Fast detectors for prompt gamma timing in hadrontherapy applications

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Context

Range monitoring with prompt gammas

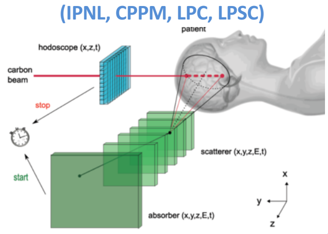
The high ballistic precision of hadrontherapy makes it particularly prone to dose delivery errors in the distal region of the Bragg peak.

In order to assure a correct dose delivery to the patient, an online range verification system is highly desirable. A possible approach is to detect Prompt Gammas (PG) emitted in the patient to indirectly measure the ion range in-vivo.

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

- Nearly isotropic
- 0<E<10 MeV
- Emission within < 1 ps
- Their longitudinal spatial distribution of emission correlates with the position of the Bragg peak

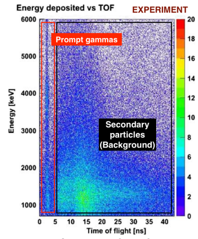
Compton Camera CLaRyS (IPNL, CPPM, LPC, LPSC)



TOF detection of prompt gammas

Low resolution (~ns)

95 MeV/u ^{12}C beam on PMMA target (BaF_2 at d>50cm from target) [1]



Background reduction
=> Increased sensitivity

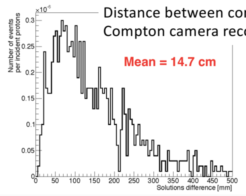
High resolution (~100 ps)

- A 200 MeV proton travels at ~c/2

A 100 ps TOF resolution allows determining the ion vertex within 1.5 cm => No PG collimation required

- Compton Imaging (line-cone intersection):

Distance between cone intersections in Compton camera reconstruction [2]



Current solution: Either line-cone intersection (2 points with equal weights) or time-consuming MLEM

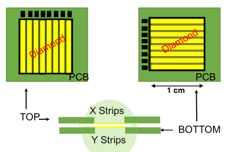
NO Compton reconstruction needed => Real Time

R&D at LPSC

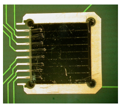
A fast beam tagging hodoscope based on diamond

Aimed performances:

- Time resolution ~ 100 ps (achieved in prototype)
- Count rate ~ 10 MHz per channel
- Spatial resolution ~1 mm (achieved in prototype)
- Radiation hard



PC diamond from E6

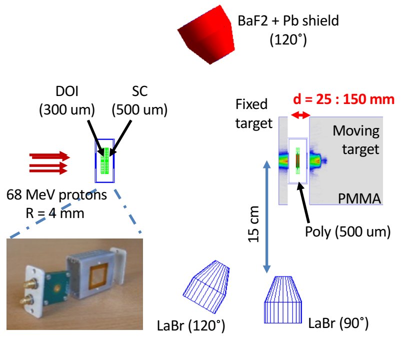


Double-side stripped diamond demonstrator of reduced size already developed and tested [3]

Prompt gamma timing at ARRONAX (68 MeV protons)

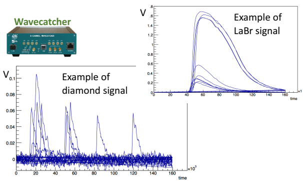
Experiment set-up

The experiment **goal** is to separate PG produced in the two targets by measuring the time occurred between diamond and gamma detector triggers. This corresponds to measuring the proton range.



DATA ACQUISITION

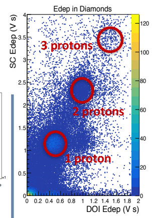
- Signals from all detectors sampled with the Wavecatcher (3.2 Gs/s) [4]



- Trigger on each gamma detector separately
- Signal timing determined with digital constant fraction discriminator at 50%

DIAMOND PERFORMANCES

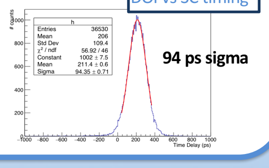
Low intensity beam to avoide pile-up



CUT
1 proton selection = electronic collimation (~15% events kept)

	ΔE/E (FWHM)
SC	31%
DOI	58%

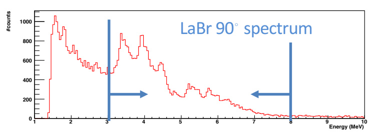
DOI vs SC timing



94 ps sigma

Results

Energy selection in gamma detectors



CUT for gamma detectors (~50% events kept):
Edep < 8 MeV: for background rejection (scattered protons)
Edep > 3 MeV:

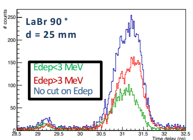
1. improves time resolution for all gamma detectors
2. improves target separation (better correlation PG-range)

1. SC diamond vs. Gamma detector Timing (sigma in ps)

	Edep<8 MeV	3 <Edep<8 MeV
BaF2 120°	115.2	101.7
LaBr 120°	146.9	140.0
LaBr 90°	191.0	134.5

The time resolution is extracted from the first PG peak in the time delay distributions (PG produced in the diamond detector).

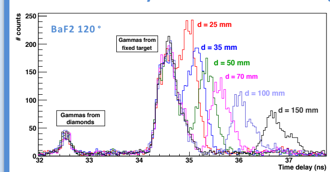
2. Time delay between gamma detector and diamond



The 3 MeV cut reduces the contribution of PG produced in the fixed target and contributes improving peak separation.

Target separation from prompt gamma TOF

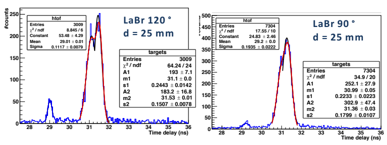
Time delay between diamond and gamma detector triggers



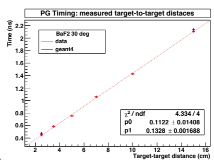
As the second target shifts to larger distances, the third peak of the TOF distribution shifts accordingly. Target to target distance is calculated as the time difference between target peak maxima.

Detection angle

The 90° configuration is less sensitive since the same target distance corresponds to lower TOFs.



Comparison of measured TOF and actual target-to-target distance



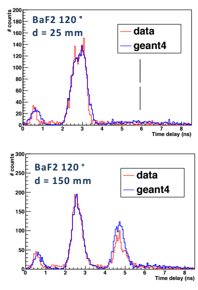
Possible to discriminate differences in proton range of <5 mm (probably higher sensitivity).

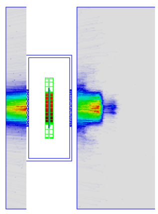
Open issues:

- Robust definition of TOF distance
- Precision vs. experimental statistics

=> Need for systematic study of sensitivity through high statistics MC simulation

Comparison with G4 simulations





Top: Simulated energy deposit. 68 MeV protons impinging on two PMMA targets.

G4 simulations allowed reproducing the data and understanding the limits of the experiment:

- The bump in the last peak is due to beam spreading in diamond holder (requires fine tuning between beam characteristics and holder geometry in G4).
- The asymmetric shape of the fixed target peak is due to the PC-diamond placed between the targets.
- Accuracy of peak positioning ~ few 10 ps.

Conclusions and perspectives

1. We successfully measured 68 MeV proton range in PMMA through a TOF measurement of PG:
   - we achieved a time resolution of **100-140 ps sigma**
   - we could resolve target separations of 25 mm
2. The construction of a **large area hodoscope**:
   - will reduce PG peak asymmetries and make it easier to define a metric for the evaluation of peak separation
   - will dramatically reduce acquisition time (electronic collimation not necessary)
3. Need to run high statistics Monte Carlo simulations to study the relationship between statistics and technique sensitivity.

References:
[1] E Testa et al. Rad Env Bio 2010
[2] JL Ley, PhD manuscript 2015
[3] ML Gallin-Marterl et al. ANIMMA 2017 Conference Record, EPJ Web of Conferences 170, 09005 (2018)
[4] D Breton, et al. TWEPP2009 conference record, Topical Workshop on Electronics for Particle Physics. Paris 21-25 September 2009.

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