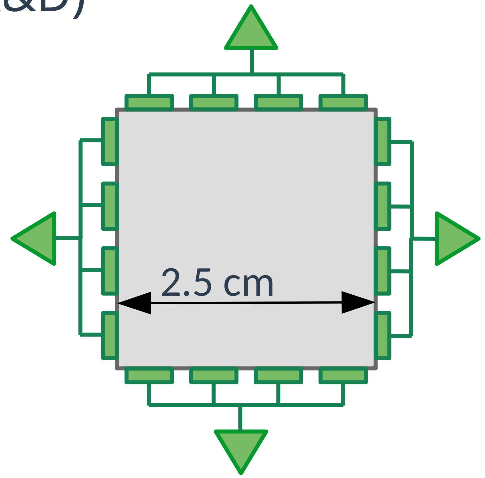


TOF spectrum obtaind with a diamond beam monitor and collimator

The proton beam is larger than the diamond beam monitor

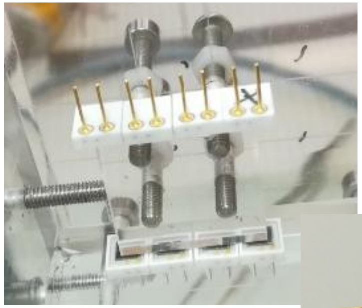
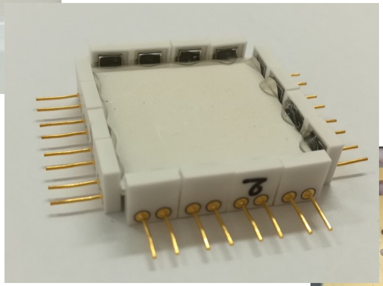
Beam monitor – Plastic scintillator development

3rd version of the prototype
(18 month R&D)

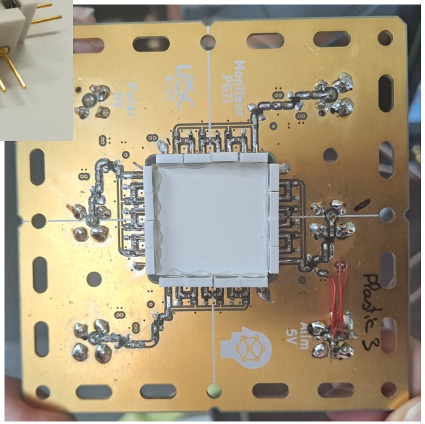


- Plastic scintillator (EJ-204) 1x25x25 mm^3
- Read-out by 16 Silicon Photomultipliers (Hamamatsu SiPM 3x3 mm^2)

Article in preparation

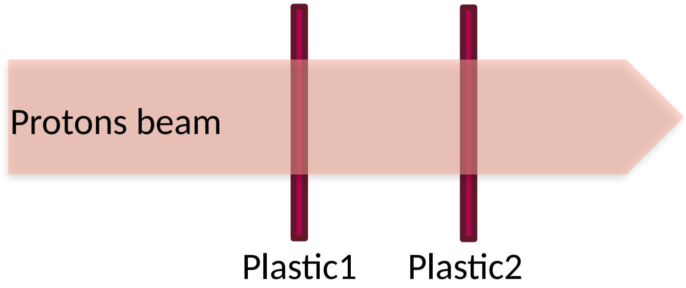
Prototype assembly - SDI

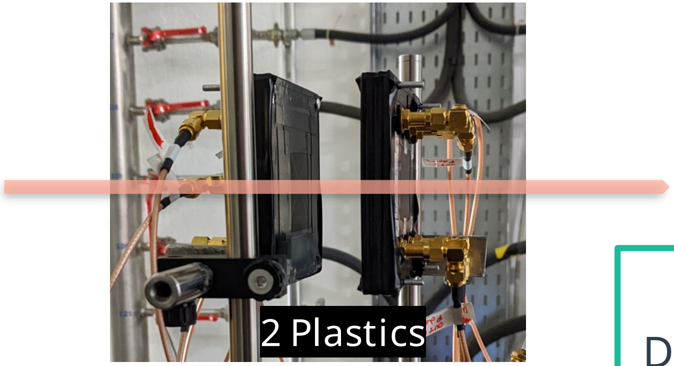


Each SiPM strip is amplified and acquire separately - Electronic service

Beam monitor – Plastic scintillator characterization

Experimental set-up

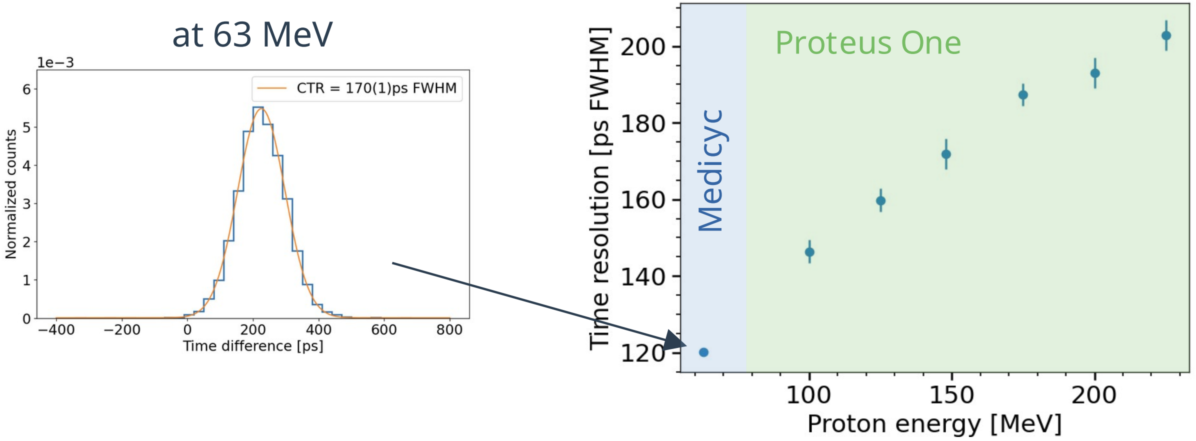




Time resolution

TOF between the 2 monitors at 63 MeV

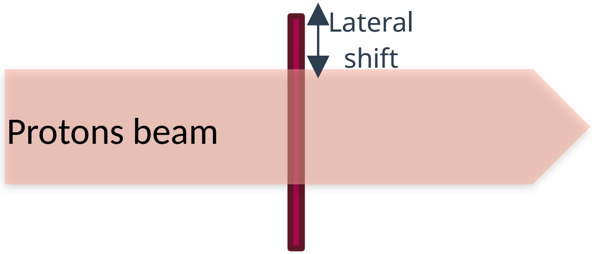
Detector time resolution below 235 ps FWHM in the relevant energy range

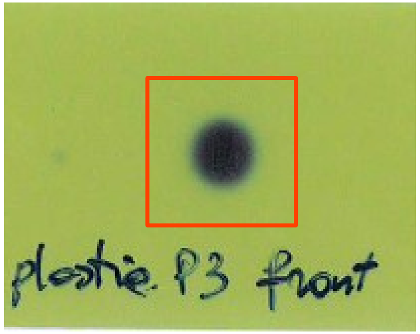


Coincidence Time Resolution (CTR)

Detector Time Resolution (DTR) = CTR/√2 = 120ps FWHM (at 63MeV)

Experimental set-up

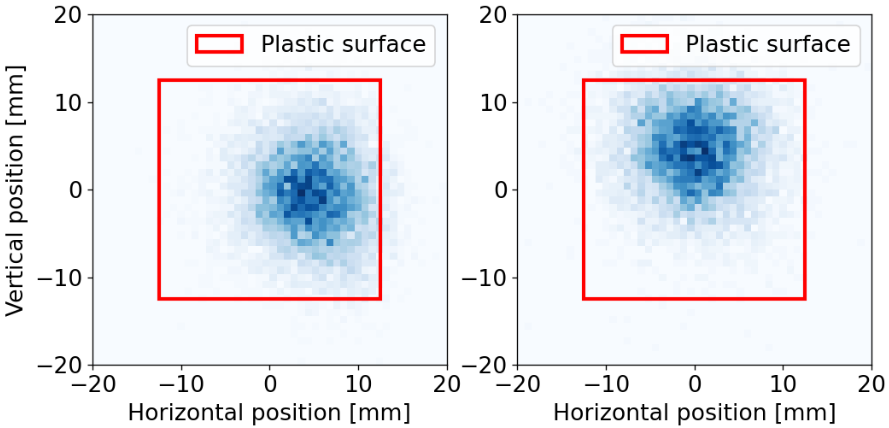




Radiation sensitive film (Gafchromic)

Spatial resolution

Beam images for 2 positions (5mm,0) and (0,5mm)



1 proton spatial resolution = 1.8 mm σ

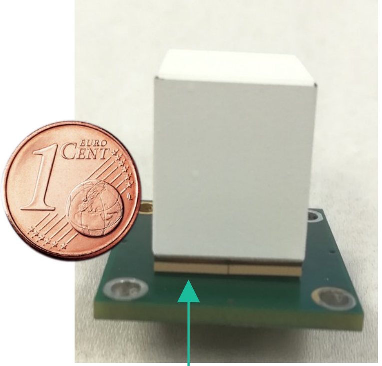
For PGTI only the position of the center of the beam is required

→ Position resolution = $1.8/\sqrt{N}$

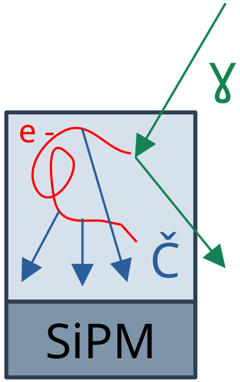
With N the number of protons detected

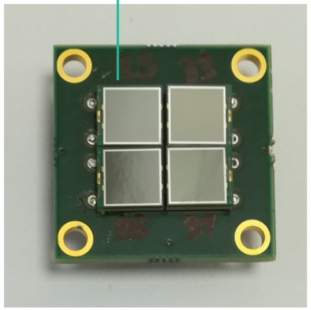
TIARA module development

Final version of the prototype (18 month R&D)



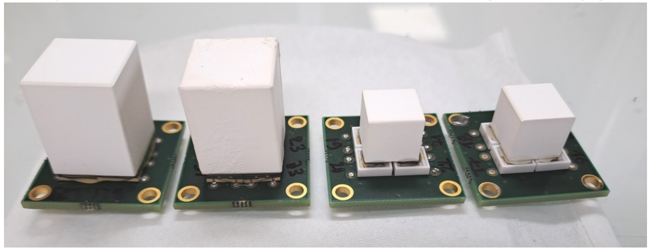
Cherenkov radiator
2 x 1.5 x 1.5cm³ lead fluoride cristal (PbF_2)



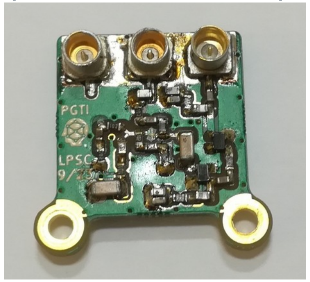


Read-out by 4 Silicon Photomultipliers (SiPM)

Assembly of different versions of the prototype - SDI



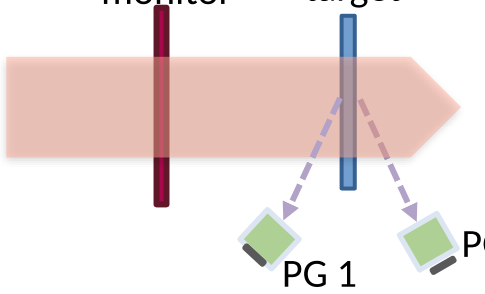
Final preamplifier – Electronique service

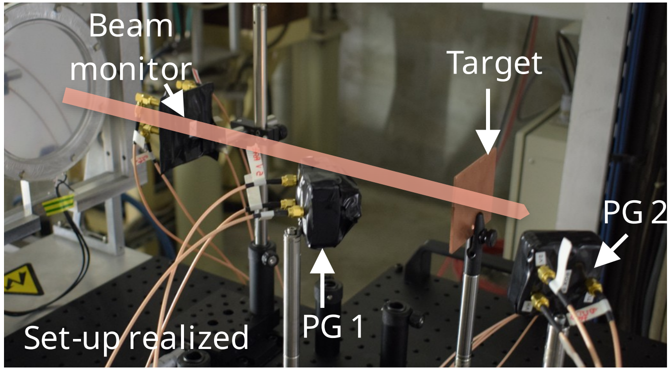


Preliminary characterization at LPSC

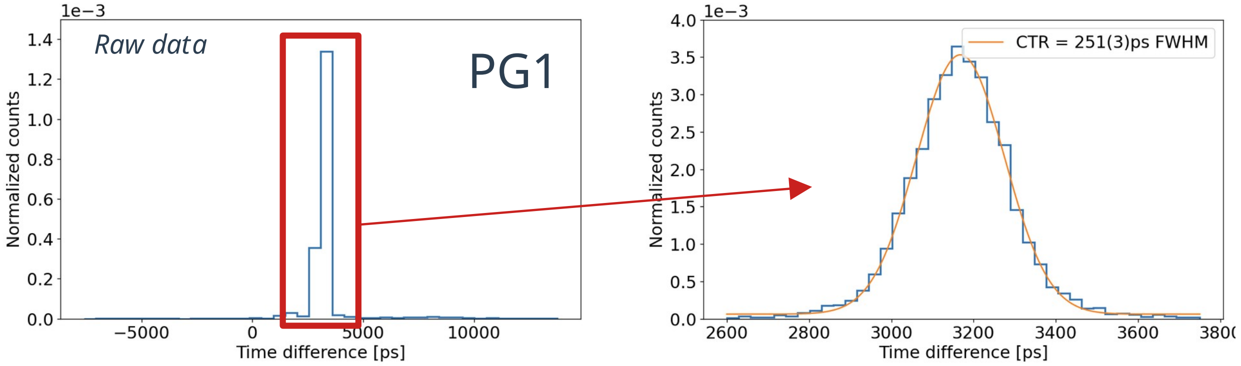
TIARA modulecharacterization

Medicyc (CAL) 63 MeV proton beam in November 2023





Time difference between the TIARA module and the beam monitor



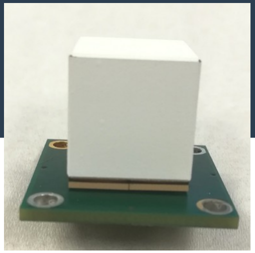
Module insensitive to neutron background

Time resolution

CTR = 251ps FWHM
Monitor = 120ps FWHM
DTR = 220ps FWHM

Final version of TIARA module

TIARA module characterization



Summary of the different versions of the TIARA module

Version	SiPM number	Crystal (mm^3)	Front-end	PG module DTR (ps) FWHM	When
1	1	10^3	Commercial	275	June 2021
2	1	20*10*10	LPSC, single	202	April 2022
3	4	15^3	LPSC, hybrid	211	December 2022
4	4	15*15*20	LPSC, parallel	197	June 2023
5 (final version)	**4**	**15*15*20**	**LPSC, hybrid compact**	**220**	**November 2023**

Maxime PhD

Internship

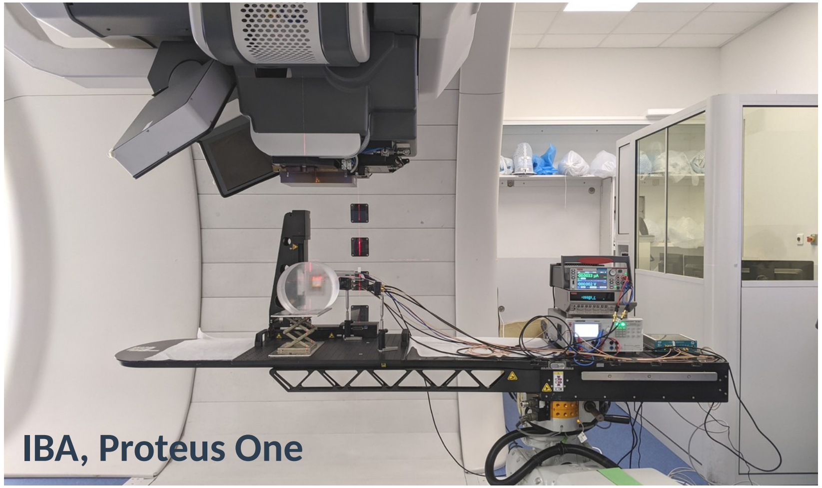
PhD

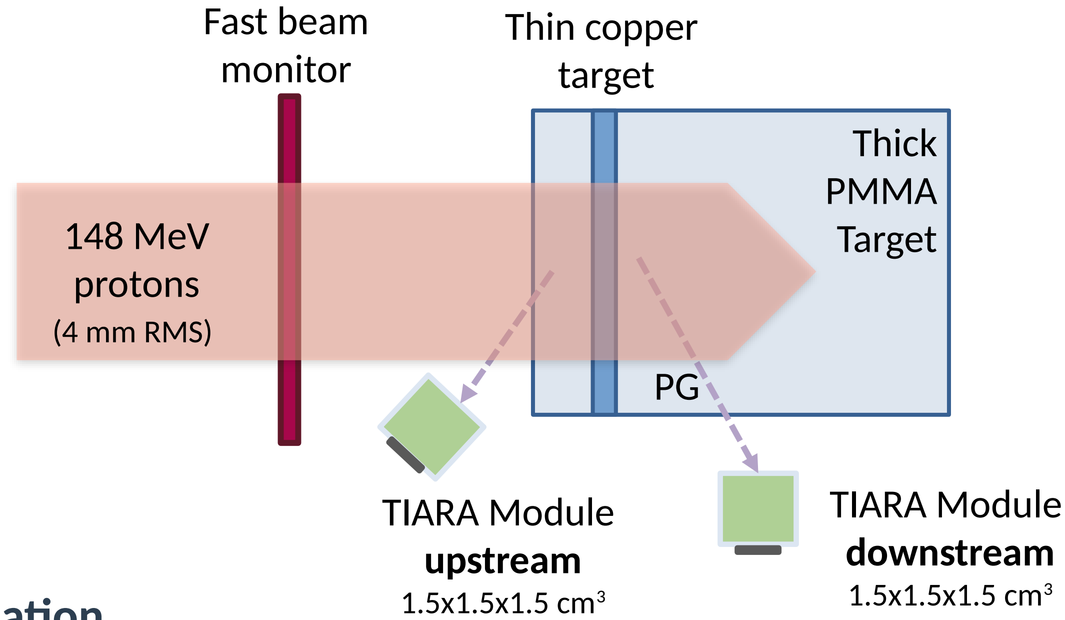
Final version of the TIARA module is a compromise to optimize:
the time resolution, detection efficiency and compactness

8 TIARA modules for the next beam test (18 March 2024)

PGTI experimental measurement

TOF measurement under 148 MeV proton beam in June 2023





3 setup :

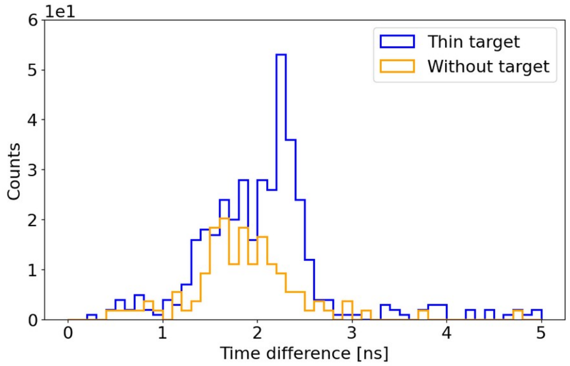
1st: Thin target => **calibration**
2nd: Without target => **background characterisation**
3rd: Thick target => **TOF measurements**

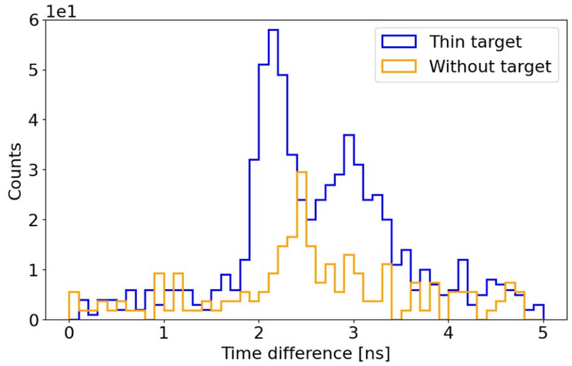
PGTI calibration measurement

Upstream module

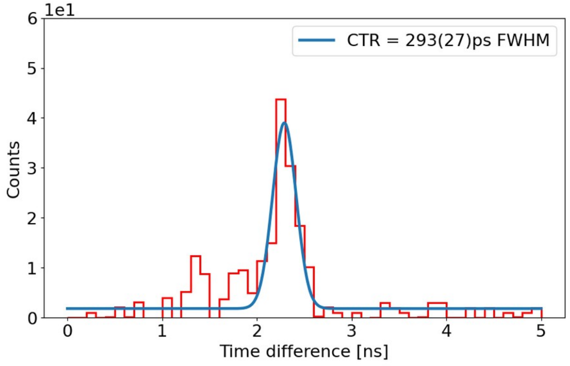
Downstream module

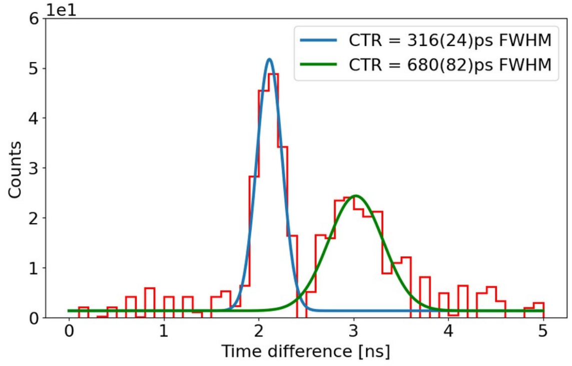
Background TOF profile superimposed on raw data





TOF profile after subtracting the background

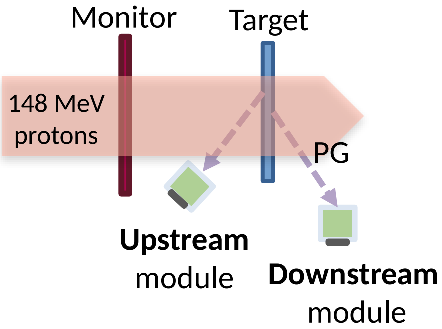




Thin target

Objectives :

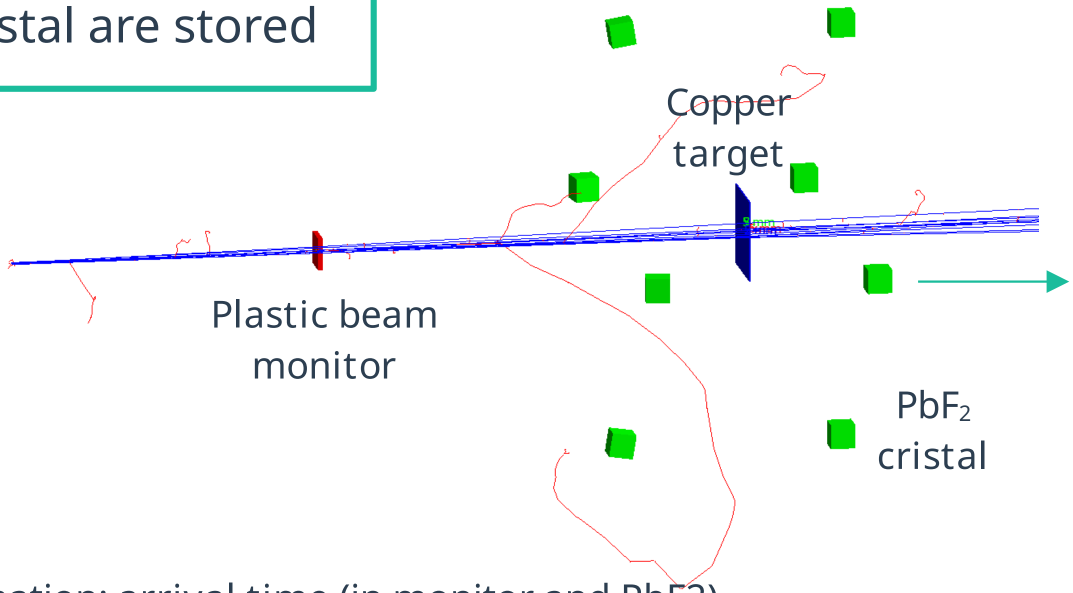
- Delay calibration
- CTR determination



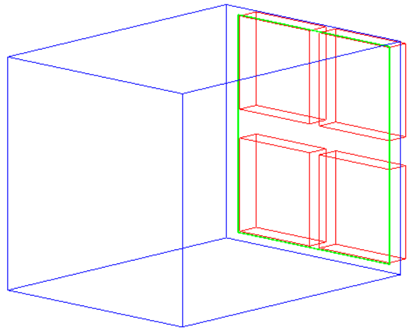
PGTI TOF simulation

Experimental geometry reproduced in Geant4

All particles reaching a PbF_2 crystal are stored



Persective
Optical simulation of the TIARA detector



Stored information: arrival time (in monitor and PbF2), arrival position in the crystal and position of emission.

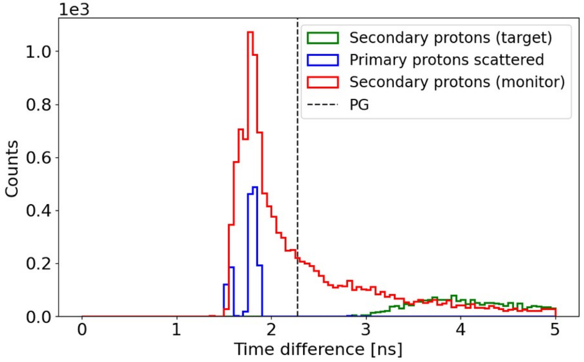
PGTI background analysis

PGTI
PROMPT GAMMA TIME IMAGING

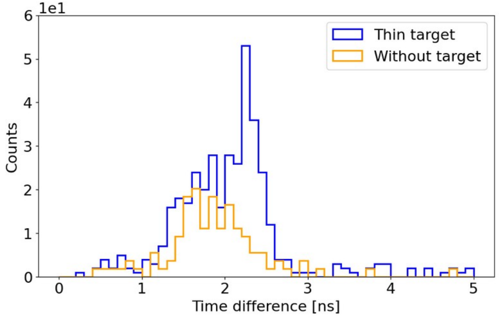
Experimental results compared to Monte Carlo simulation (Geant4)

Upstream module

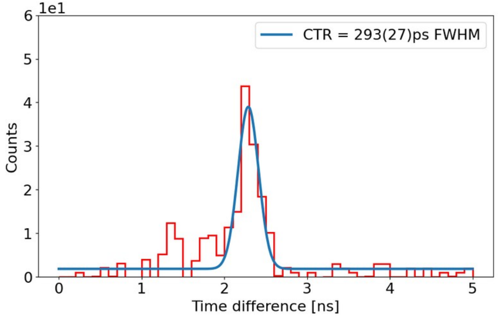
Protons TOF profile obtained by simulation



Raw data and background

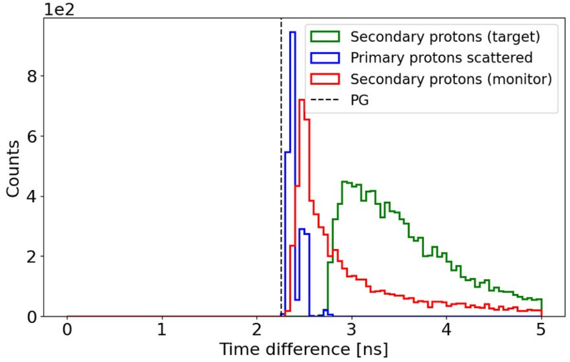


Filtered data

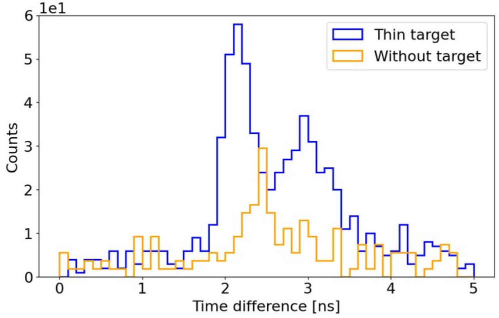


Downstream module

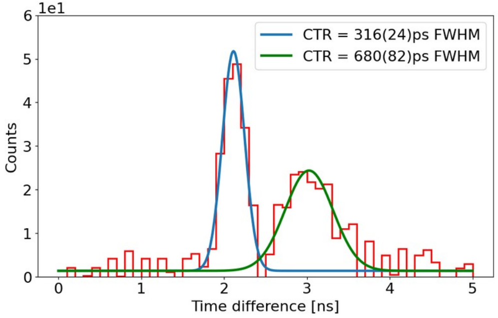
Protons TOF profile obtained by simulation



Raw data and background



Filtered data



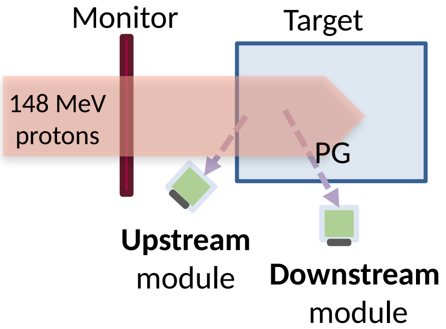
PGTI TOF profile measurement

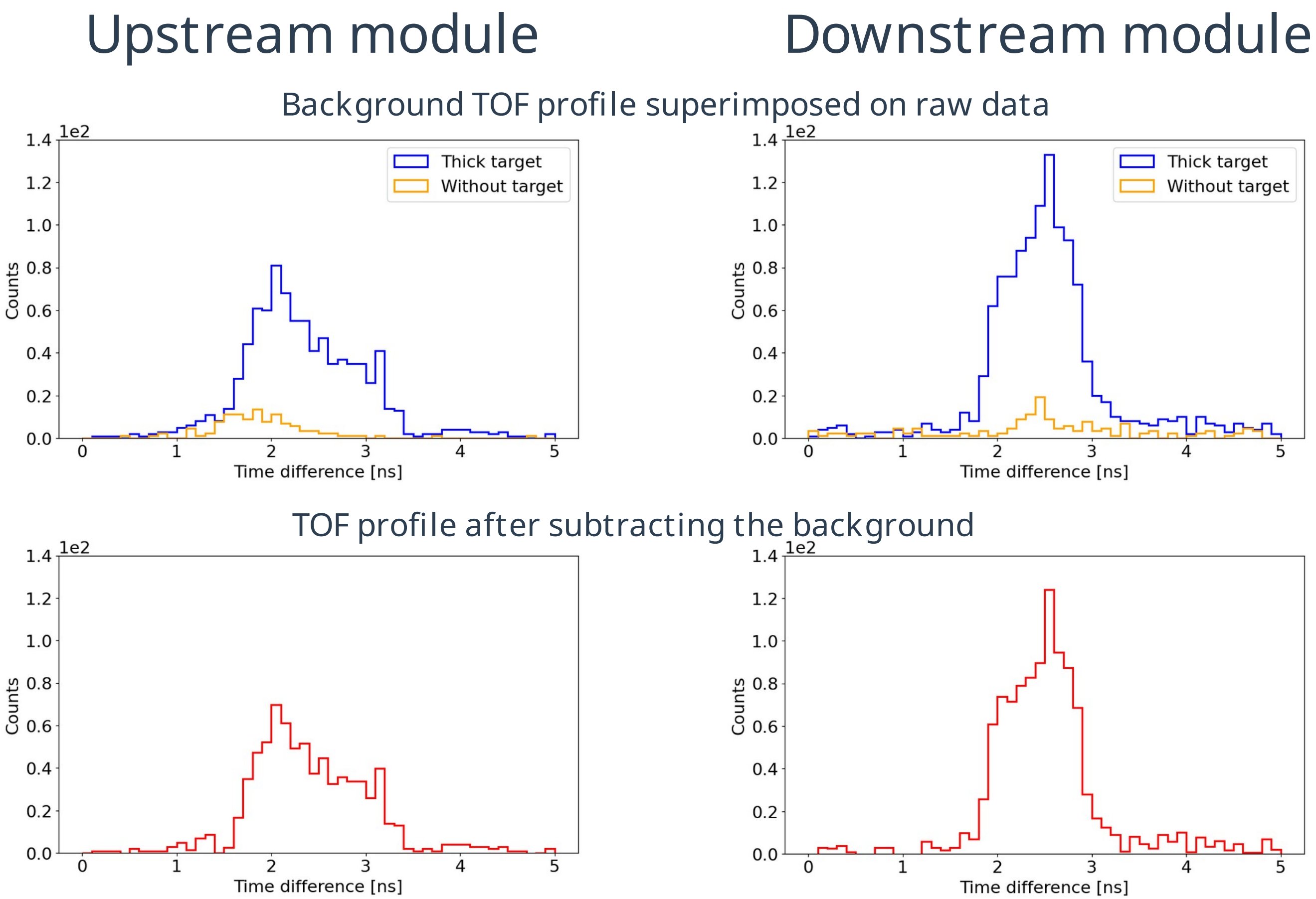
Thick target

→ Higher SNR

→ TOF profiles depend on the PG module position

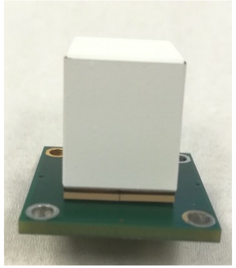
Next step: PGTI reconstruction!

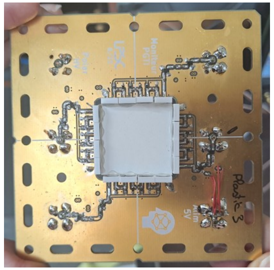




Conclusion

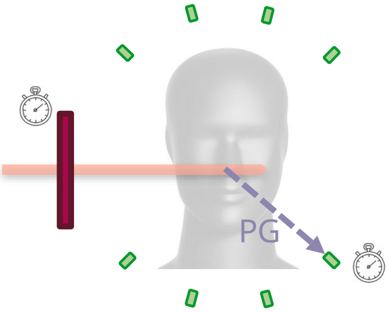
- Full development and characterisation of the plastic beam monitor
- Final development and characterisation of the PG module
- PGTI TOF measurement with clinical proton accelerator
- Background sensitivity evaluation via Geant4 simulations





Perspectives

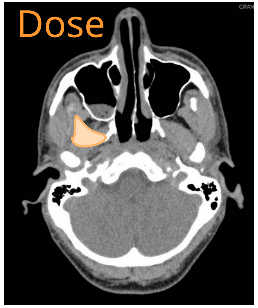
- Optical simulation of the PG module response
- PGTI TOF measurement with clinical phantom and 8 PG modules:
    - CAL ProteusOne (single proton regime)
    - CNAO (nominal intensity)
- Reconstruction of the experimental TOF measurements (CPPM collaboration)



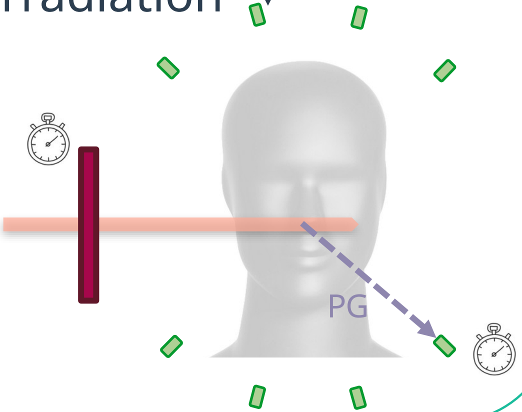
Summary

Clinical treatment

Treatment plan



Irradiation



Monte Carlo simulations

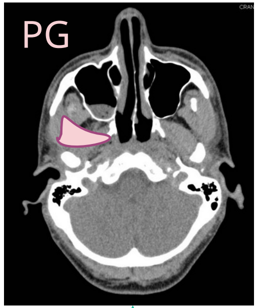
- [x] PG emission
- [ ] Detector response

PG measurement

- [x] Fast Detection system (beam monitor + PG module)
- [ ] Spatial reconstruction

PGTI verification

Computed



Comparison

Measured