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

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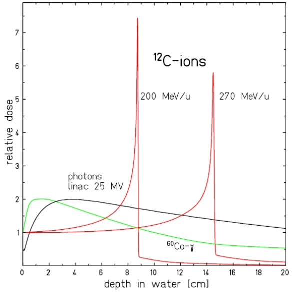
Tours, France

Introduction

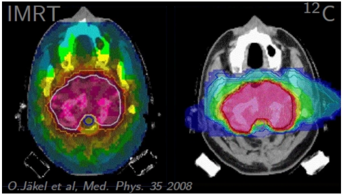
- monitoring of the ion range during hadrontherapy
- nuclear medicine

ions vs photons



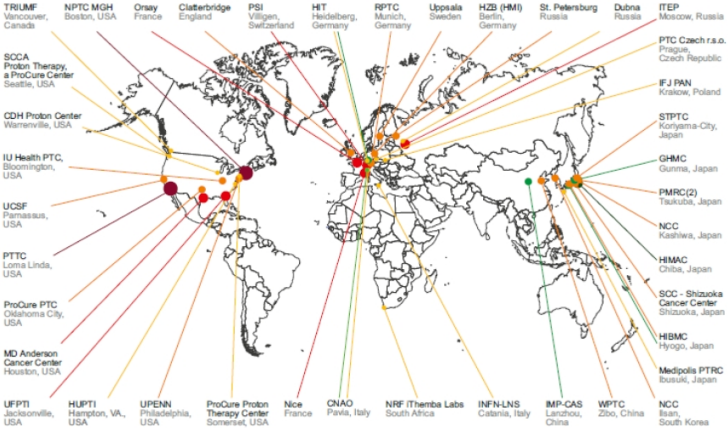
D. Schardt *et al.* Rev. Med. Phys. 82 (2010)

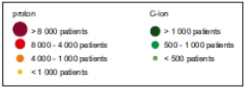
- Bragg peak
- higher RBE



- increased sensitivity to range uncertainties
  $\Rightarrow$ online monitoring needed

Hadrontherapy worldwide

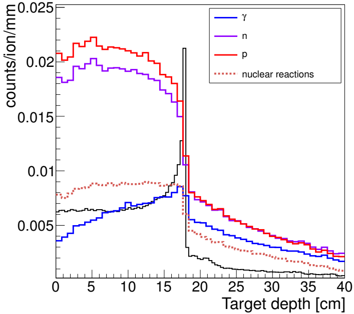




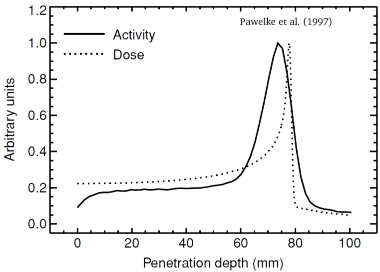
- 46 centers in operation
- 27 centers under construction
- 11 centers in planning phase

http://www.ptcog.ch/

Ion range monitoring during hadrontherapy



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



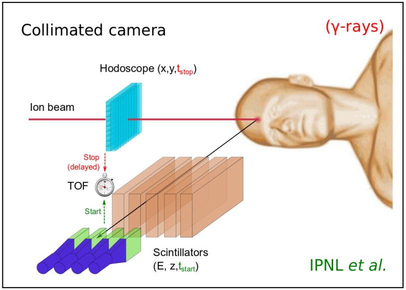
- correlation between ion range and nuclear reaction depth profile
- two types of radiation relevant for monitoring
  - β^+ activity ⇒ PET
  - prompt secondary radiation (p,γ)

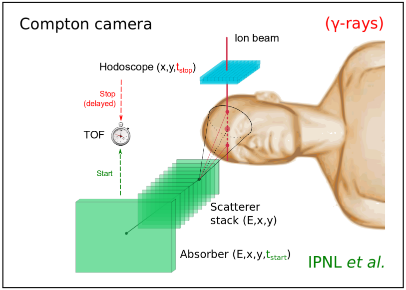
typical treatments (PBS)

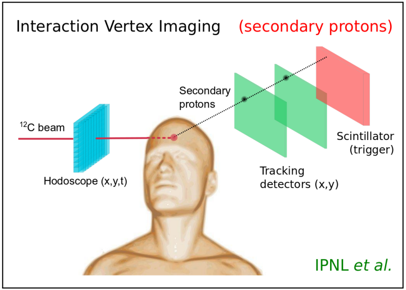
	number of ions (distal slice)	
	proton	carbon
energy slice	$\sim 10^{10}$	$\sim 10^{8}$
single spot	$\sim 10^{8}$	$\sim 10^{6}$

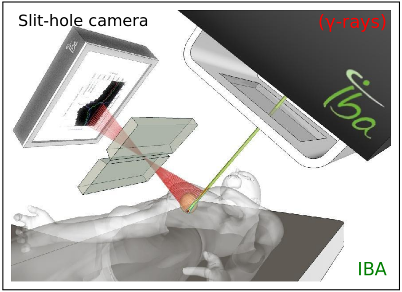
Krämer *et al.* PMB 2000, Grevillot *et al.* PMB 2011, Smeets *et al.* PMB 2012

Methods for ion range monitoring

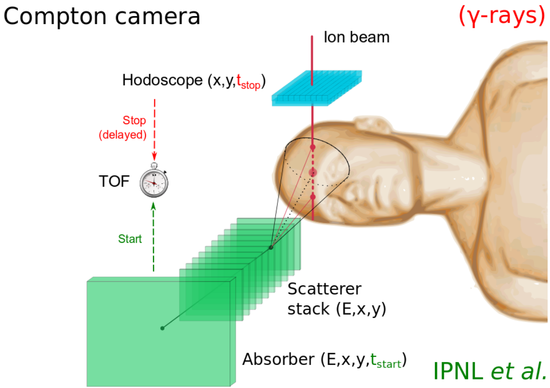








Time-of-flight Compton Camera

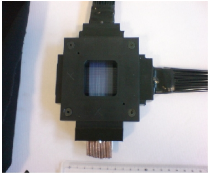


- ≈ 1 gamma per proton/carbon (E_γ up to 10 MeV)
  ⇒ high detection efficiency needed
- neutron background: shielding or use of time-of-flight
- principle: line / cone intersection
- components: hodoscope, scatterer, absorber

Components: hodoscope

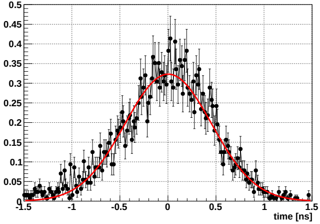
- goals:
  -position resolution 1 mm
  -time resolution 1 ns
  -count rate 10^8 1/s
- array of scintillating fibers (1×1 mm^2 BCF 10/12)

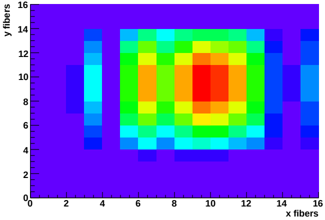
- prototypes: 2×32 and 2×128 fibers
- readout: optical fibers FORETEC
- coupling to multianode PM H-8500



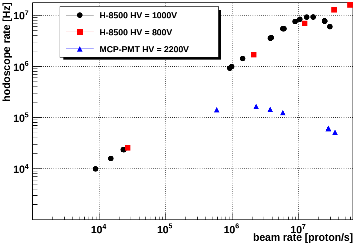
Hodoscope: performance tests

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





- H-8500 $\Leftrightarrow$ MCP-PMT
- max. rate > 10 MHz, for H-8500 at 800 V
- MCP-PMT at 2200 V $\Rightarrow$ less performant

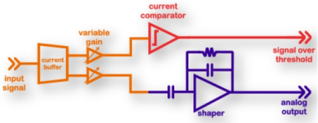


Hodoscope: front end electronics

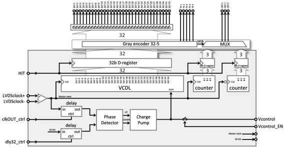
- goals: rate 10^8 1/s, time information,
  analog output (monitoring of fiber aging)

- first version of ASIC:
  - current comparator
  - CSA

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

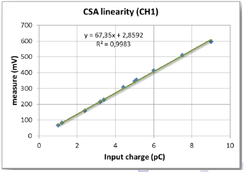


- second version of ASIC:
  - inclusion of time stamper
  - 160 MHz clock + DLL
  - 32 to 5 Gray encoder

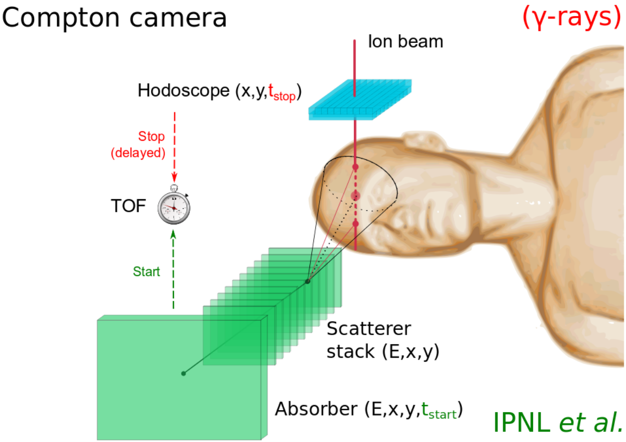


- ASIC currently under test

  L. Caponetto VLSI Marseille (2014)



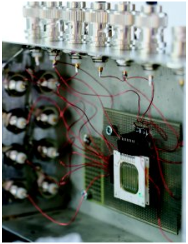
Compton Camera



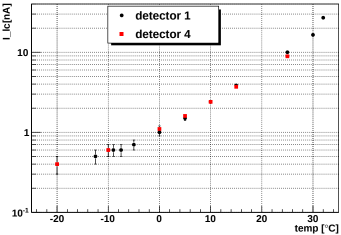
- principle: line / cone intersection
- components: hodoscope, scatterer, absorber

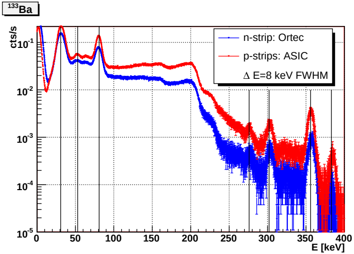
Components: scatter detector

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



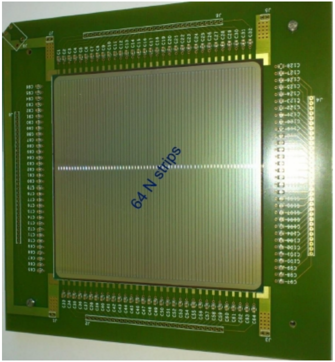
measurement of leakage current and energy resolution





Scatter detector: real size SSD

- large SSD: $90\times90\times2$ mm^3
- 7 planes in total
- 2×64 strips
  (p- and n-side)
- bias voltage -750 V
  (full depletion)
- bonding of detectors
  at IPNL
- PCB: polarization resistors
  decoupling capacitors

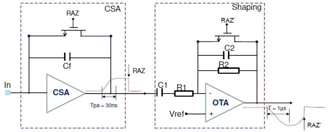


detector under characterization

Scatter detector: front end electronics

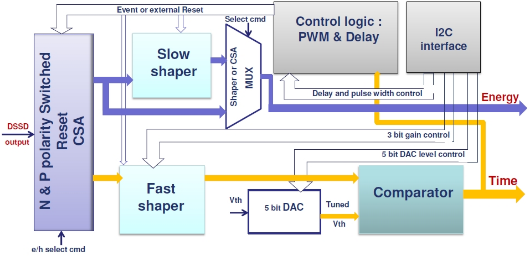
specifications

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



⇒ switched system

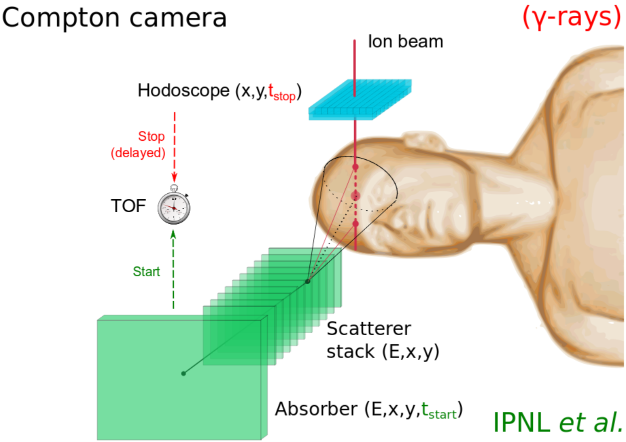
scheme of ASIC for SSD:



- ASIC under test

M. Dahoumane: VLSI Marseille (2014)

Compton Camera



- principle: line / cone intersection
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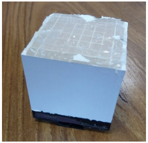
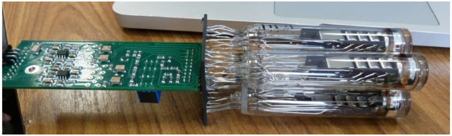
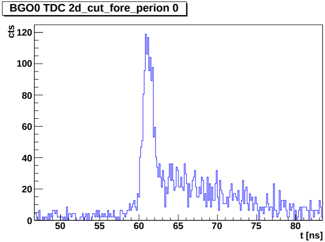
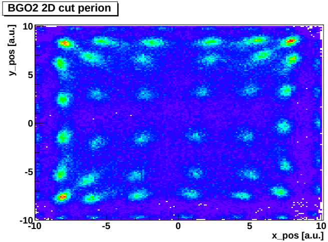
Components: absorber



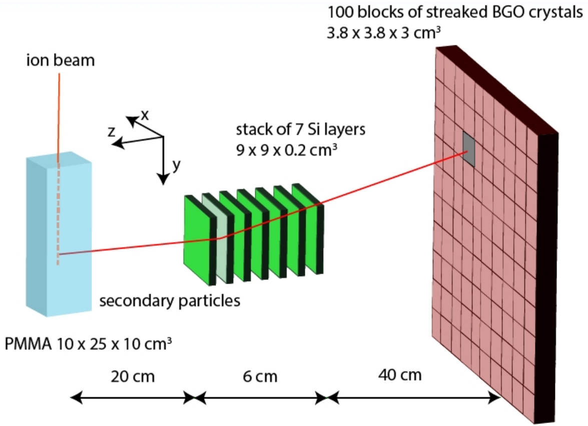


- streaked BGO crystals 35×38×30 mm^3 read by 4 PMs
- 8×8 (pseudo)-pixel, 96 crystals in total
- energy resolution 17% at 511 keV, time resolution 2 ns
- position reconstruction via centroid
- detector assembly and readout electronics: LPC Clermont





Compton Camera: simulation

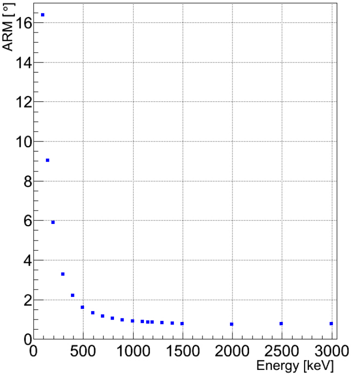


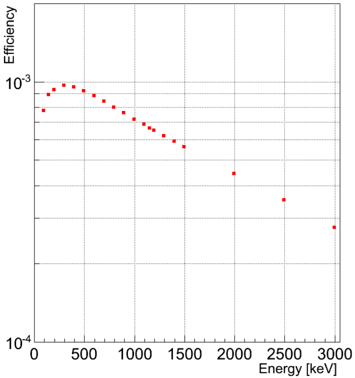
Geant4 simulations

- optimization of the setup
- check of feasibility for medical applications

Simulation: nuclear medicine (SPECT)

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





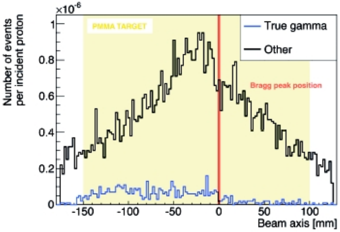
J.L. Ley PhD thesis

Simulation: hadrontherapy

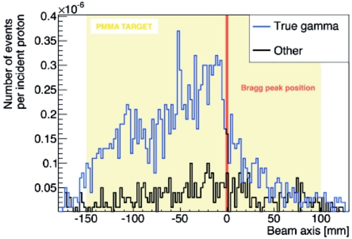
simulation parameters:

- 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



J.L. Ley PhD thesis

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 μ-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

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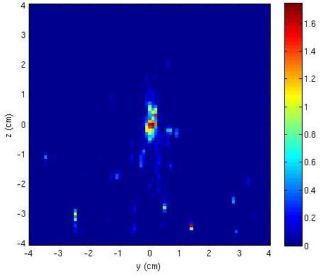
FP7-ENVISION (WP3, WP6), FP7-ENTERVISION, FP7-ULICE, ANR Gamhadron project, Rhône-Alpes Regional Program for Hadrontherapy Research, MI2B GDR, LabEx PRIMES

backup: reconstruction

- development of analytical and iterative algorithms (CREATIS Lyon)
- iterative algorithm MLEM

- point source of prompt γ
- camera 10×10 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

plane⊥camera, 1cm slice



Lojacono *et al.* GRETSI'11 2011