# Design and development of a Time-of-Flight Compton camera for on-line control of hadrontherapy

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## Hadrontherapy control & prompt radiation

- **Hadrontherapy control: a crucial issue**
  To make the best use of the very good ballistics of hadrontherapy, it is necessary to make sure that the dose is deposited in agreement with the treatment plan. The precision required is of the order of the millimetre. The main sources of uncertainties in the dose delivery are :
  - patient mis-positionning,
  - patient or organ movement,
  - and density changes within the irradiated volume.

- **Current system of verification**: in-beam PET (GSI)
  The in-beam PET developed at GSI for more than 10 years has demonstrated its ability to control hadrontherapy. Nevertheless, it seems that it will be very difficult to obtain a real-time monitoring with such a device (Enghardt *et. al.* [1])

- **Promising technique : detection of prompt radiation issued from nuclear fragmentation**
  1. An important fraction of the incident ions undergo nuclear fragmentation:
     - $^{12}$C at 100 MeV/u : ~8 %
     - $^{12}$C at 400 MeV/u : ~70 %
  2. For each nuclear fragmentation event, several γ, neutrons, protons and light fragments are emitted and these emissions are strongly correlated to the ion range (and therefore may allow to control the longitudinal dose distribution).
     Simulations show that high enough statistics of protons and gamma-rays are available to provide real-time monitoring of hadrontherapy.
  3. Finally, 3D control of the dose can be obtained by coupling the γ-ray and proton detection with the measurements of the transverse positions of the incident ions.

- **Main constraint :**
  Prompt-radiation detection requires that radiations coming directly from the ion track be discriminated from those scattered in the surrounding matter, namely, neutrons and charged particles, and Compton-scattered γ -rays

## Preliminary measurements (on prompt γ-rays)

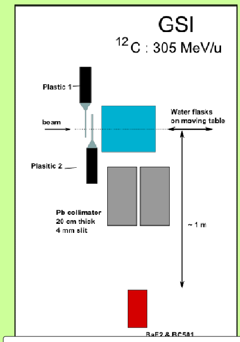


**Fig.1** Scheme of GSI experimental set-up

**Experiments** have been performed with the following carbon ion beams :

- $^{12}$C at 95 MeV/u and $^{13}$C at 75 MeV/u (GANIL, Caen France)
- $^{12}$C at 305 MeV/u (GSI, Darmstadt Germany)

The features of our experimental set-up are the following:

- **PMMA or water target** (with some **inserts of bone- and lung-equivalent tissue**)
- **lead collimator** with a thickness of 20 cm and adjustable slit width (2-4 mm)
- one or several **scintillators** to detect γ-rays and neutrons
- the **TOF technique** is used to discriminate photons from neutrons

Main results:

- prompt gamma profiles are correlated with ion ranges [3, 4]
- prompt gamma yields are compatible with an on-line monitoring of hadrontherapy [5]

Ongoing developments:

- Multi-detector design with optimized shaping of the LYSO detectors: background reduction
- Test with proton beams (collaboration with IBA)

**C ions at 73 MeV/u**

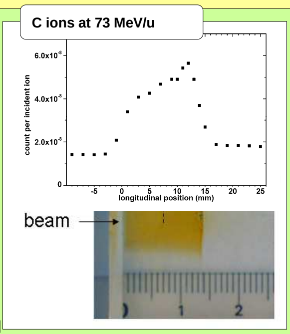


**Fig.2** First experiment: verification of the γ profile – ion range correlation (the scaled photograph of the irradiated PMMA sample shows the darkened area that allows to determine the ion path) Testa *et. al.* [3, 4]

**C ions at 300 MeV/u**

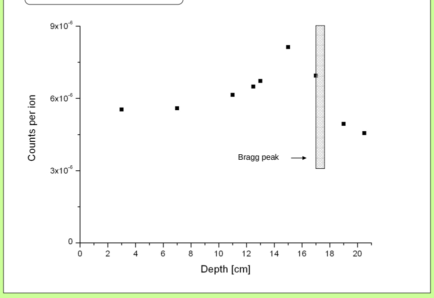


**Fig.3** verification of the the γ profile – ion range correlation at high energy. This correlation is kept over ~15 cm ion range.

## Prompt gamma camera design

- A beam hodoscope
  - a time stamp of the ion impact for the TOF measurement,
  - the transverse positions of incident ions that provides a good estimation of the transverse position of nuclear reaction points. This allows in principle a 3D control of the dose.
- A prompt gamma Compton camera

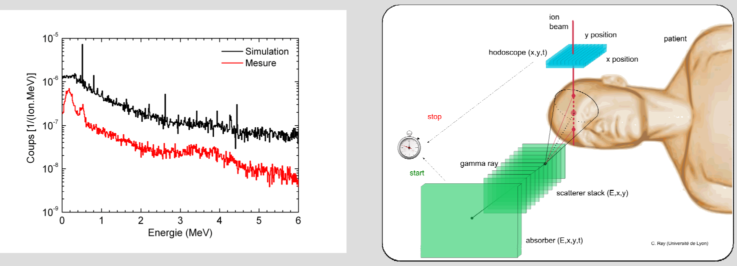


**Fig.4 Left : simulated and measured prompt gamma spectra during carbon irradiation of a PMMA target [8]. Right:** artistic scheme of amonitoring system by prompt gamma detection with a Time-of-Flight Compton camera

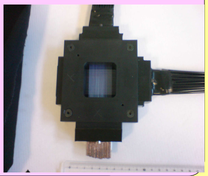
## Beam hodoscope: *requirements & prototype*

A beam hodoscope, placed in front of the patient, is required for :
- Time of Flight measurements of the secondary radiation (background rejection)
- X,Y information on the incident beam for 3D imaging

- Requirements:
  - timing resolution: 1 ns
  - maximum counting rate: $10^8$ ions / s
  - spatial resolution ~ 1 mm
  - Radiation hardness: fluence up to $10^{12}$ ions/cm$^2$ without loss of efficiency
  - Thin material to avoid beam perturbation

- Hodoscope prototype:
  - 2 planes of scintillating square fibers (1 mm$^2$): vertical and horizontal fibers
  - 32 fibers per plane coupled to optical fibers and a flat panel PM

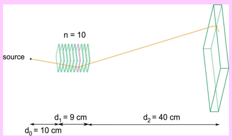
**Test of the prototype at GANIL:**
- σ =350 ps time resolution
- Fluence of $4\times10^{12}$ carbon ions/cm$^2$ (75MeV/u) was sent with efficiency > 85%
  ~1 year operation in clinical conditions
- Under development: dedicated readout electronics

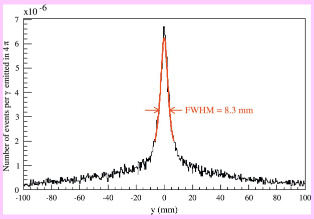


**References :**
[1] W. Enghardt *et al.,* Nucl. Instrum. Methods Phys. Res. A **525** (2004) 284.
[2] C.-H. Min *et al.*, Appl. Phys. Lett. **89**, 183517 (2006).
[3] E. Testa *et al.*, Applied Physics Letters, **93** (2008) 093506
[4] E. Testa *et al.* Nucl. Instrum. Methods Phys. Res. B 267 (2009) 993–996
[5] M. Testa *et al.,* Rad. Env. Bio. 49 (2010) 337-343 - PTCOG 48
[6] M.-H. Richard et al, IEEE TNS 1 2011, 94
[7] F. Röhlinghoff et al, NIM A 2011
[8] F. Le Foulher et al. IEEE TNS (2010)

## Compton camera design

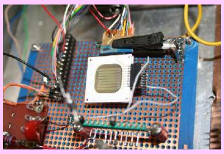
### Simulations

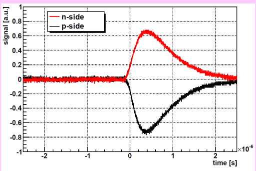




-scatterer: stack of silicon strip detectors (SSD) 8 x 8 x 0.2 cm3
-absorber: LYSO detector 30 x 30 x 2.5 cm3
-photons: point source
-simulation: select events with 1 Compton interaction in SSDs
+ hit in absorber **single scattering : efficiency=2.5 x $10^{-4}$** [6,7]

### Lab tests of small size Si detectors





Test detectors (12 x 12 mm2)
Signal after amplification and shaping recorded with scope
For further investigations: 2 x NI PXI 5105 sampling ADC
60 MS/s, 8 channels each
Delivery of final SSD detectors (80 x 80 mm2)

## Conclusion and perspectives

- Prompt gamma detection using TOF can provide a on-line monitoring of hadrontherapy with carbon ions

- A challenging detection setup development is currently in progress to construct a first prototype of monitoring system
  - a beam hodoscope:
    - a prototype has been successfully tested
    - Life time > 1 year
  - a Compton camera using time of flight: a stack of typically ten silicon detectors with 1.5 mm strips with a LYSO absorber

→ design of this camera with simulations to be validated by experiments
→ development of ASIC for front-end readouts and data acquisition system within 3 years

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