A Compton Camera for Medical Applications based on SSD and Scintillation Detectors

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Introduction

- monitoring of the ion range during hadrontherapy
- nuclear medicine

ions vs photons

- Bragg peak
- higher RBE


- increased sensitivity to range uncertainties
  ⇒ online monitoring needed
Hadrontherapy worldwide

- 46 centers in operation
- 27 centers under construction
- 11 centers in planning phase

http://www.ptcog.ch/
Ion range monitoring during hadrontherapy

310 MeV/u $^{12}$C, H$_2$O target

measurement of $\beta^+$ activity (200 MeV/u $^{12}$C on a PMMA phantom)

- correlation between ion range and nuclear reaction depth profile
- two types of radiation relevant for monitoring
  - $\beta^+$ activity $\Rightarrow$ PET
  - prompt secondary radiation ($p, \gamma$)

<table>
<thead>
<tr>
<th>number of ions (distal slice)</th>
<th>proton</th>
<th>carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy slice</td>
<td>$\sim 10^{10}$</td>
<td>$\sim 10^{8}$</td>
</tr>
<tr>
<td>single spot</td>
<td>$\sim 10^{8}$</td>
<td>$\sim 10^{6}$</td>
</tr>
</tbody>
</table>

Typical treatments (PBS)

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Methods for ion range monitoring

Collimated camera (γ-rays)
- Hodoscope (x,y,t_stop)
- Ion beam
- TOF (delayed)

Compton camera (γ-rays)
- Hodoscope (x,y,t_stop)
- Ion beam
- TOF
- Scatterer (E,x,y)
- Absorber (E,x,y,t_start)

Interaction Vertex Imaging (secondary protons)
- 12C beam
- Hodoscope (x,y,t)
- Secondary protons
- Scintillator (trigger)
- Tracking detectors (x,y)

Slit-hole camera (γ-rays)
- IBA

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Time-of-flight Compton Camera

- $\approx 1$ gamma per proton/carbon ($E_\gamma$ up to 10 MeV)
- high detection efficiency needed
- neutron background: shielding or use of time-of-flight
- principle: line / cone intersection
- components: hodoscope, scatterer, absorber
Components: hodoscope

- **goals:**
  - position resolution 1 mm
  - time resolution 1 ns
  - count rate $10^8$ 1/s

- **array of scintillating fibers**
  - $(1 \times 1 \text{ mm}^2 \text{ BCF 10/12})$

- **prototypes:** $2 \times 32$ and $2 \times 128$ fibers
- **readout:** optical fibers FORETEC
- **coupling to multianode PM H-8500**
Hodoscope: performance tests

- GANIL: 75 MeV/u $^{13}$C, IPN Orsay: 25 MeV protons
- time reference: cyclotron HF ⇒ time resolution 1 ns FWHM

- H-8500 ⇔ MCP-PMT
- max. rate > 10 MHz, for H-8500 at 800 V
- MCP-PMT at 2200 V ⇒ less performant
Hodoscope: front end electronics

- goals: rate $10^8$ 1/s, time information, analog output (monitoring of fiber aging)

- first version of ASIC:
  - current comparator
  - CSA

  S. Deng et al. NIM A 695 (2012)

- second version of ASIC:
  - inclusion of time stamper
  - 160 MHz clock + DLL
  - 32 to 5 Gray encoder

- ASIC currently under test

  L. Caponetto VLSI Marseille (2014)
Compton Camera

principle: line / cone intersection

components: hodoscope, scatterer, absorber

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Components: scatter detector

- double sided silicon strip detector (SSD)
- test detector $14 \times 14 \times 2 \text{ mm}^3$
- $2 \times 8$ strips (p- and n-side)
- cooling at $-15^\circ\text{C}$ foreseen

measurement of leakage current and energy resolution
Scatter detector: real size SSD

- large SSD: $90 \times 90 \times 2 \text{ mm}^3$
- 7 planes in total
- $2 \times 64$ strips (p- and n-side)
- bias voltage $-750 \text{ V}$ (full depletion)
- bonding of detectors at IPNL
- PCB: polarization resistors decoupling capacitors

detector under characterization
Scatter detector: front end electronics specifications

- dynamic: $3 \cdot 10^3 - 3 \cdot 10^6 \, \text{e}^-$
- count rate: $10^5 \, \text{1/s}$
- low noise: $120 \, \text{e}^- \, \text{RMS}$ (1 keV FWHM)
- shaping: $15 \, \text{ns}$ and $1 \, \mu\text{s}$
- selection: electron / holes

⇒ switched system

scheme of ASIC for SSD:

- ASIC under test
  
  M. Dahoumene: VLSI Marseille (2014)
Compton Camera

- **principle**: line / cone intersection
- **components**: hodoscope, scatterer, absorber

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Components: absorber

- streaked BGO crystals $35 \times 38 \times 30 \text{ mm}^3$ read by 4 PMs
- $8 \times 8$ (pseudo)-pixel, 96 crystals in total
- energy resolution 17% at 511 keV, time resolution 2 ns
- position reconstruction via centroid
- detector assembly and readout electronics: LPC Clermont
Compton Camera: simulation

- Simulation of Geant4
- Optimization of the setup
- Check of feasibility for medical applications

![Diagram of Compton Camera setup]

- 100 blocks of streaked BGO crystals
  - $3.8 \times 3.8 \times 3 \text{ cm}^3$
- Stack of 7 Si layers
  - $9 \times 9 \times 0.2 \text{ cm}^3$
- PMMA $10 \times 25 \times 10 \text{ cm}^3$
- Distances: $20 \text{ cm}$, $6 \text{ cm}$, $40 \text{ cm}$

**Geant4 simulations**

- **optimization** of the setup
- **check of feasibility** for medical applications
Simulation: nuclear medicine (SPECT)

- simulation: point source
- **Angular Resolution Measure**: $\text{ARM} = \Theta_{\text{compton}} - \Theta_{\text{geom}}$
- $\Theta_{\text{compton}}$ from Compton kinematics
- $\Theta_{\text{geom}}$ from (known) geometrical source
Simulation: hadrontherapy

**Simulation parameters:**

- Time resolution: 15 ns FWHM (SSD), 2 ns FWHM (BGO)
- Statistics: $10^8$ protons $\Rightarrow$ 1 distal spot in PBS
- Beam: energy 160 MeV, HF 100 MHz, intensity $2 \cdot 10^{10}$ 1/s
- Reconstruction of vertices via line/cone interaction
- Clinical intensity: 200 protons/bunch

**Reduced intensity:** 1 proton/bunch

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J.L. Ley PhD thesis

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Conclusions and outlook

medical applications

- ion range monitoring during hadrontherapy
  - reduction of beam intensity to 1 proton per bunch
  - treatment time < 1 s per spot
- nuclear medicine (SPECT)
  - replace mechanical collimation
  - new radioisotopes with higher energies ($\approx$1 MeV)

instrumentation and reconstruction

- all detector components have been delivered
- front end electronics: ASICs under test
- DAQ: cards for $\mu$-TCA system will be delivered in summer
  CPPM Marseille, derived from LHCb DAQ
- mechanics: support structure under construction,
  cooling system has been delivered
- include iterative algorithm for reconstruction
people, institutions and acknowledgements


IPNL Lyon, Creatis Lyon, LPC Clermont, CPPM Marseille, IPN Orsay, CAL Nice, GANIL Caen, HIT Heidelberg, GSI Darmstadt, ...

FP7-ENVISION (WP3, WP6), FP7-ENTERVISION, FP7-ULICE, ANR Gamhadron project, Rhône-Alpes Regional Program for Hadrontherapy Research, MI2B GDR, LabEx PRIMES
development of analytical and iterative algorithms (CREATIS Lyon)

iterative algorithm MLEM

point source of prompt $\gamma$

camera $10 \times 10$ cm$^2$ (scatterer)

3000 events reconstructed pencil-beam basis, proton PBS

10 iterations, 10 min on a cluster $\Rightarrow$ need for GPU

resolution 5 mm

Lojacono et al. GRETSI'11 2011