A beam hodoscope for ion therapy monitoring by means of secondary radiations

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607. Haereus Seminar
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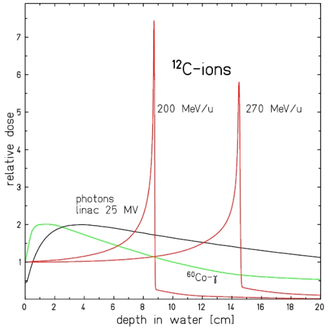
Bad Honnef

Introduction

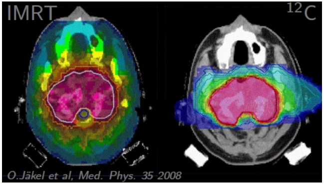
hadrontherapy = tumor treatment with protons or carbon ions

conventional radiotherapy vs hadrontherapy

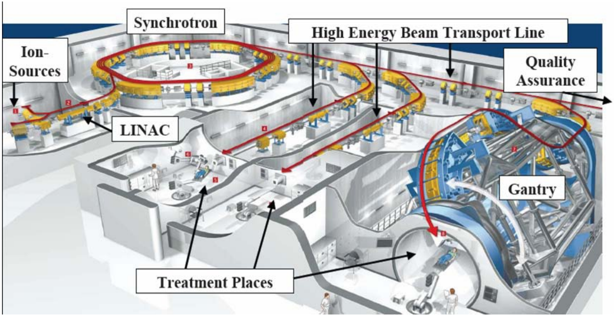


[D. Schardt Rev. Med. Phys. 2010]

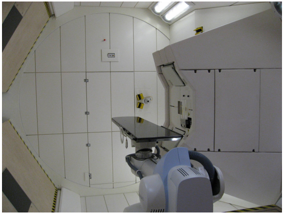
- Bragg peak
- higher RBE
  relative biological effectiveness



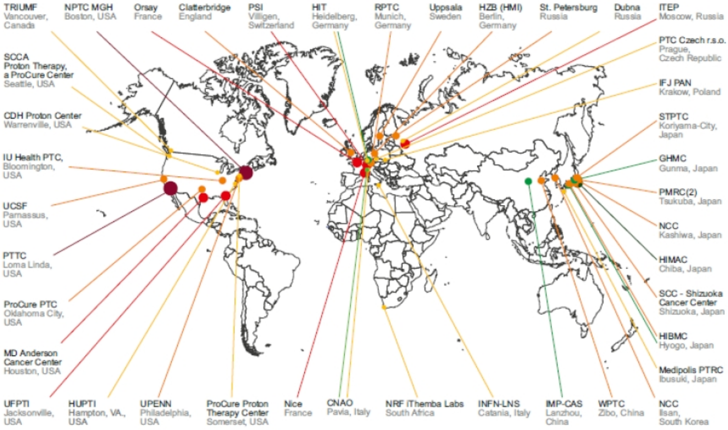
The Heidelberg Ion Therapy center (HIT)

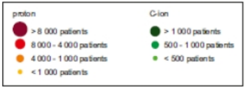


[Th. Haberer Cern Accelerator School 2012]



Hadrontherapy worldwide

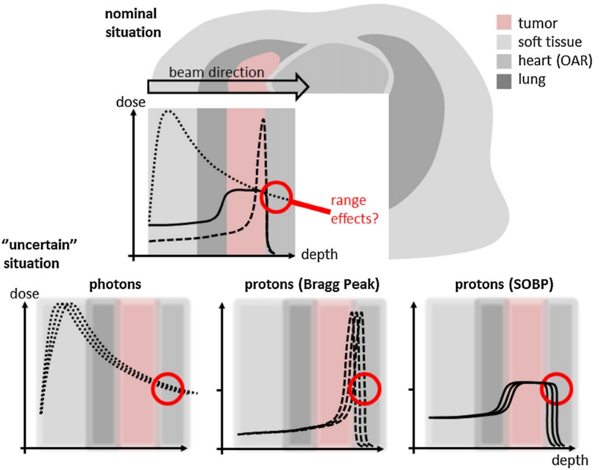




- 55 centers in operation
- 34 centers under construction
- 16 centers in planning phase
- strong growth in the number of centers

[http://www.ptcog.ch/]

Hadrontherapy: sensitivity to range uncertainties

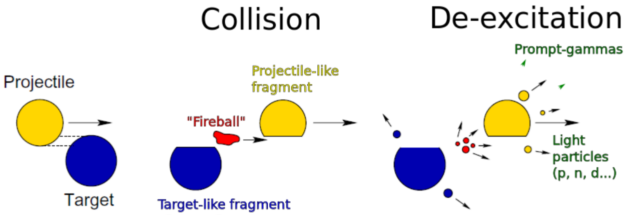


[Knopf et al. Phys. Med. Biol. 2013]

- safety margins ($\approx$ 3 % + 1.2 mm) [H. Paganetti PMB 2012]
  $\Rightarrow$ full potential not yet exploited
- $\Rightarrow$ online monitoring highly desired

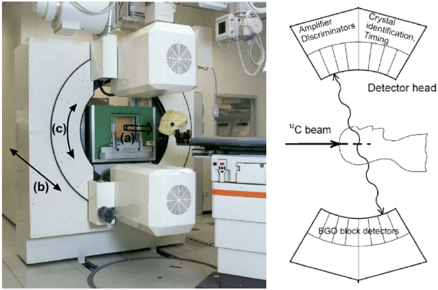
Nuclear reactions

phases and products



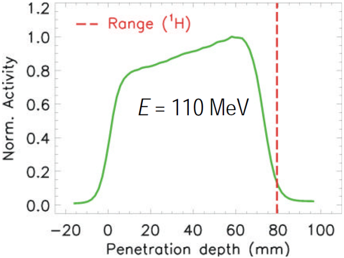
- projectile-like and target-like fragments
  e.g. β^+ emitters: ^{11}C, ^{15}O, ...
  $\Rightarrow$ PET monitoring (offline)
- prompt γ-rays, neutrons, light charged particles
  $\Rightarrow$ real-time monitoring
- high probability (for ranges $\sim$10 cm)
  $\sim$10% for protons, $\sim$40% for carbons

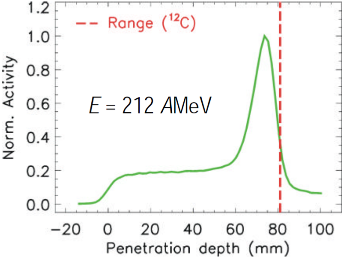
PET monitoring



- detection of gammas (positron annihilation)
- activity distributions
- p: target fragments
- ^{12}C: from projectiles
- biological washout

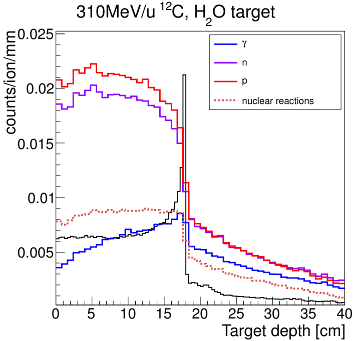
[Enghardt et al. NIM A 2004]





Prompt secondary radiation for ion range monitoring

emission yields (Geant4 9.4)



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 PMB 2000], [Grevillot PMB 2011], [Smeets PMB 2012]

- correlation between ion range and nuclear reaction depth profile
- radiation for real-time monitoring of the ion range:
  - prompt γ-rays (energy up to $\sim$10 MeV
  - light charged particles (mainly from projectile fragmentation)

Hadrontherapy: Context

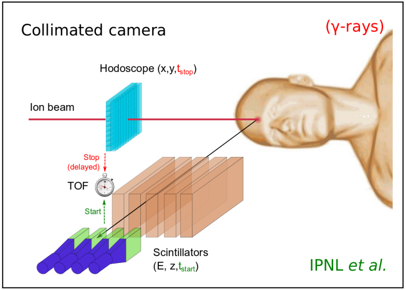
Beam parameters

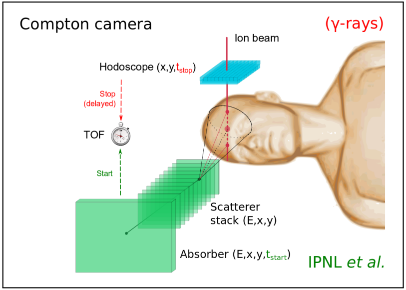
- proton therapy: cyclotron (e.g IBA C230)
  - bunch length: 2 ns
  - time between bunches: 10 ns
  - 200 protons per bunch
- carbon ion therapy: synchrotron (HIT/CNAO)
  - bunch length: 20-40 ns
  - time between bunches: 200 ns
  - 10 ions per bunch

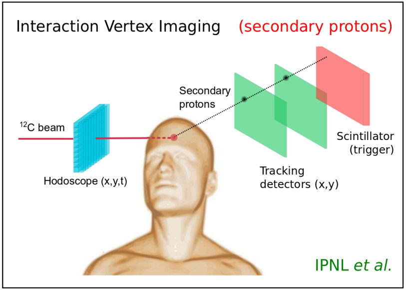
Specifications for beam monitoring

- count rate: 100 MHz
- time resolutions: 1 ns
- spatial resolution: 1 mm
- irradiated matrix: 15×15 cm^2

Hadrontherapy: real-time monitoring





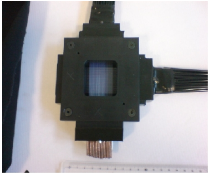


- *passive* collimation
  - multi-slit
  - knife-edge
- *electronic* collimation
  - Compton camera
- charged particles
  - proton IVI

Common device: beam tagging hodoscope

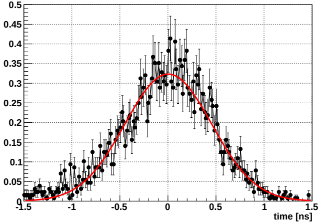
- goals:
  -position resolution 1 mm
  -time resolution 1 ns
  -count rate 10^8 1/s
- array of scintillating fibers (1×1 mm^2 BCF 10/12)

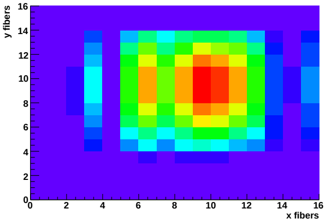
- prototypes: 2×32 and 2×128 fibers
- readout: optical fibers FORETEC
- coupling to multianode PM H-8500



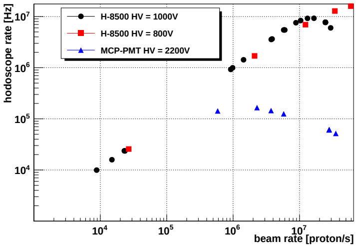
Hodoscope: performance tests

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



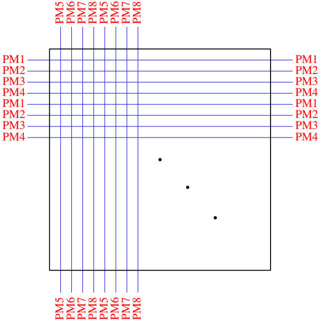


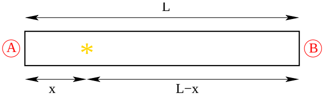
- H-8500 $\Leftrightarrow$ MCP-PMT
- max. rate > 10 MHz, for H-8500 at 800 V
- MCP-PMT at 2200 V $\Rightarrow$ less performant



Hodoscope: distribution of signals

- distribute signals from neighboring fibres to different PMs
  $\Rightarrow$ increase of maximum count rate
- read fibres from both sides:
  $\Rightarrow$ increase of efficiency
  $\Rightarrow$ timing independent on hit position

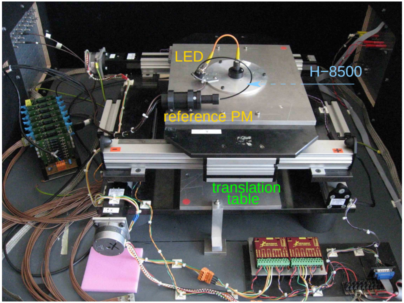


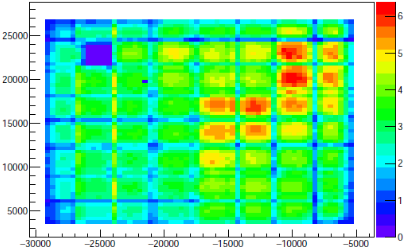


- $t_A = \frac{x}{c}$, $t_B = \frac{L-x}{c}$
- $\bar{t} = \frac{1}{2}(t_A + t_B) = \frac{1}{2}\frac{L}{c}$

Hodoscope: Test bench for multianode PMs

- 8 PMs H-8500 to characterize
- 64 channels each
- LED on translation table
- reference PM to compensate for variations
- automatic measures via LabView
- variation in gain for different pixels
  factor 2-3



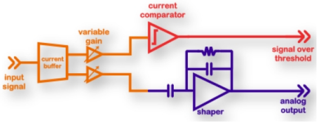


Hodoscope: front end electronics

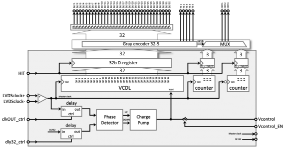
- goals: rate 10^8 1/s, time information,
  analog output (monitoring of fiber aging)

- first version of ASIC:
  - current comparator
  - CSA

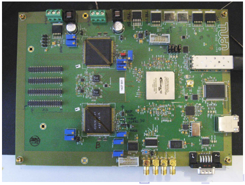
  S. Deng *et al.* NIM A 695 (2012)



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

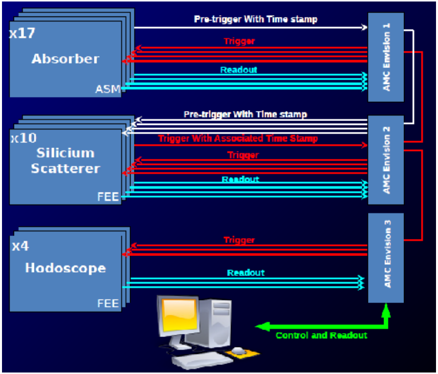


- ASIC + DAQ card tested
  final version in production



Fast DAQ system: μ-TCA

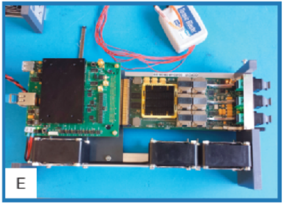
acquisition diagram



[C. Abellan ICTR-PHE 2014]

μ-TCA crate

AMC board (CPPM)



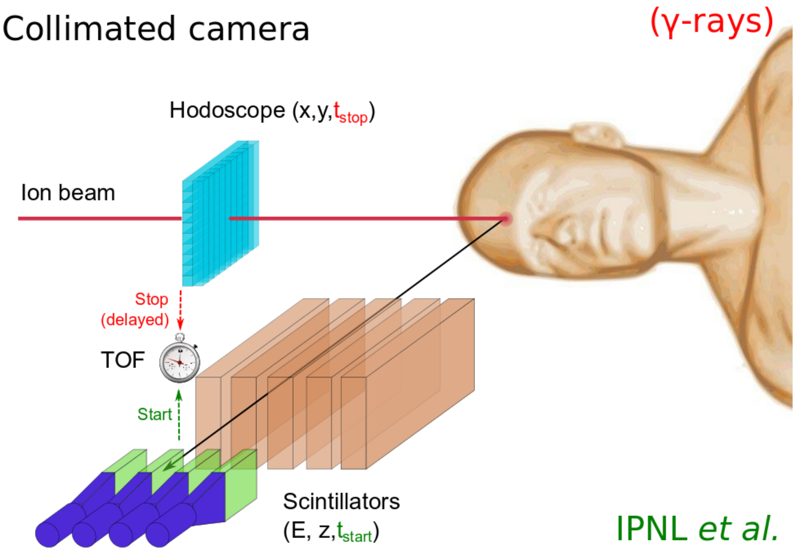
- front-end electronics: IPNL Lyon, LPC Clermont
- AMC board: CPPM Marseille

Alternative approach: Diamond detectors

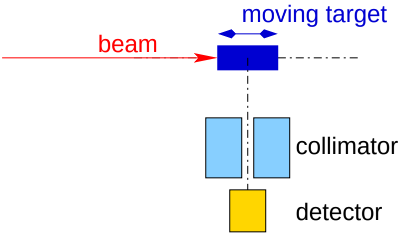
MONIDIAM project (LPSC Grenoble)

- fast response,
  high count rate capability
- radiation hardness
- production: PECVD (Plasma Enhanced Chemical Vapor Deposition)
- maximum size:
  50×50 mm^2 polycrystalline,
  7×7 mm^2 monocrystalline
- tests: ^{241}Am source (alpha 5.4 MeV)
  95 MeV/u ^{12}C at GANIL
- perspectives: ASIC development,
  thinning to 200-300 μm

prompt-γ detection with collimated detectors



prompt-γ detection with collimated detectors



target

- on a moving table
- PMMA, H_2O, ...

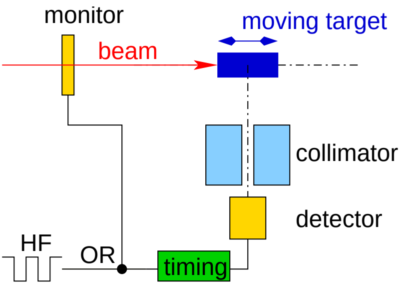
collimator

- material: tungsten, Pb

scintillation detector

- $LaBr_3$, LYSO, BGO, ...

prompt-γ detection with collimated detectors



target

- on a moving table
- PMMA, H_2O, ...

collimator

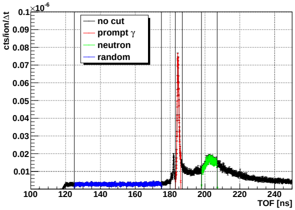
- material: tungsten, Pb

scintillation detector

- $LaBr_3$, LYSO, BGO, ...

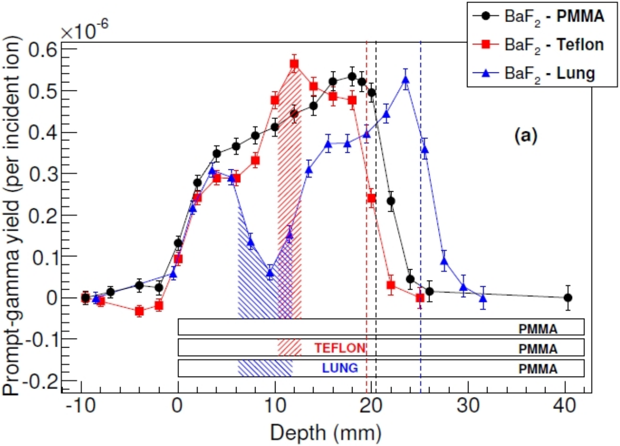
Time-of-Flight (TOF) measurements

- reduction of neutron background
- time reference:
  - monitor detector intercepting the beam (synchrotron)
  - accelerator HF (cyclotron)



prompt-γ profiles: heterogeneous targets

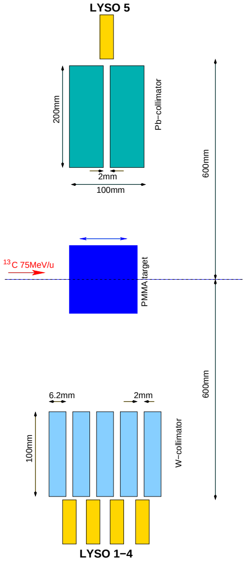
95 MeV/u ^{12}C (GANIL)



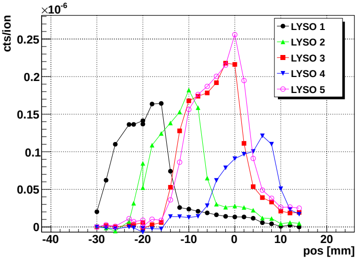
- influence of heterogeneities close to Bragg peak
  $\Rightarrow$ change in ion range

[M. Pinto et al. Med. Phys. 2015]

prompt-γ profiles: multislit collimator



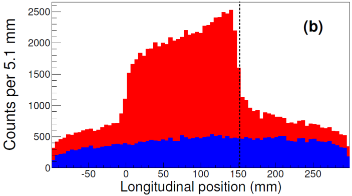
^{13}C 75 MeV/u (GANIL)

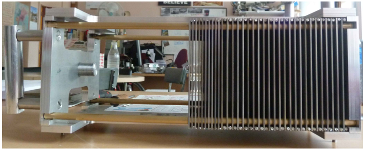


[J.K. et al. JINST 2015]

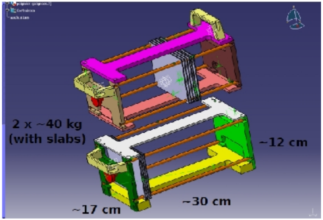
- carbon beams at GANIL and GSI
- prompt-γ profiles
- inter-detector scattering $\Rightarrow$ contribution < 10 %

Collimated cameras: multislit (IPNL)

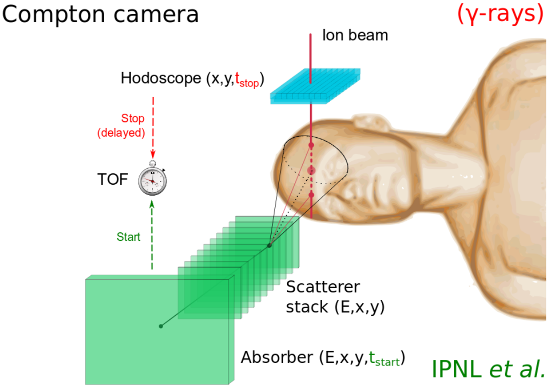




- collimator optimized for falloff retrieval precision
  $\Rightarrow$ expected $\sigma \sim 1$ mm for 10^8 protons ($\triangleq$ 1 spot)
  [M. Pinto et al. PMB 2014]
- 20 cm height (2 layers)
- BGO detectors



Compton camera (TOF): principle

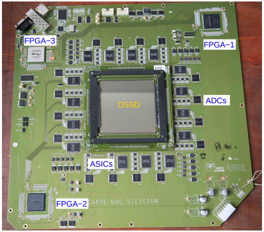


- idea: replace passive by *electronic* collimation
  $\Rightarrow$ potential increased efficiency
- 3 D information available
- here: line / cone intersection
- components: hodoscope, scatterer, absorber

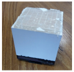
Compton camera: components

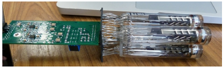
- beam tagging hodoscope

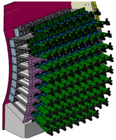
- scatter detectors



- absorber

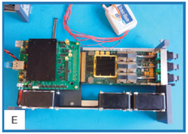






- streaked BGO
  64 pseudo pixel
- total 96 crystals
- LPC Clermont

- μ-TCA DAQ system

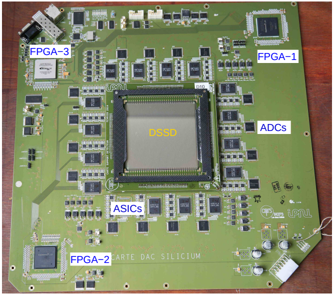


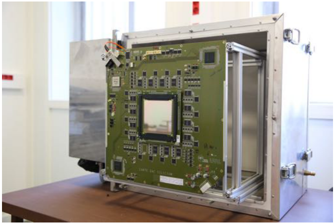
IPNL Lyon, LPC Clermont,
CPPM Marseille

[J.K. et al. NIM A 2015]

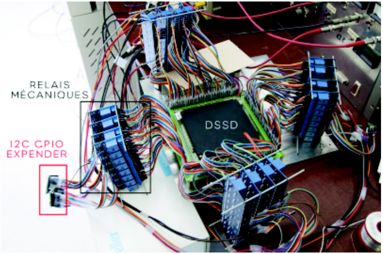
Components: scatter detector

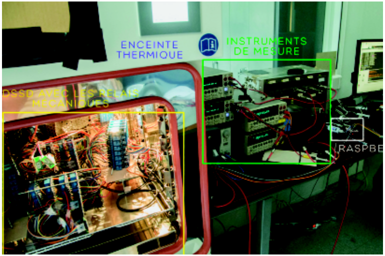
- double sided silicon strip detectors
- size: $90 \times 90 \times 2$ mm^3
- 7 planes in total
- 2×64 strips (p- and n-side)
- front-end electronics ASICs (8 ch.), low noise, 1×10^5 cts/s slow (1 μs) and fast (15 ns) shaping
- cooling system

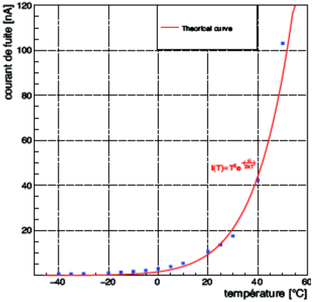


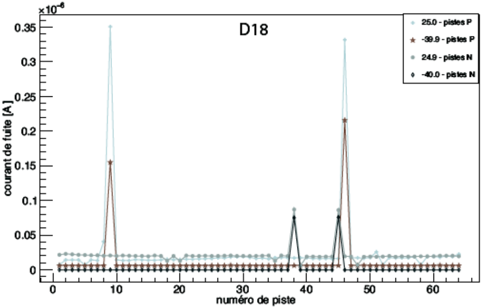


Scatter detector: leakage currents





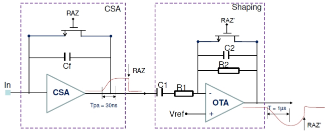




Scatter detector: front end electronics

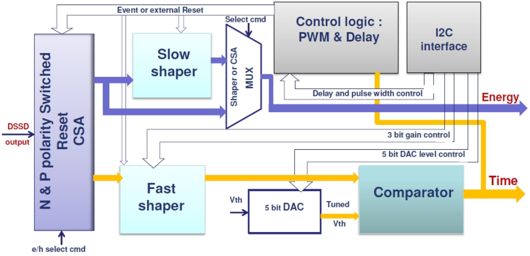
specifications

- 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



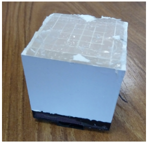
$\Rightarrow$ switched system

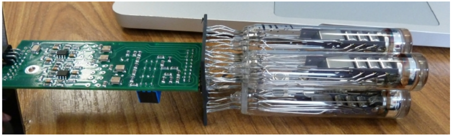
scheme of ASIC for SSD:



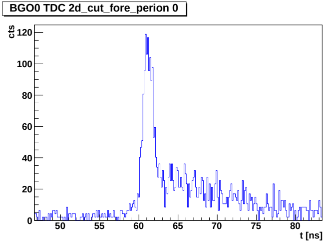
[M. Dahoumane et al. IEEE NSS/MIC (2014)]

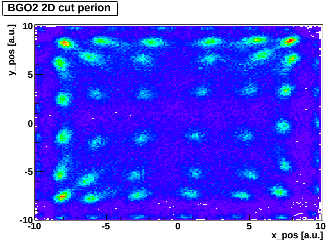
Components: absorber





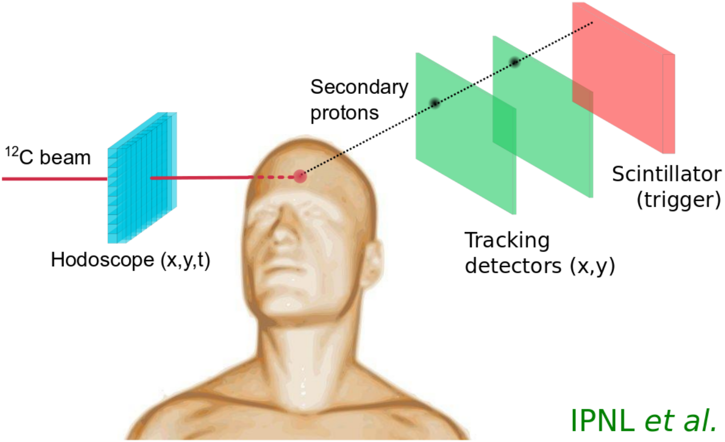
- streaked BGO crystals $35\times38\times30$ mm^3 read by 4 PMs
- 8×8 (pseudo)-pixel, 96 crystals in total
- energy resolution 17% at 511 keV, time resolution 2 ns
- detector assembly and readout electronics: LPC Clermont
- position reconstruction via centroid





[J.K. et al. NIM A 2014]

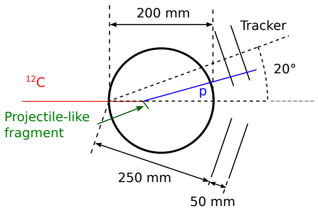
Interaction Vertex Imaging (secondary protons)

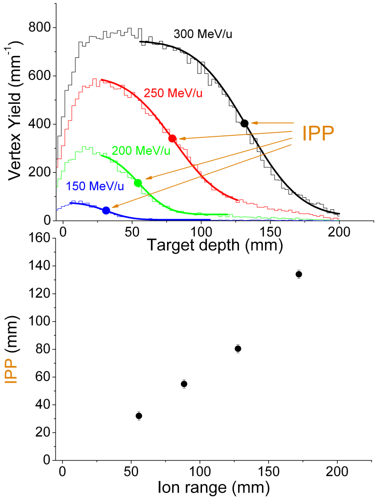


IPNL *et al.*

proton IVI Simulations (head like phantom)

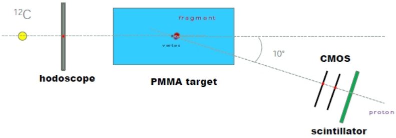
[P. Henriquet et al. PMB 2012]





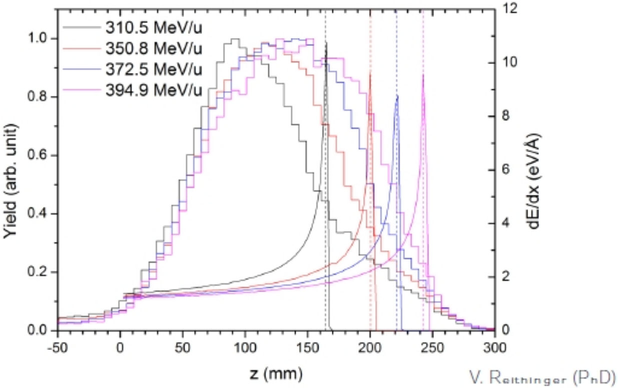
- various ^{12}C energies
- fit of error function
- Inflection Point Position
- correlation with energy
- ion range monitoring
- millimetric precision for homogeneous target, single-spot basis (PBS)

proton IVI measurements: homogeneous targets

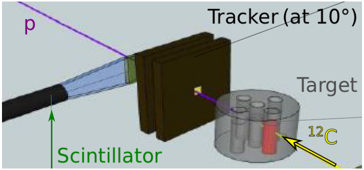


- CMOS detectors: MIMOSA 26 IPHC Strasbourg
- measurement at HIT

[V. Reithinger et al. PTCOG 2013]

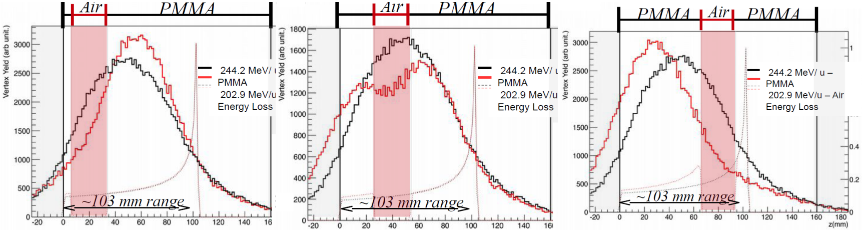


proton IVI measurements: heterogeneous targets



- measurements at HIT
- target: PMMA cylinder with inserts “bone” and “air”
- normalization to integrals

- “air” inserts at 3 positions ⇒ dip at insert position



[R. Rescigno ICTR-PHE 2014]

Summary

beam tagging hodoscope

- scintillating fibers
- diamond detectors

ion therapy monitoring

- prompt-γ detection: collimated- and Compton camera
- charged particles: proton IVI

Outlook

- towards clinical application
- realistic phantoms
- improvement of simulations
  $\Rightarrow$ prediction of signals

thank you very much for your attention

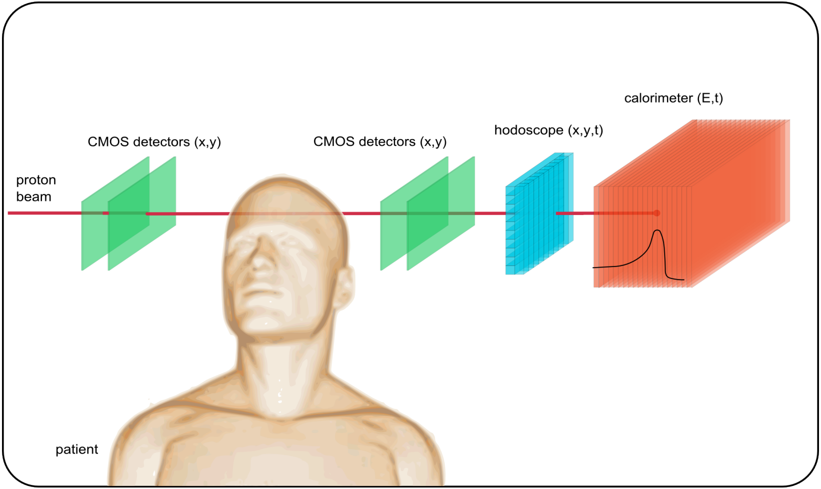
collaborators / institutions

- IPNL Lyon
- CREATIS Lyon
- IPN Orsay
- LPC Clermont
- CPPM Marseille
- IPHC Strasbourg
- CAL Nice
- GANIL Caen
- HIT Heidelberg
- GSI Darmstadt
- WPE Essen
- IBA
- ...

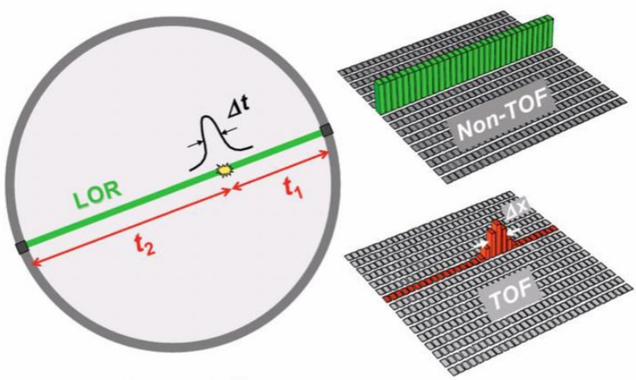
acknowledgements

France Hadron, ANR, FP7 Envision, FP7 Entervision, FP7 Ulice, LabexPrimes, PRRH

backup: proton radiography (proton CT)



backup: Time-of-Flight PET



$\Delta x = c\Delta t/2$

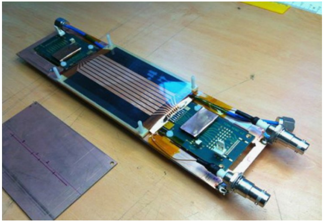
100ps resolution ⇔ 1.5 cm

- use of TOF information ⇒ increased SNR

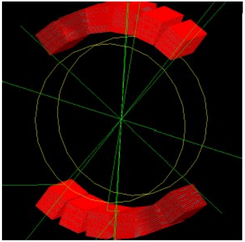
backup: In Beam TOF-PET

- small activity produced, in comparison to diagnosis
- short half lifes: ^{11}C (20 min.), ^{15}O (2 min.),...
- preferred solution: in beam TOF-PET
  with sub-ns time resolution

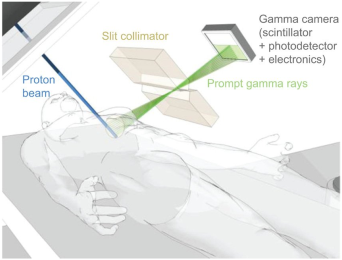
- study of configurations and detection methods
  - scintillator-based TOF-PET
  - RPC-based TOF-PET (MRPC)
- Coincidence Resolving Time CRT in the order of 200 ps



[Amaldi et al. NIM A 2015]



backup: Collimated cameras: knife-edge (IBA)



- principle: slit-hole camera
  [Bom PMB 2012]
- prototype optimization: falloff retrieval precision $\sim$ 1 mm for a distal spot
  [Smeets PMB 2012]
- tests with prototype and IBA C230 cyclotron
  [Perali PMB 2014]
- investigations with anthropomorphic phantoms in progress