Journée GDR MI2B - ARCHADE
10th November 2020

Ultra-Fast Timing for PG-based range monitoring in hadrontherapy

Sara Marcatili on behalf of the CLaRyS collaboration

LPSC, Univ. Grenoble Alpes, CNRS, Grenoble INP, Grenoble
IP2I, CREATIS, Univ. Lyon, Univ. Claude Bernard Lyon 1, Villeurbanne
Aix-Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
Centre Antoine Lacassagne, Nice

Range monitoring with prompt gammas

Prompt gammas (PG)

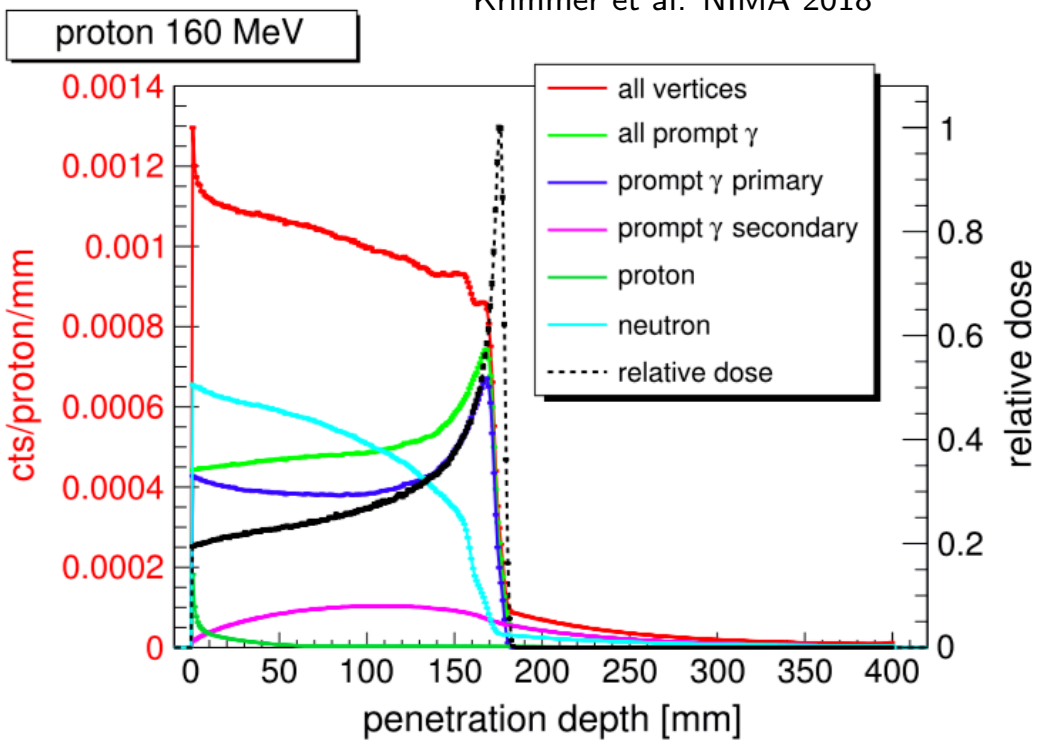
Emitted by nuclear de-excitation following NN collisions in the patient

- nearly isotropic
- $0 < E_\gamma < 10$ MeV
- emission within < 1 ps

Range monitoring principle

PG emission vertices are **spatially** and **temporally** correlated to hadron range

Krimmer et al. NIMA 2018

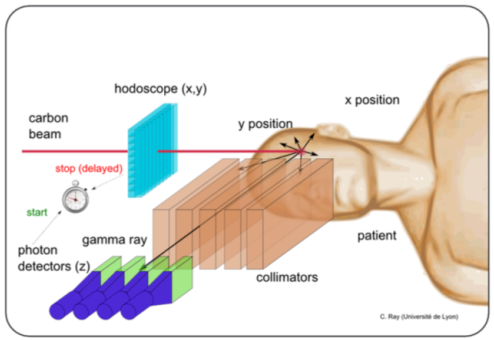


Drawback: low statistics!

A 160 MeV proton in water produces 0.05 PGs/proton
(0.3 PGs/^{12}C at the same energy)
$\rightarrow$ **High detection efficiency detector needed**

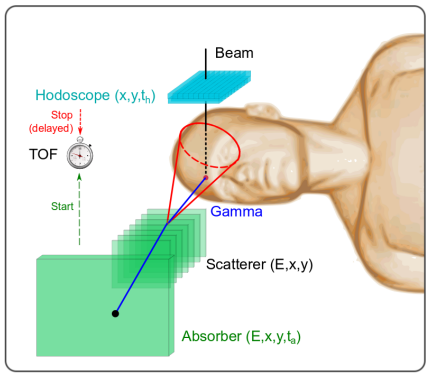
PG–based range monitoring in the CLaRyS collaboration

Multi-slit camera



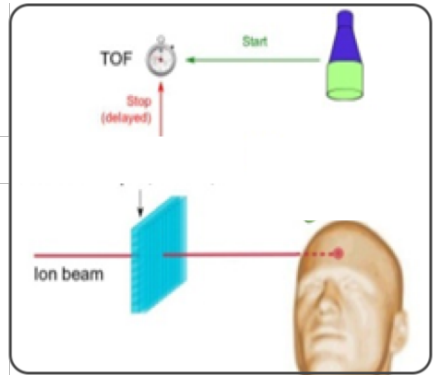
- 1D
- physical collimation
- $\sim 10^{-4}$ det. eff.
- real time

Compton camera



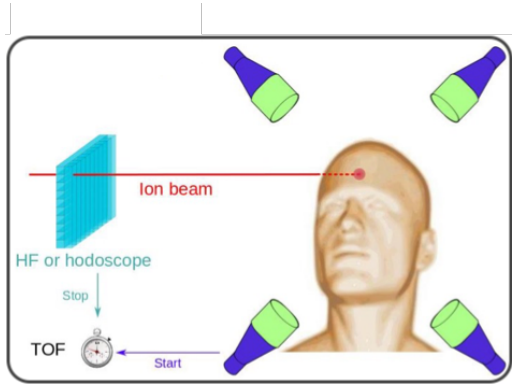
- 3D
- electronic collimation
- $\sim 10^{-4}$ det. eff.
- iterative reconstruction

PG timing



- 1D
- no collimation
- $\sim 10^{-3}$ det. eff.
- real time

PGPI



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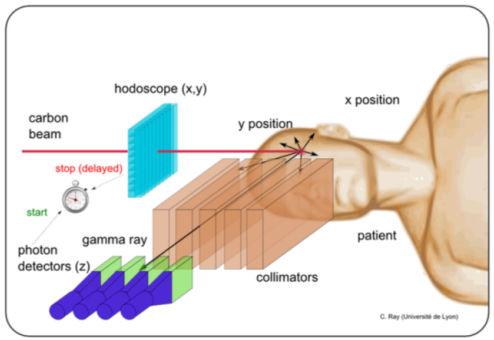

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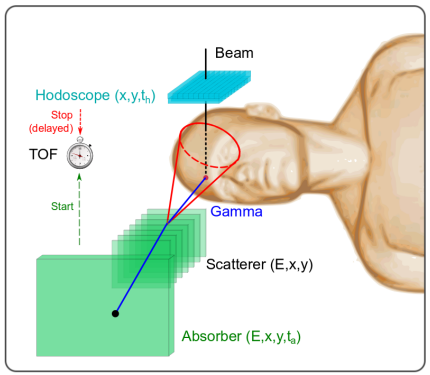

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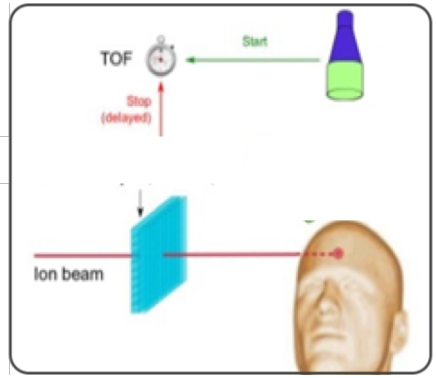

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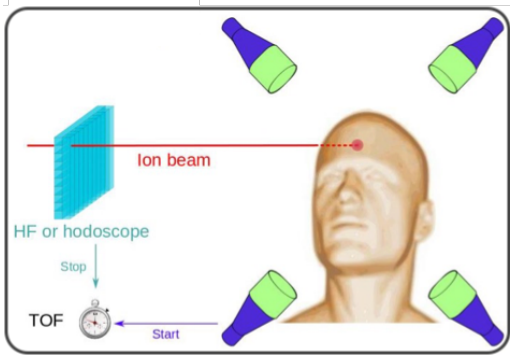

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Hodoscope: a common tool for spatial and temporal tagging

- Existing prototype based on scintillating fibres: $\sim$ **1 ns** time resolution
- Diamond based hodoscope under development at LPSC: $\lesssim$ **100 ps** time resolution

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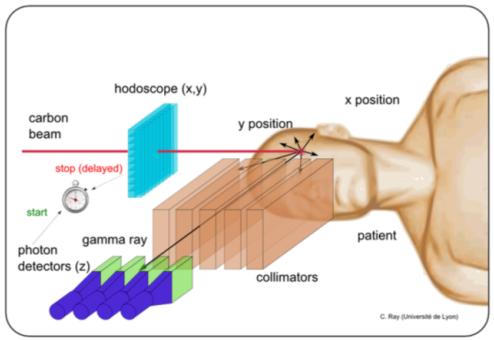

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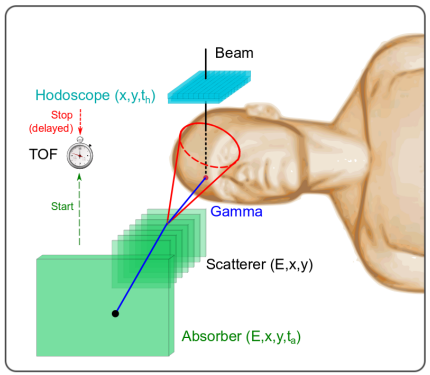

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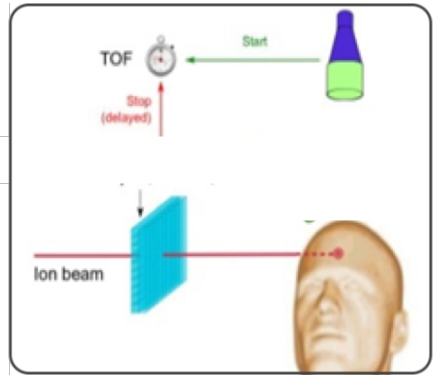

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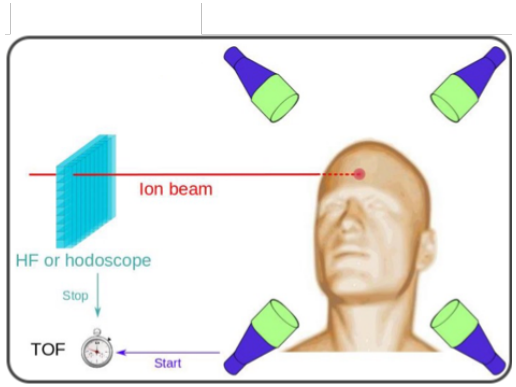

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Hodoscope: a common tool for spatial and temporal tagging

talk by Gallin-Martel

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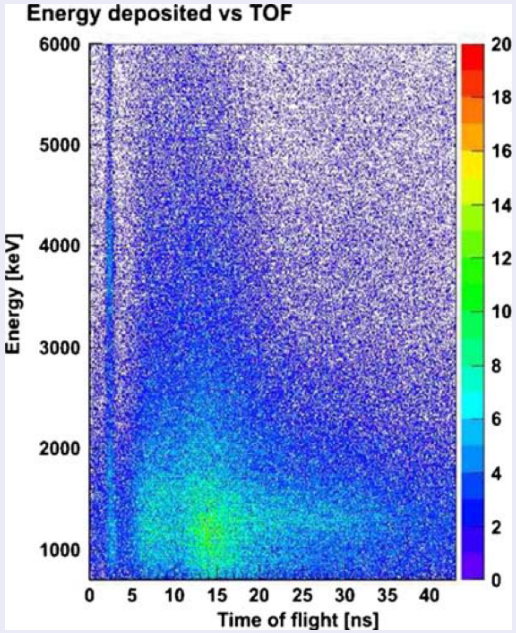
TOF detection of prompt gammas

Background reduction (increased sensibility)

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



M Testa et al. Rad Env Bio 2010

TOF resolution $\sim$ 1 ns required

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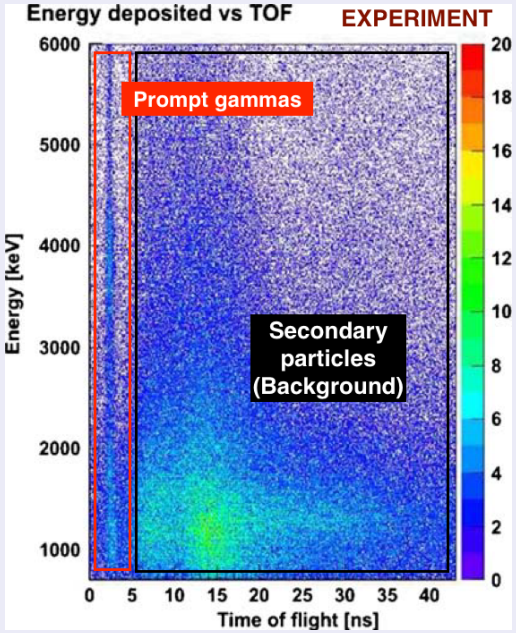

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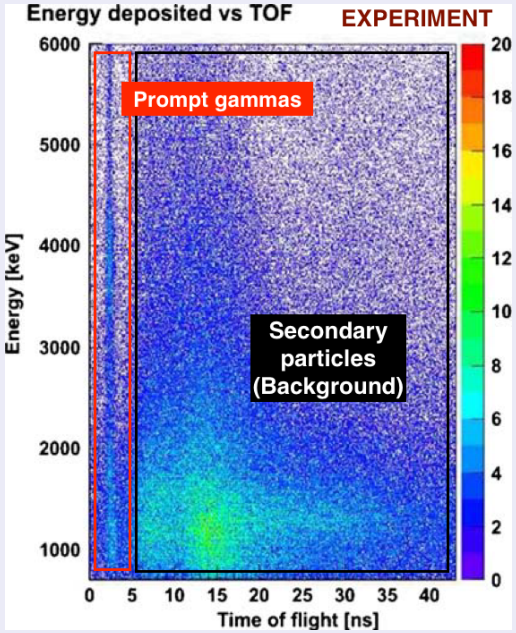

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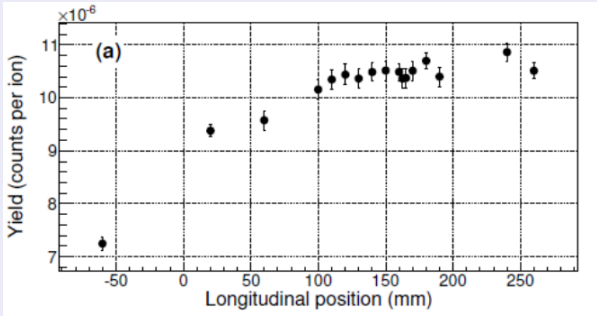
TOF resolution $\sim$ 1 ns required

Necessary for ^{12}C treatment

300 MeV/u ^{12}C beam on PMMA target

Prompt gamma profiles **WITHOUT** TOF



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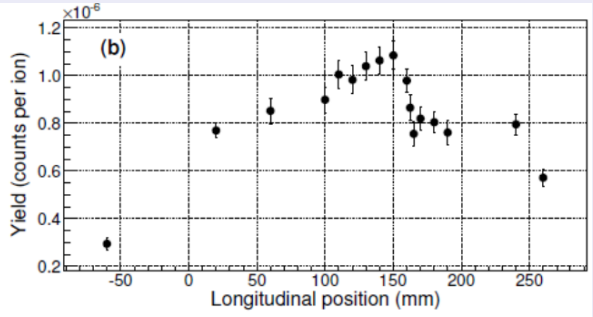

M Pinto et al. New J Phys 2015

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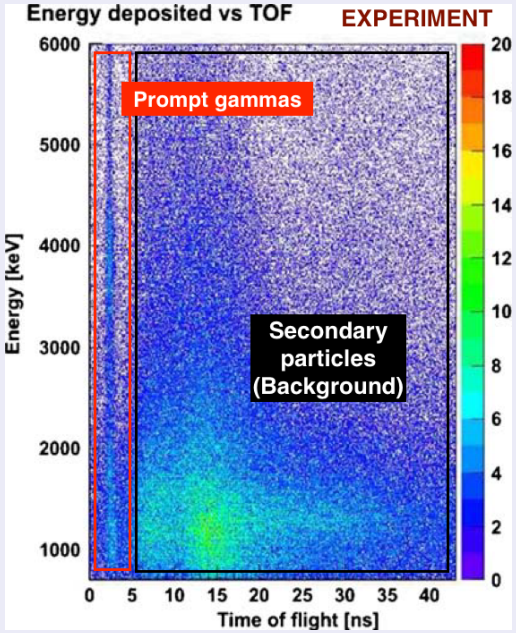

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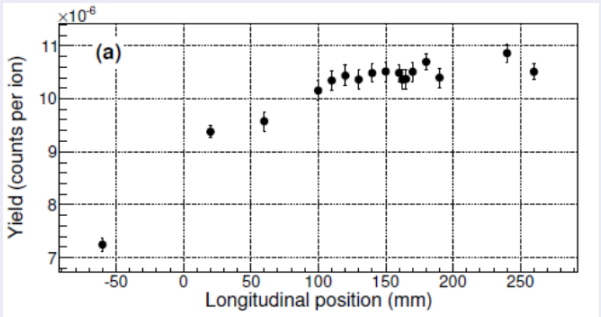

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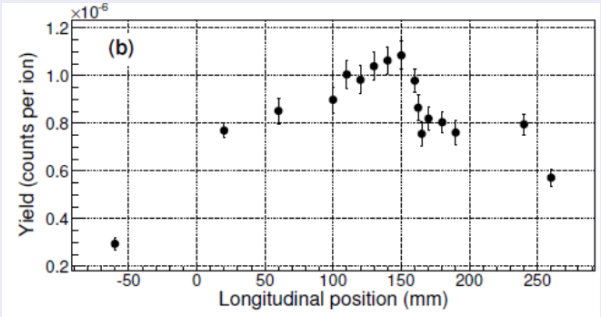

M Pinto et al. New J Phys 2015

An external detector is necessary for multi-energy treatment (RF phase varies!).

Single hadron regime

Beam temporal structure

		synchrotron (CNAO, HIT)		cyclotron (IBA, Varian)	synchro-cyclotron (S2C2, IBA)
		ions C	Protons		
Intensité type (ions/s)		10^7	10^9	10^{10}	$\sim 10^{10}$
Macrostructure	Période (s)	$1-10$		Ø	10^{-3}
Microstructure	Largeur paquet (ns)	$20-50$		$0.5-2$	8
	Période (ns)	$100-200$		10	16 (à l'extraction)
	Ions/paquet	$2-5$	$200-500$	200	4000

Carbontherapy (Synchrotron)

$\sim$ 30 ns bunch every 200 ns

10 ions/bunch $\rightarrow$ **Ion tagging**

Protontherapy (Cyclotron IBA/C230)

$\sim$ 2 ns bunch every 10 ns

200 p/bunch $\rightarrow$ **Bunch tagging**

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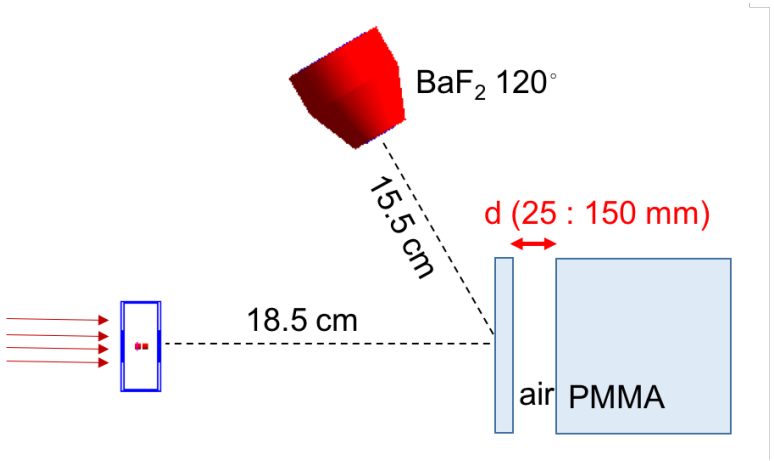
Reduction of beam intensity within the first (few) irradiation spot(s)

Dauvergne et al. Frontiers Physics (2020); 8; 434

PG Timing in single proton regime

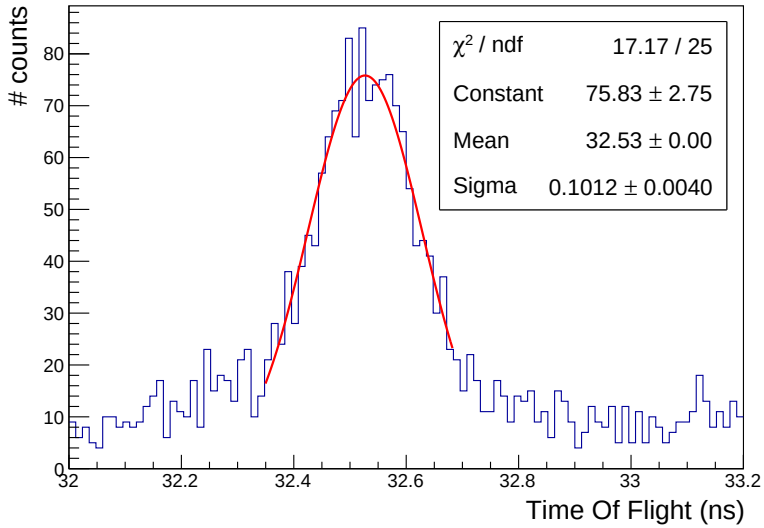


Aim:

Exploit the system ultra-fast Coincidence Time Resolution to detect range variations induced by target heterogeneities

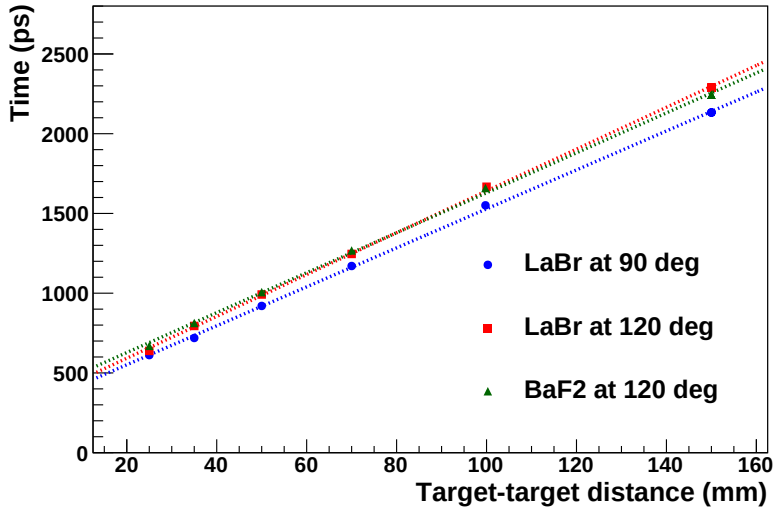
Set-up: A variable thickness air cavity produces a shift in proton range

101 ps (1 σ) CTR

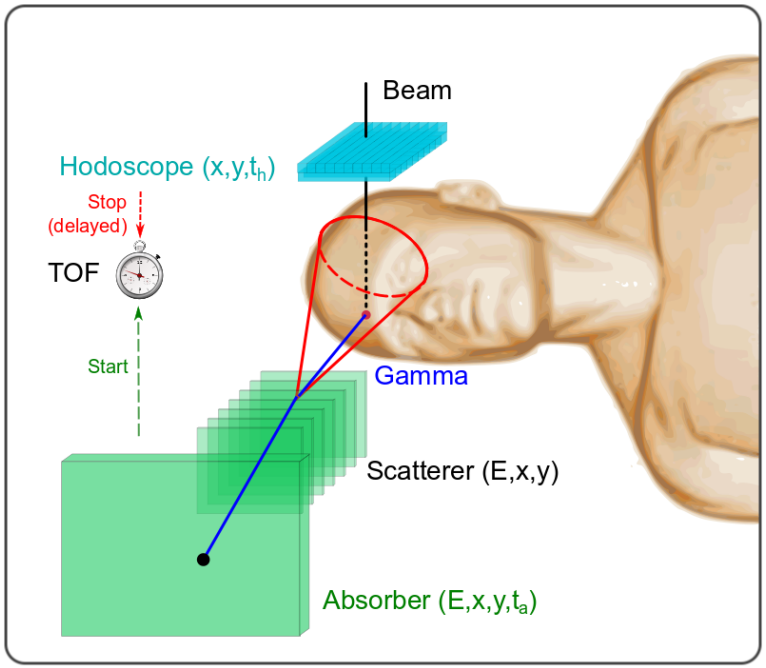


Marcatili et al. PMB (2020) accepted

The measured time-shift correlates to the air cavity thickness



Line-cone reconstruction for Compton camera



Proposed solution

A 200 MeV proton travels at $\sim$ c/2

A 100 ps TOF resolution allows determining the γ vertex within 1.5 cm

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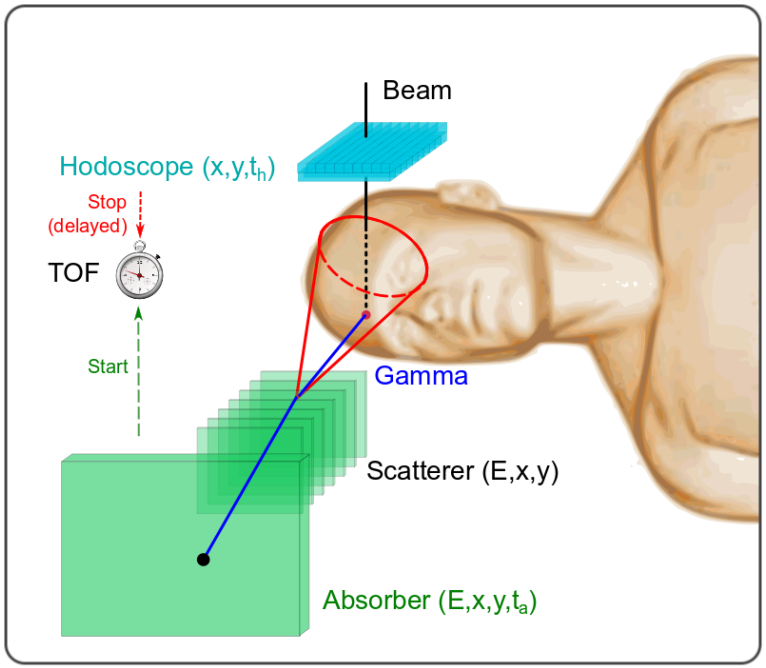
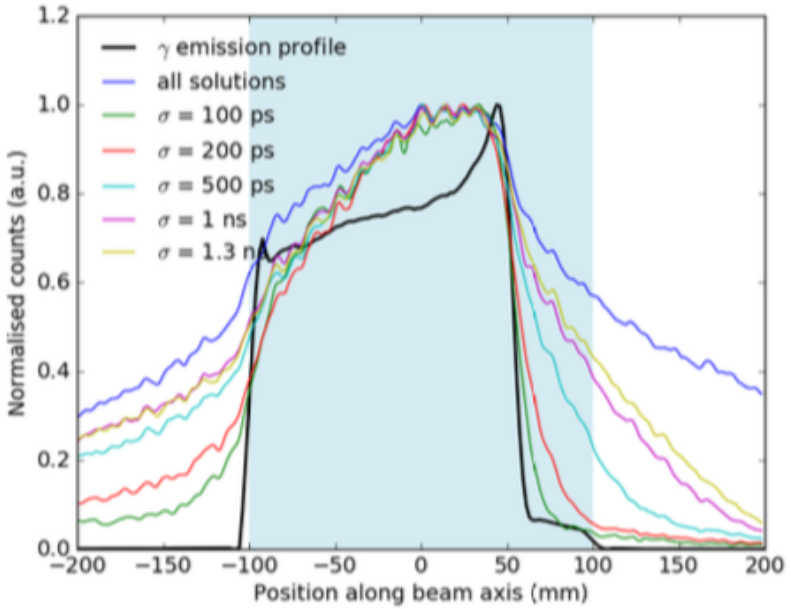


Reconstructed PG profile



Livingstone et al. in preparation

Proposed solution

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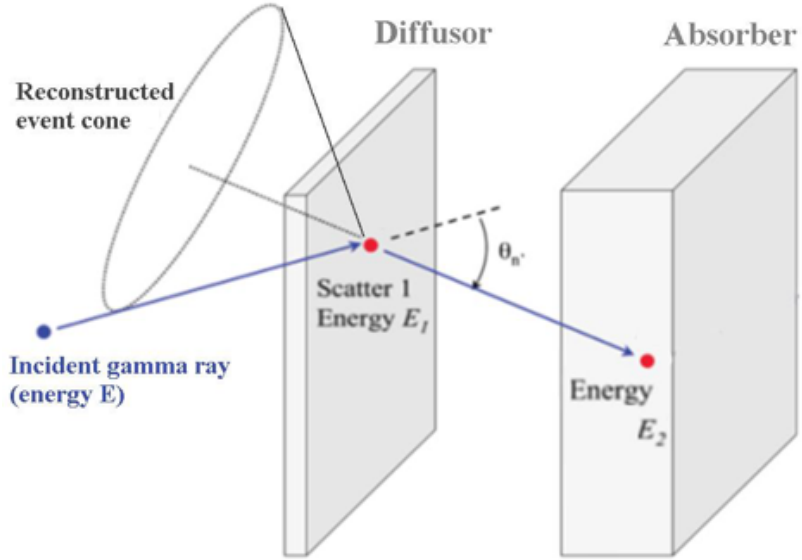
MC simulations

A precision of 2.30 $\pm$ 0.15 mm was achieved for 10^8 **primary protons** and a temporal resolution of **200 ps (rms)**.

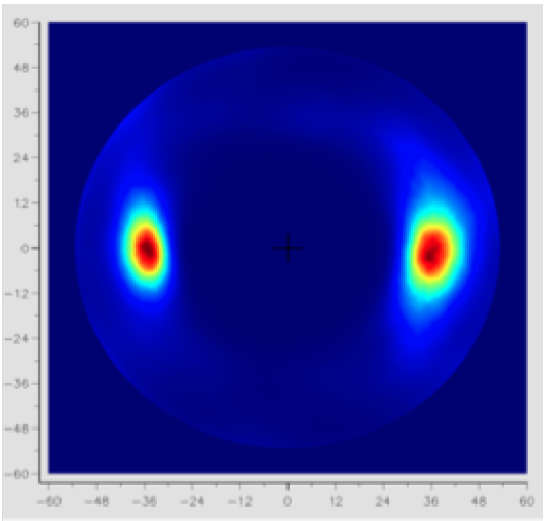
Compton imaging becomes a REAL TIME technique!

TEMPORAL camera

Nuclear waste application:



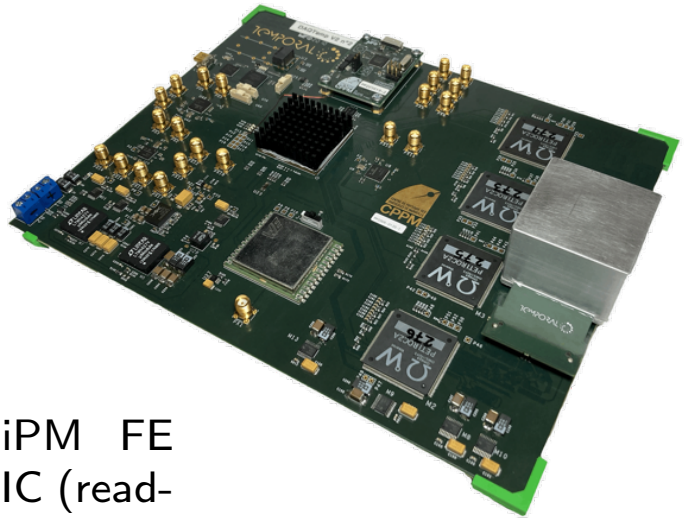
Two ^{18}F sources at 60 cm distance



Characteristics

- monolithic $CeBr_3$ read-out by SiPM matrices
- 3D vertex localisation
- 100 ps (rms) time resolution at 1 MeV

⇒ Compton Camera CLaRyS

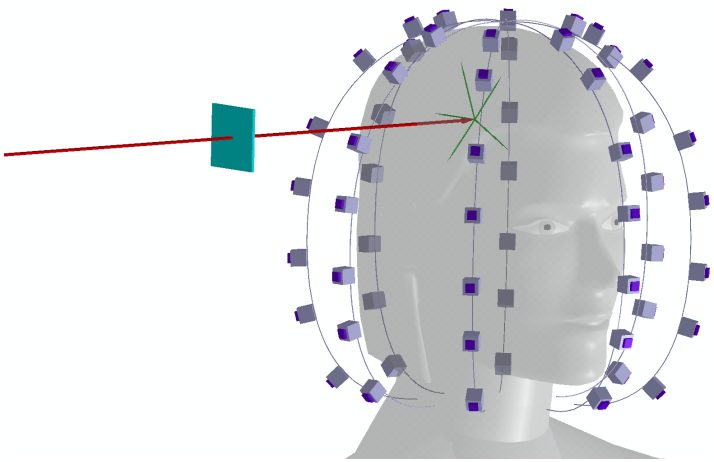


Developments

DAQTemp board for SiPM FE based on the PetiROC ASIC (read-out based on the μTCA AMC40 board).

TIARA: a Time-of-flight Imaging ARrAy for hadrontherapy

Goal: 3D reconstruction of PG vertex distribution on event-by-event basis



Composed of $\sim$ 30 detectors:

- small size $\sim$1 cm^3 (PG hit coordinates)
- fast (high CTR with hodoscope)
- high pixel detection efficiency (to compensate small size)

Pixel technology:

- Cherenkov radiator (PbF_2)
- SiPM photodetector

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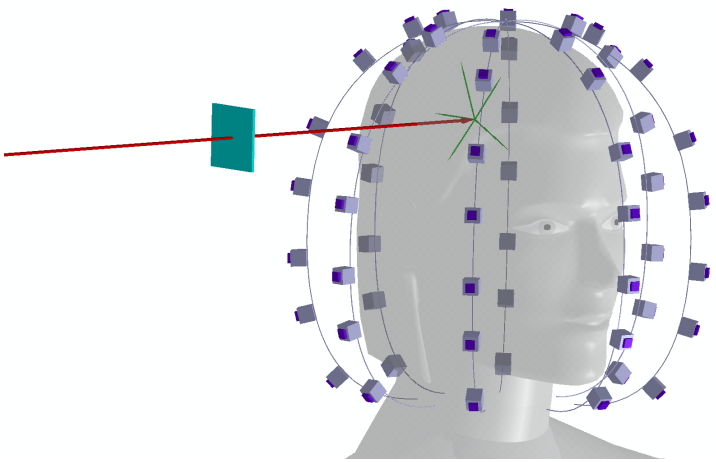

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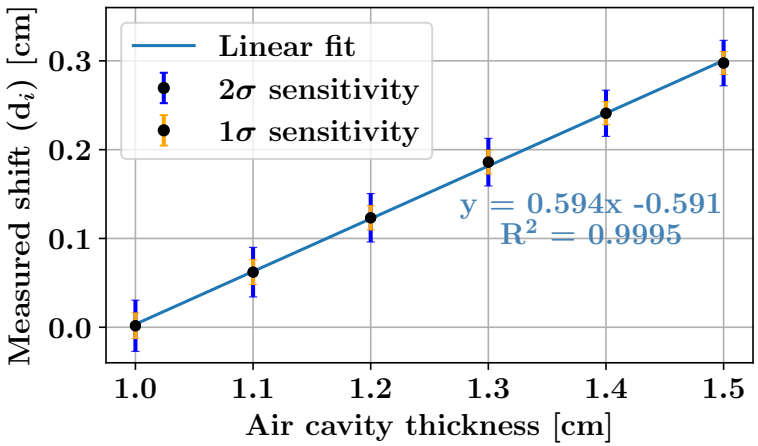
1D reconstruction developed

Distal proton range shift sensitivity (at 2σ) obtained from MC simulations:

- 1 mm for 10^8 **protons** and **100 ps (rms)** CTR
- 2 mm for 10^9 **protons** and **1 ns (rms)** CTR

Jacquet et al. in preparation

Measured vs. actual shift



- The availability of **ultra-fast, TOF-based, PG detection systems** opens up a whole range of possibilities for increasing the sensitivity of on line treatment monitoring in hadrontherapy.
- Interest in **ions heavier than protons** to increase the system TOF resolution

Many original developments within the CLaRyS collaboration:

- Compton imaging reconstruction
- TEMPORAL camera
- TIARA
- but also, PGT, IVI, PGPI ...

Current projects:

- CLaRyS-UFT (PCSI INCa/INSERM)
- TEMPORAL camera (ANR-ANDRA/PIA)
- TIARA (PCSI INCa/INSERM; IDEX-UGA)
- DIAMMONI (ANR-PRC)