Fast Prompt Gamma detection system for time-of-flight based proton therapy monitoring

A. André[1], M. Pinson[1], D. Maneval[2], C. Hoarau[1], Y. Boursier[3], A. Cherni[3], M. Dupont[3], M.-L. Gallin Martel[1], A. Garnier[3], J. Hérault[2], J.-P. Hofverberg[2], P. Kavrigin[1], C. Morel[3], J.-F. Muraz[1] and S. Marcatili[1]

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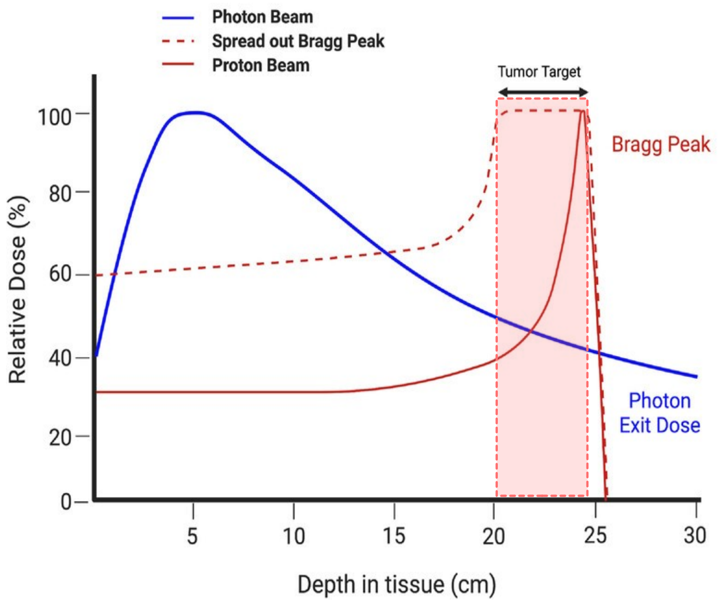
2. Centre Antoine Lacassagne, Nice, France
3. CPPM and Aix-Marseille University, Marseille, France

October 9th, 2024 – AG GdR MI2B

Context – Proton therapy monitoring

Proton therapy

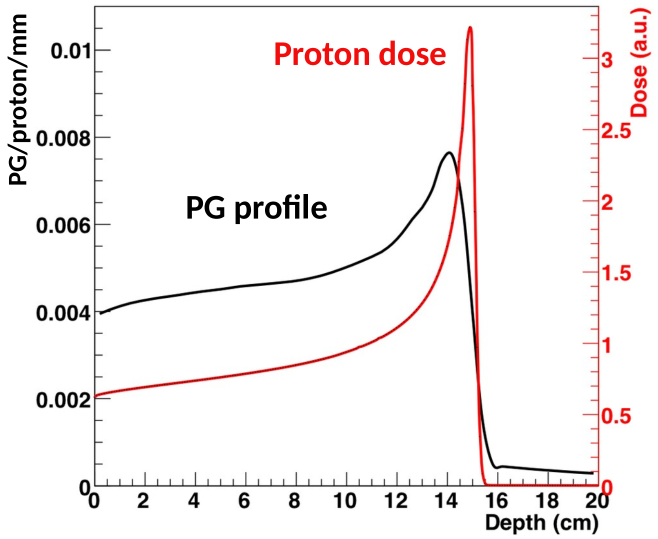
High ballistic precision of the dose deposition (**Bragg peak**)



From: N. Mohamed et al. Precision Radiation Oncology (2021)

Real time control by Prompt Gamma detection

PG emission is spatially correlated to the dose deposition



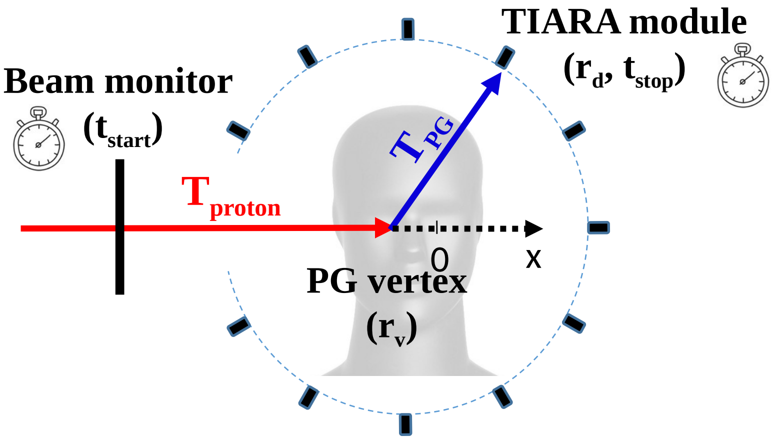
Prompt Gamma (PG)
- 1 < E < 10 MeV
- Emission within < 1 ps
- Production rate ~ 1% /cm /p

Constraints:
- Low statistics
- Background (neutron)

Context – PGTI (Prompt Gamma Time Imaging)

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

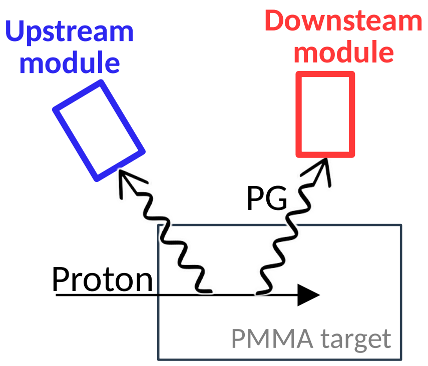
TIARA = TOF Imaging ARrAy

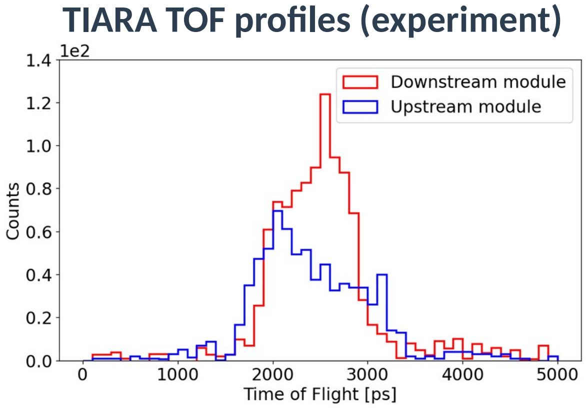


$$TOF = T_{proton}(\vec{r_v}, \vec{v}) + \frac{1}{c}\left\|\vec{r_d} - \vec{r_v}\right\|$$

A reconstruct algorithm of PG distribution is under development in our collaboration

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





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

Context – PGTI (Prompt Gamma Time Imaging)

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

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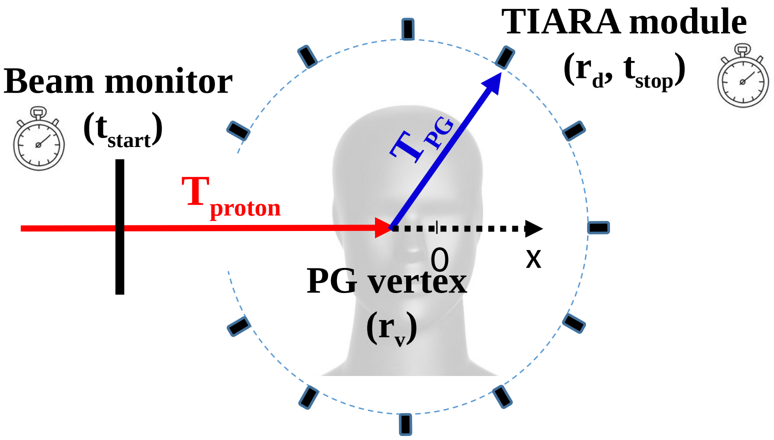

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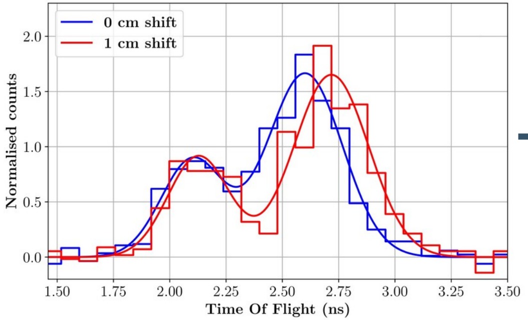
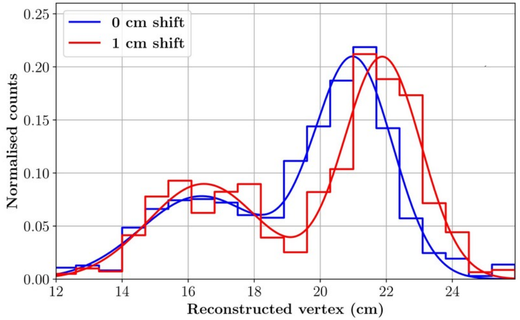
TIARA TOF profiles (experiment)

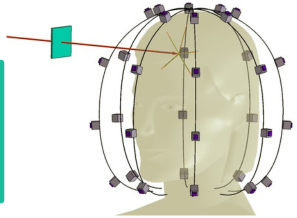


TIARA spatial profiles (reconstructed)



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

Final detection system
~ 30 TIARA modules



Jacquet et al. ***A high sensitivity Cherenkov detector for Prompt Gamma Timing and Time Imaging, Scientific Reports, vol. 13, no. 1, p. 3609, Mar. 2023.*** ***(https://arxiv.org/abs/2309.03612)***

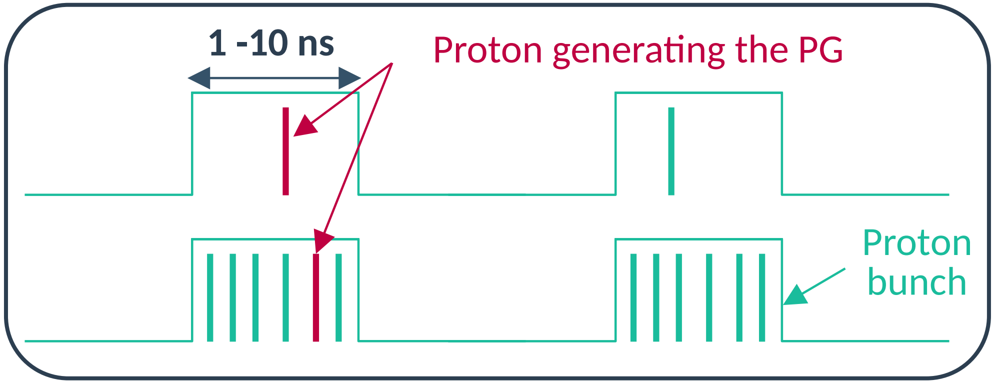
Context – PGTI regimes

Two possible regimes:

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

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

Clinical proton beam structure



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

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	

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

Jacquet et al. *A Time-Of-Flight-Based Reconstruction for Real-Time Prompt-Gamma Imaging in Protontherapy, Physics in Medicine & Biology, vol. 66, no. 13, p. 135003, Jun. 2021* (*https://arxiv.org/abs/2012.09275*)

Context – PGTI regimes

PGTI
PROMPT GAMMA TIME IMAGING

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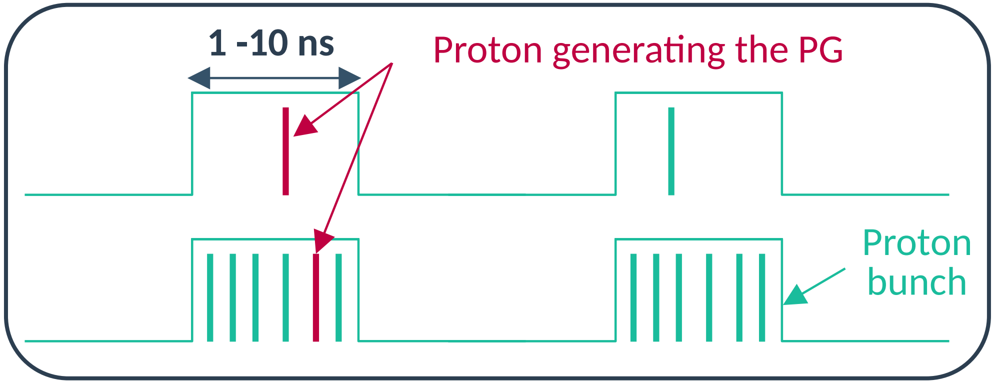

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PGTI **sensitivity** depends on events **statistic** and the system **Coincidence Time Resolution (CTR)**

A detection system of 235 ps FWHM CTR is required

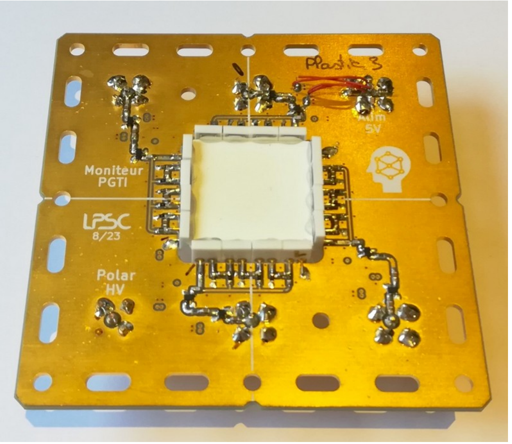
Jacquet et al. *A Time-Of-Flight-Based Reconstruction for Real-Time Prompt-Gamma Imaging in Protontherapy, Physics in Medicine & Biology, vol. 66, no. 13, p. 135003, Jun. 2021 (https://arxiv.org/abs/2012.09275)*

Detectors development – Plastic scintillator beam monitor

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)

Detectors and electronics are developed at LPSC (SDI, SE)

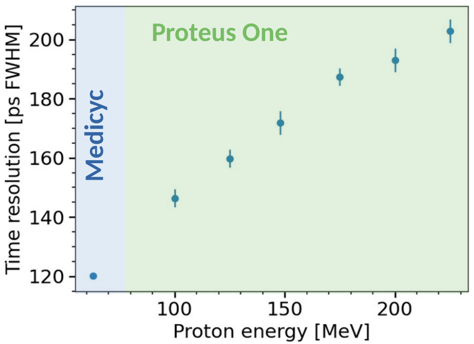


4 SiPM strips surrounding the scintillator
Each SiPM strip is amplified and acquired separately

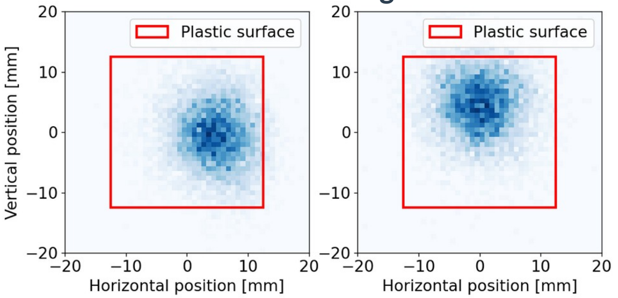
Prototype characterization

- **Time resolution = 120 ps FWHM at 63 MeV**
(< 235 ps FWHM in the relevant energy range)
- **100 % detection efficiency**
- **Spatial resolution = 1.8 mm** σ/ incident proton (at 63 MeV)

Time resolution



Beam images



Position (0, 5) mm

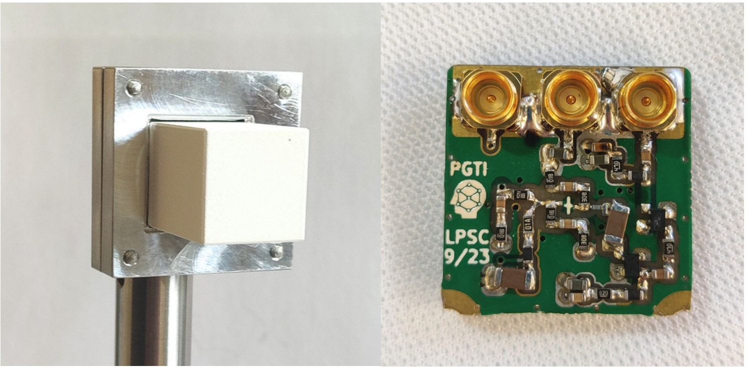
Position (5, 0) mm

André et al. *A fast plastic scintillator for low intensity proton beam monitoring*, submitted to IEEE Transactions on Radiation and Plasma Medical Sciences

Detectors development – Prompt Gamma module

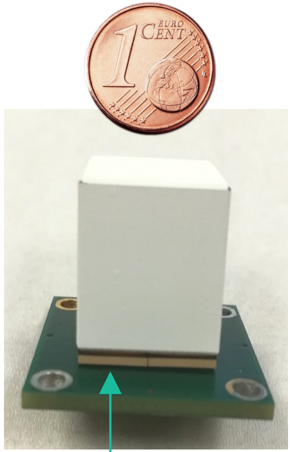
Final version of the prototype (30 month R&D)

Detectors and electronics are developed at LPSC (SDI, SE)

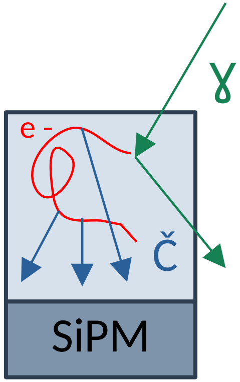


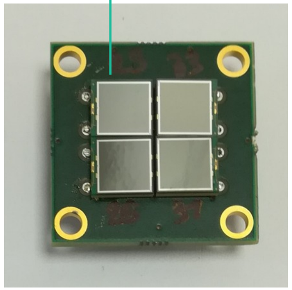
- Fast signal
- High density (detection efficiency)
- No sensitive to neutron
- No energy measurement

8 TIARA modules prototype developed



Cherenkov radiator
2 x 1.5 x 1.5cm^3 lead fluoride crystal (PbF_2)

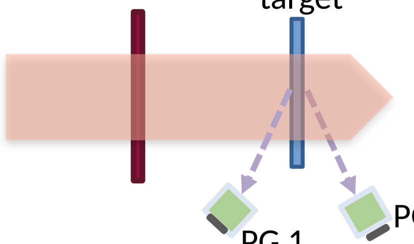


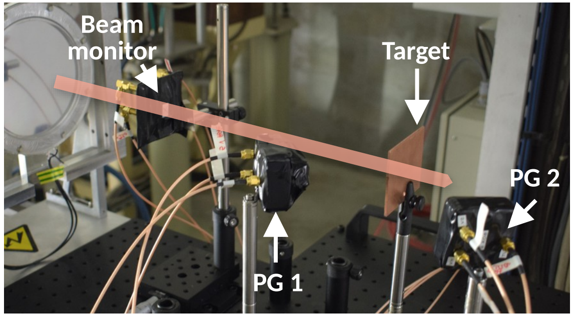


Read-out by 4 Silicon Photomultipliers (SiPM)

Detectors characterization – Prompt Gamma module

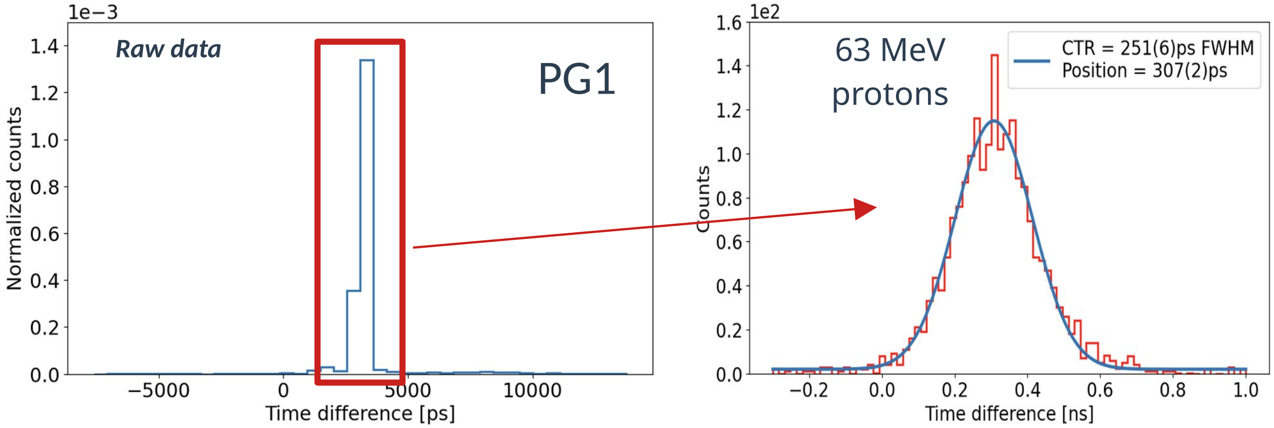
Time resolution characterization set-up





The thin copper target is used as a point-like PG source

Time difference between the TIARA module and the beam monitor



-No background

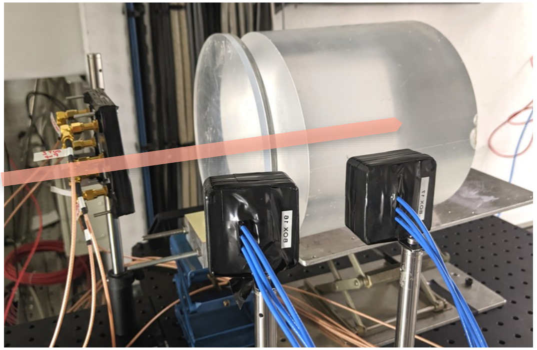
-Coincidence Time Resolution = 251ps FWHM

Last version of the TIARA module (March 2024)

Gamma detector time resolution = 220 ps FWHM

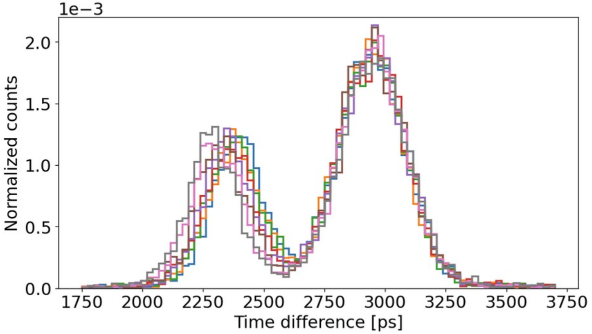
TIARA sensitivity measurement at cyclotron (63 MeV)

Set-up realized

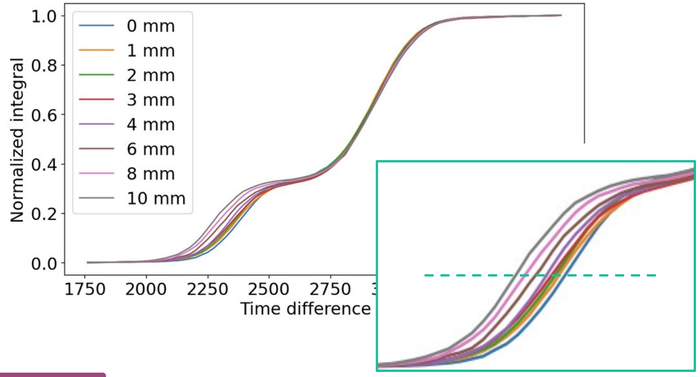


The thin target (10 mm thick) is translated from 0 to 10 mm in steps of 1 mm

1. TOF distributions upstream module

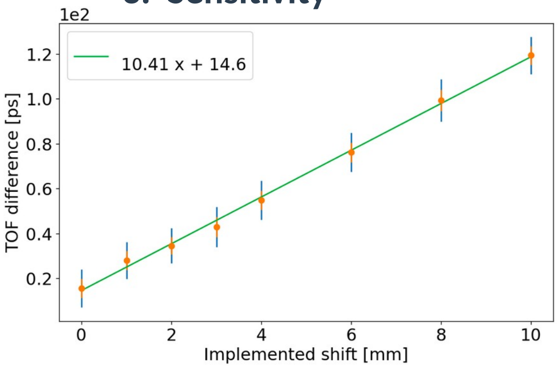


2. TOF integral distributions



Shift measurement

3. Sensitivity



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

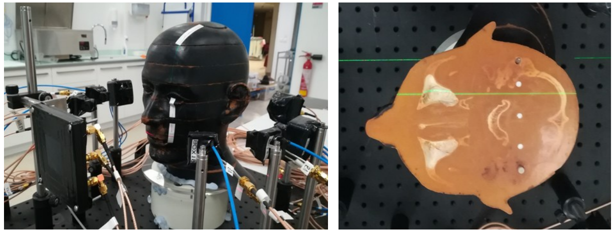
Initial MC prediction

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	

PGTI measurement at synchro-cyclotron (100 MeV)

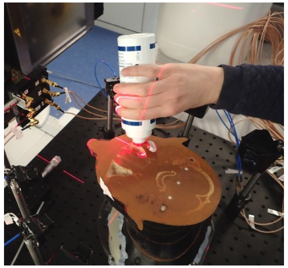
8-channels detection system to measure an anatomical change in a clinical phantom

Head phantom

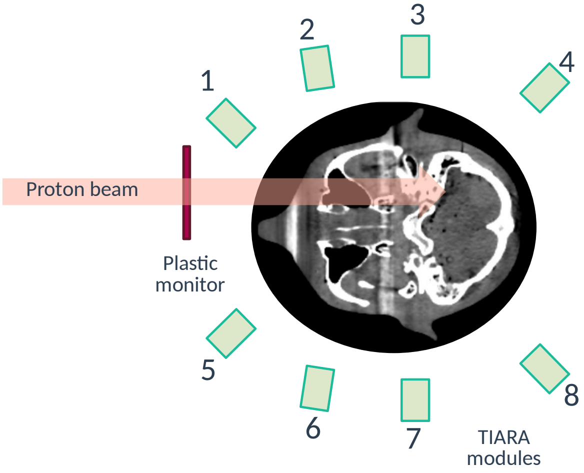


Clinical proton beam (IBA ProteusOne)

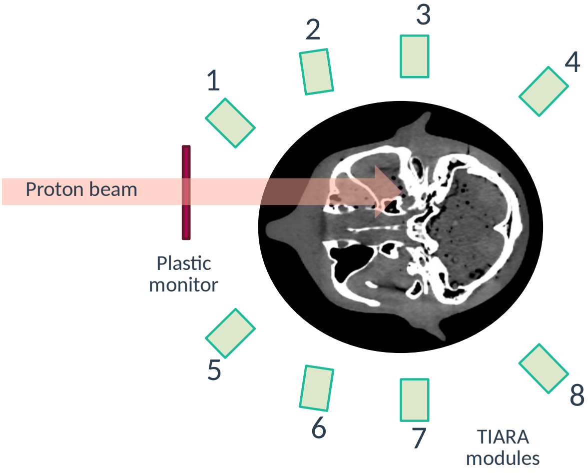
Set-up realized



Empty sinus (air cavity)



Sinus fulled with gel

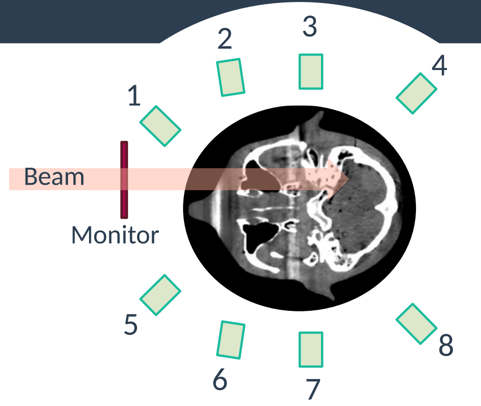


PGTI measurement

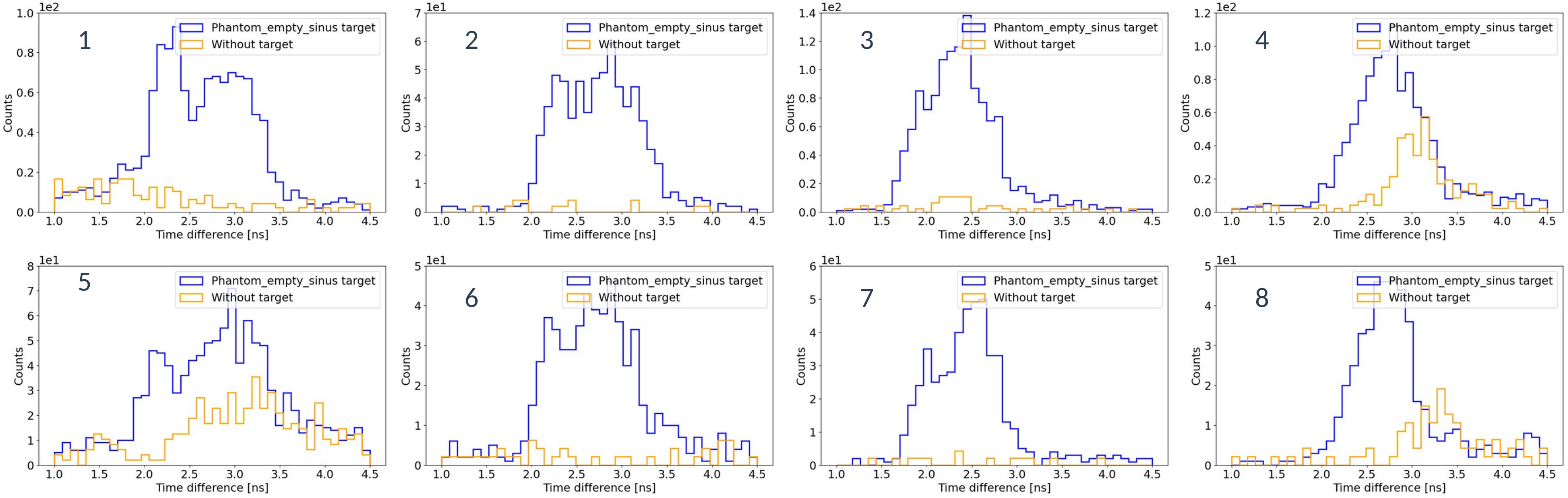
High Signal to Noise Ratio (SNR)

TIARA modules insensitive to neutrons background but sensitive to scattered protons

Set-up

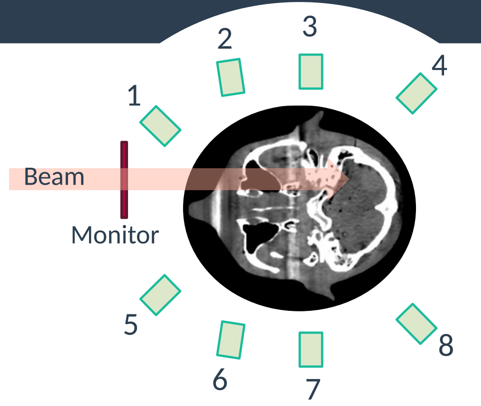


Phantom irradiation and background TOF



PGTI measurement

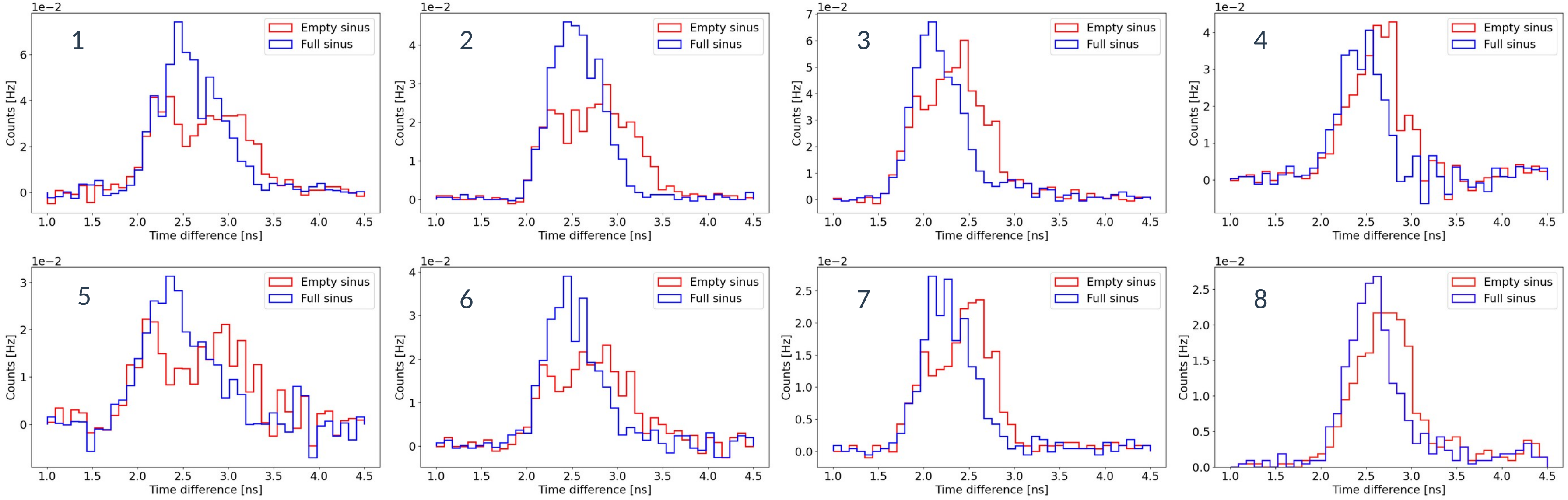
Set-up



Anatomical change visible on PGTI TOF measurement

On going comparison with TPS (MC) data **(A. Garnier's talk)**

TOF comparison between the two set-up after background subtraction

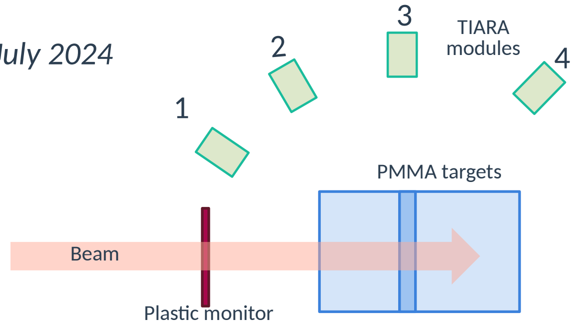


TIARA validation on synchrotron at low intensity

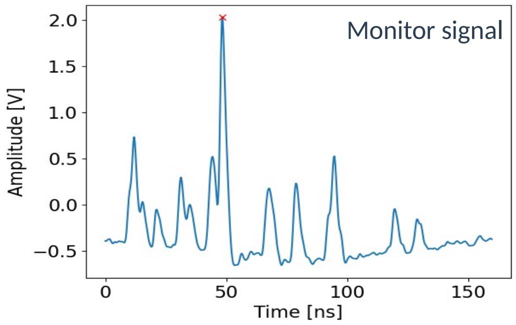
The National Center for Oncological Hadrontherapy

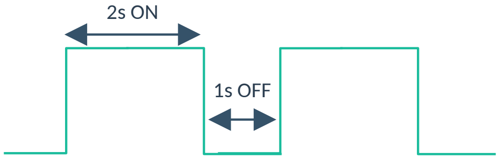
Experimental set-up (I = 6 × 10^6 p/s)

July 2024



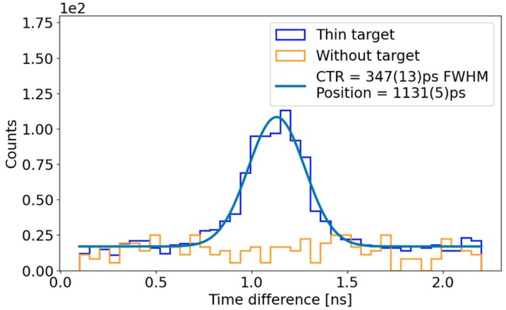
Synchrotron structure not pulsed at the detector time scale **(M.Pinson's talk)**





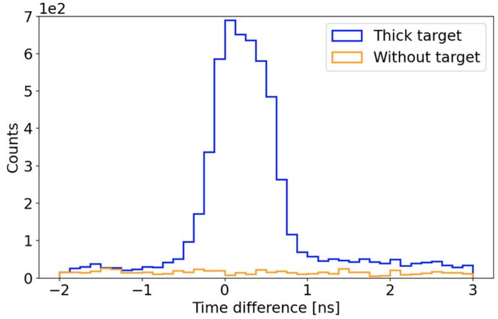
Preliminary results (protons) – Detector 1

Thin target at 100 MeV (74 mm range)



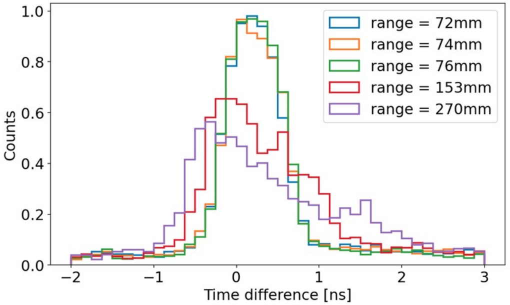
Good time resolution

Thick target at 100 MeV (74 mm range)



High SNR

Thick target at different energies



TOF sensitive to proton range

Results obtained at the CNAO experimental facility built in collaboration with INFN.

Conclusion

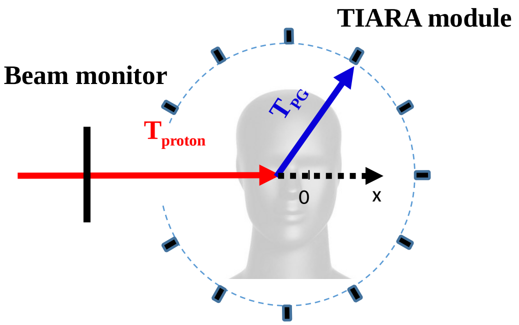
- **TIARA works with all common accelerators**: cyclotron, synchro-cyclotron, synchrotron

- **Proton range accuracy < 2 mm (2σ)** for 10^7 protons, SPR and a simple target geometry

- **8 channels prototype** available

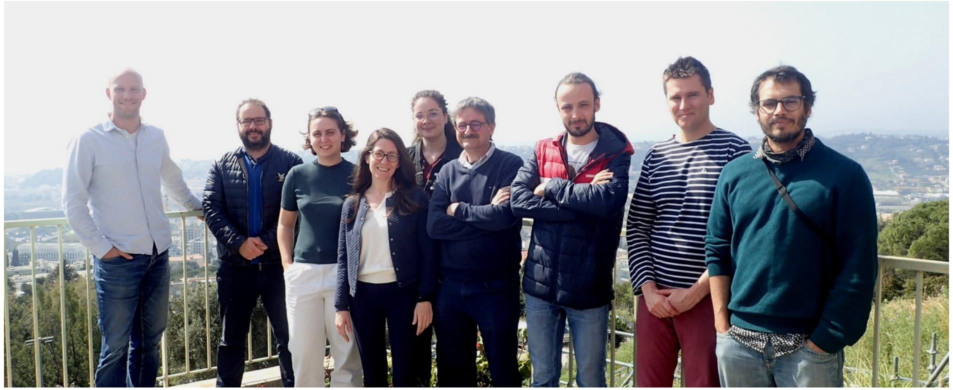
- **TIARA validation on clinical phantom (A.Garnier's talk)**

- **Encouraging preliminary results for carbon ions (M.Pinson's talk)**



Acknowledgements

PGTI
PROMPT GAMMA TIME IMAGING



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A. Garnier, J. Hérault, J.-P. Hofverberg, P. Kavrigin, D. Maneval, C. Morel, J.-F. Muraz and S. Marcatili

Funded projects

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(project ANR-15-IDEX-02)

PCSI TIARA (Convention n°20CP118-00)

ERC Starting Grant (project 101040381)

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- **CAL/IN2P3 COMEX** for the allocated beam time
- **HITRIplus** project for beam time at CNAO and related travel expenses
- **Marco Pullia** (CNAO) and his team for the nice reception
- **Labex PRIMES** for funding beam time at CAL and two M2 internships

Detection efficiency of TIARA block detector

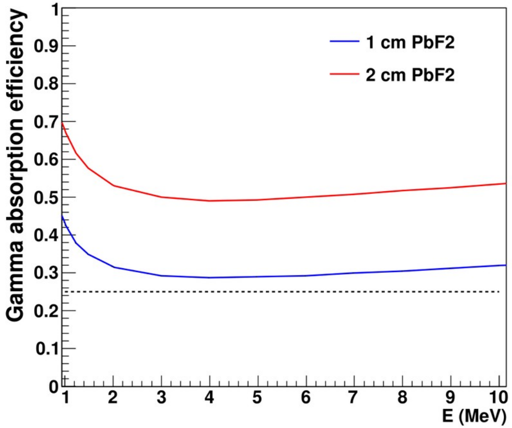
$$\epsilon = \epsilon_{geo} \times \epsilon_{PG} \times \epsilon_{opt}$$

$\epsilon_{geo} \times \epsilon_{PG}$ is given by the MC simulation of the experiment

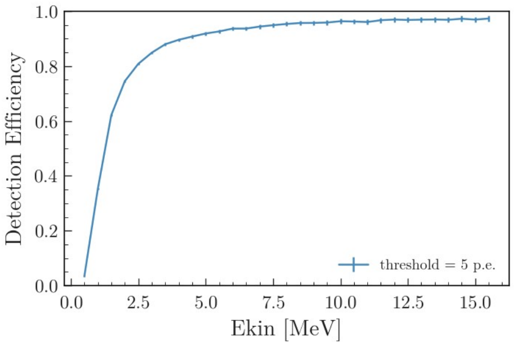
ϵ_{opt} is given the MC simulation of the detector response

$\epsilon_{PG} \times \epsilon_{opt}$ ~ 0.45 at 5 MeV, 5 p.e. threshold

PG interaction probability ϵ_{PG}



Optical efficiency ϵ_{opt}



Biased PGTI reconstruction

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

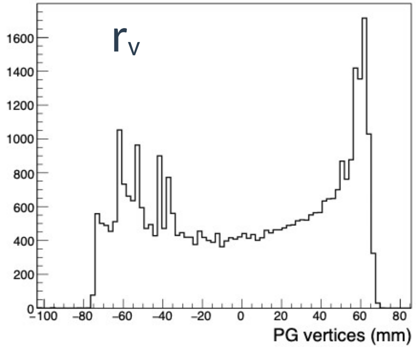
Experimental data

Given by preliminary MC based on TPS conditions

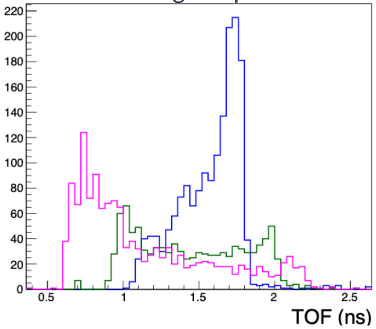
Trivial function

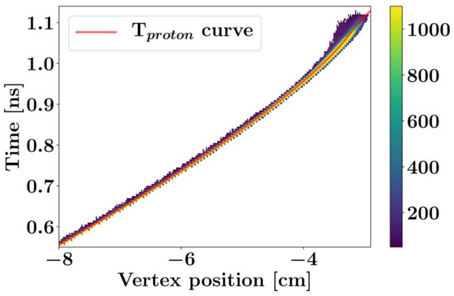
output

A unique PG vertex distribution



One TOF histogram per detector





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

Jacquet et al. ***A Time-Of-Flight-Based Reconstruction for Real-Time Prompt-Gamma Imaging in Protontherapy, Physics in Medicine & Biology, vol. 66, no. 13, p. 135003, Jun. 2021 (https://arxiv.org/abs/2012.09275)***

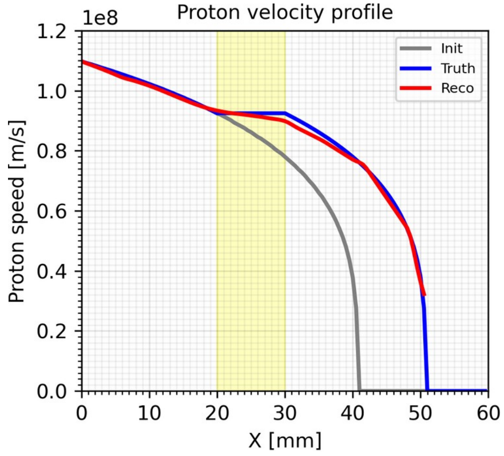
Unbiased PGTI reconstruction

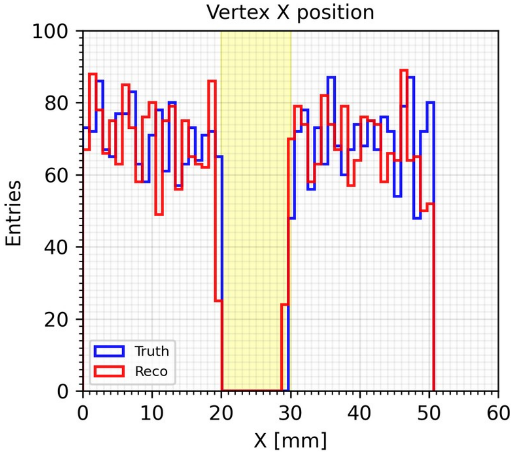
Simultaneous determination of proton velocity (v) and
PG vertex distribution (λ):

- alternating approach, minimisation (A. Cherni/Y. Boursier)
- genetic algorithm, stochastic (P. Kavrigin)

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

Preliminary results of the genetic algorithm for 70 MeV (**courtesy of P. Kavrigin**)





Does not require any a priori knowledge of the proton velocity