On-line monitoring for particle beams

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Department of Physics “E. Fermi”, University of Pisa and INFN, Italy

The 3° ELIMED Workshop:
Medical and multidisciplinary applications of laser-driven ion beams at ELI-Beamlines

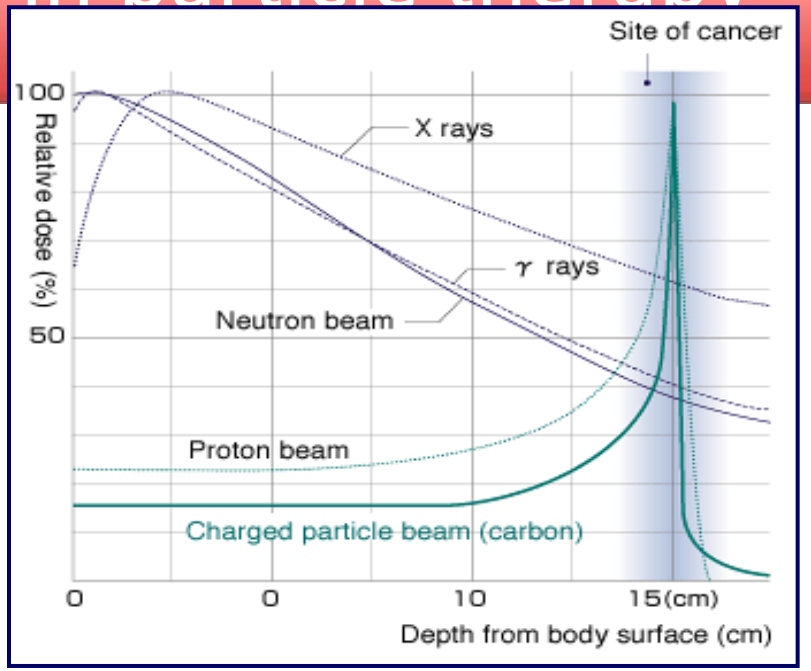
Uncertainties-monitoring in particle therapy

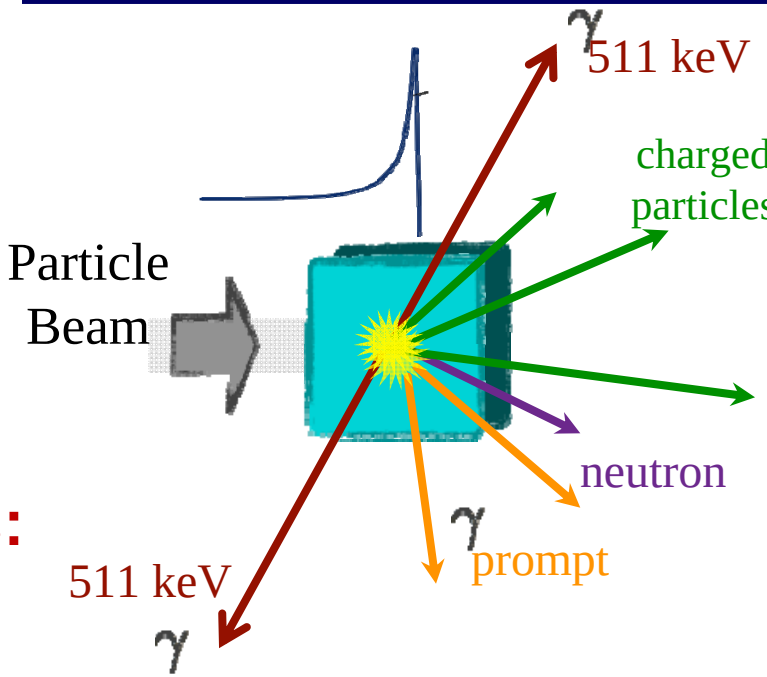
- CT HU (e.g. calibration apparatus)
- conversion to proton stopping power
- dose calculation uncertainties

- daily positioning on the couch
- internal organ motion
- tumour regression
- weight loss

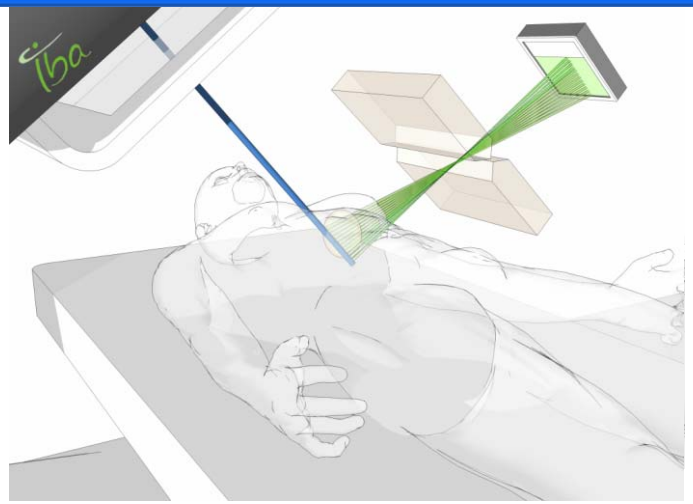
- RBE values
- Tumor heterogeneity
- Contouring uncertainties
- Reconstruction artifacts in CT
- Machine related

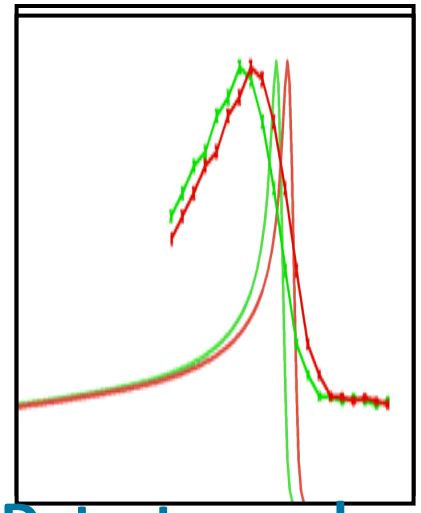
safety margins:
3% + 3mm





A Prompt Gamma Camera for real-time range control in Proton therapy





Intended application:

Measurement of the position at which the proton beam stops in the patient

Camera configuration

Knife-edge slit collimation and 1D detection of γ-ray profiles

Points of attention:

Simplicity, cost effectiveness

Collimator, software and project PI

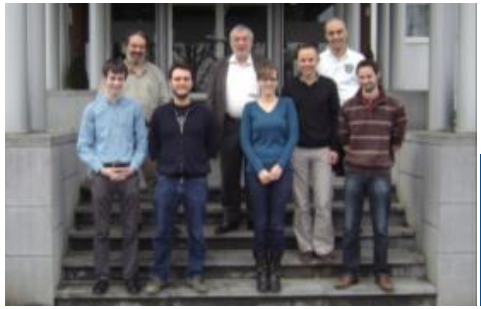
Detector and Electronics

Clinical partner

UCL Université catholique de Louvain

imagX UCL & IBA

iba



fnrs La liberté de chercher

ULB

Politecnico Milano

INFN

XGLAB X and Gamma Ray Electronics

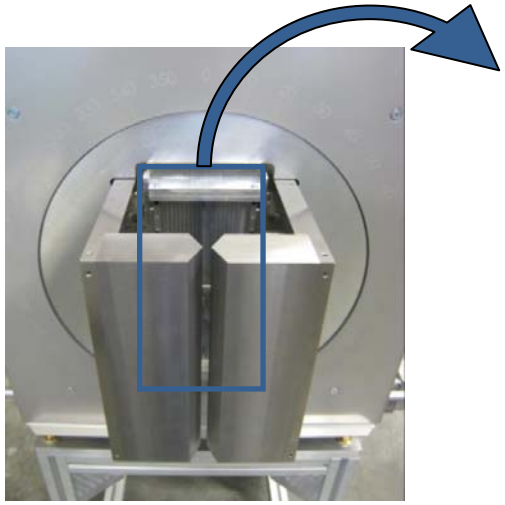
OncoRay National Center for Radiation Research in Oncology Dresden

Technische Universität Dresden

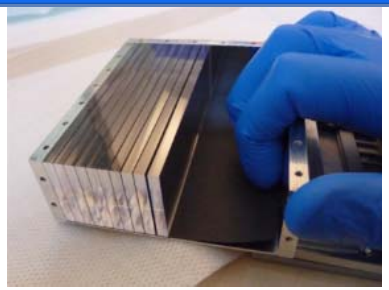
HZDR

and others…

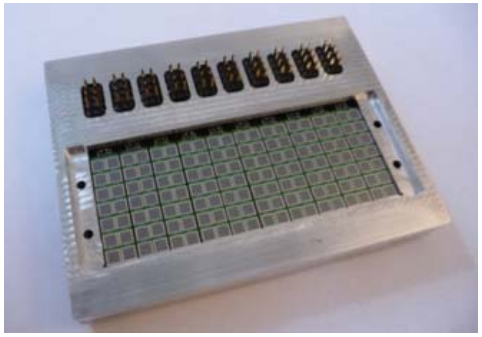
The Gamma Camera: detector and electronics



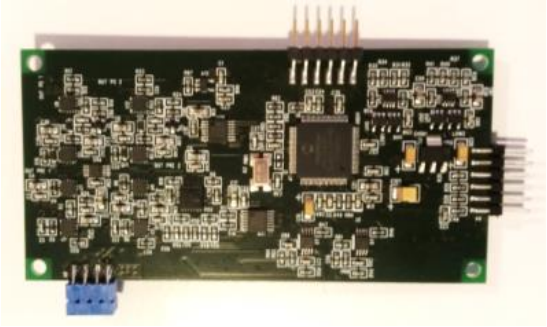
53 kg W collimator in 5:4 magnification for a 10 cm FOV



500 cm³ LYSO distributed in 2 rows of 20 slabs



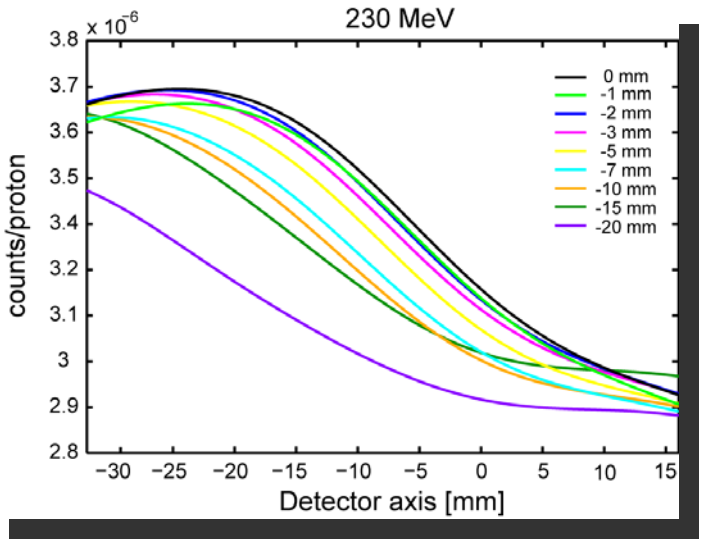
Light readout of one extremity of each LYSO slab by a row of 7 SiPM



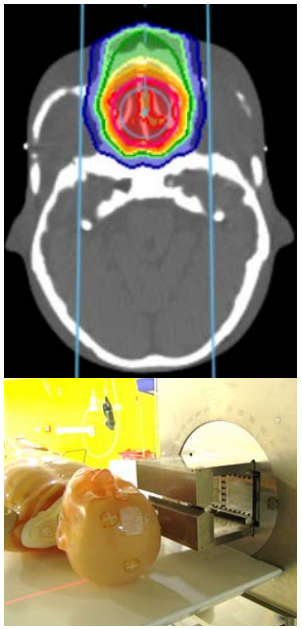
40 independent acquisition channels operating in two modes (slow calibration and fast counting)

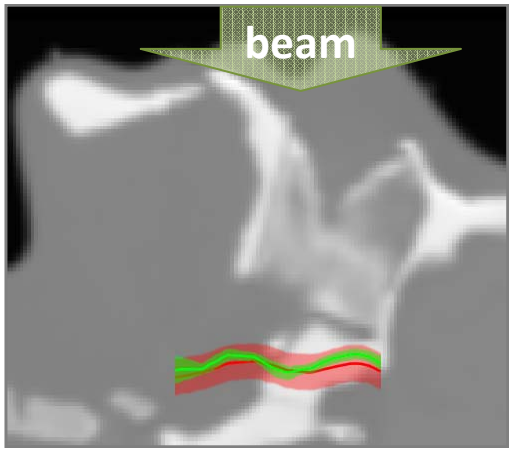
Experimental validation

Shift measurements



Nasal cavity





Planning uncertainty **> 5 mm**
(margin of 3.5% + 2 mm)
Measurement uncertainty (1.5σ)
≈ 2.0 mm

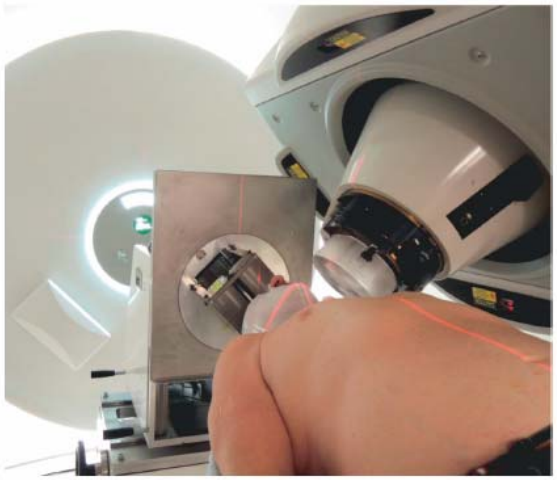


Fig. 1. PGI slit camera trolley (upper row) and its application during patient treatment (lower row).

Contents lists available at ScienceDirect

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journal homepage: www.thegreenjournal.com

Original article

First clinical application of a prompt gamma based *in vivo* proton range verification system

Christian Richter [a,b,c,d,e,*], Guntram Pausch [a,b,c], Steffen Barczyk [a,b], Marlen Priegnitz [c], Isabell Keitz [a], Julia Thiele [b], Julien Smeets [f], Francois Vander Stappen [f], Luca Bombelli [g], Carlo Fiorini [h], Lucian Hotoiu [f], Irene Perali [h], Damien Prieels [f], Wolfgang Enghardt [a,b,c,d,e], Michael Baumann [a,b,c,d,e]

[a] OncoRay – National Center for Radiation Research in Oncology, Faculty of Medicine and University Hospital Carl Gustav Carus, Technische Universität Dresden, Helmholtz-Zentrum Dresden – Rossendorf; [b] Department of Radiation Oncology, Faculty of Medicine and University Hospital Carl Gustav Carus, Technische Universität Dresden; [c] Helmholtz-Zentrum Dresden – Rossendorf; [d] German Cancer Research Center (DKFZ), Heidelberg; [e] German Cancer Consortium (DKTK), Dresden, Germany; [f] Ion Beam Applications SA, Louvain-la-Neuve, Belgium; [g] XGLab S.R.L., Milano; and [h] Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Italy

Radiotherapy and Oncology, *2016* Feb;118 (2): 232-7

The InSide Project

INnovative Solutions for In-beam DosimEtry in Hadrontherapy

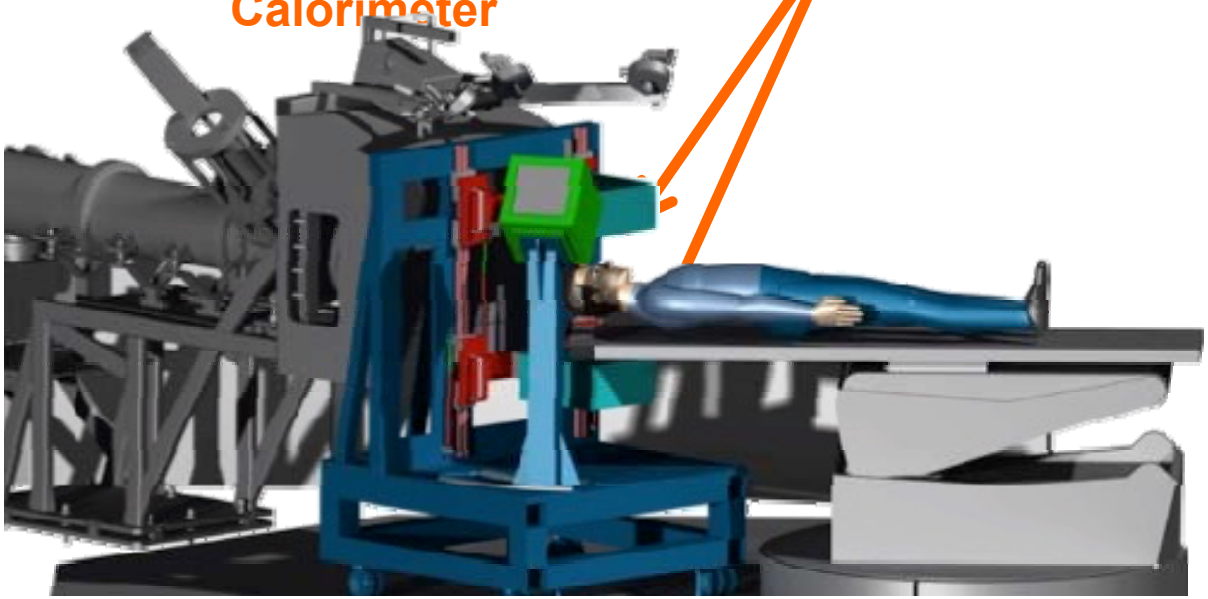
Prompt secondary particles emission

DOSE PROFILER + Tracker + Calorimeter

β^+ activity distribution

IN-BEAM PET HEADS

MULTIMODAL RANGE MONITORING SYSTEM



Features:

- integrated in the nozzle
- operated beam-on
- **provide in vivo particle range on-line**

More on INSIDE
http://131.114.131.146/insidewiki

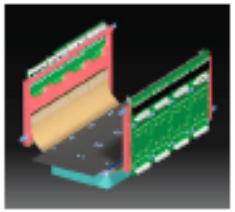
N. Belcari, M. G. Bisogni, N. Camarlinghi, A. Del Guerra, S. Ferretti, E. Kostara, A. Kraan, N. Marino, M. Morrocchi, M.A. Piliero, G. Pirrone, V. Rosso, G. Sportelli

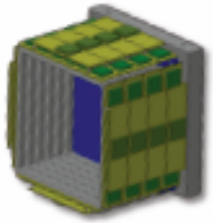
P. Cerello, S. Coli, E. Fiorina, G. Giraudo, F. Pennazio, C. Peroni, A. Rivetti, R. Wheadon, A. Attili, S. Giordanengo

E. De Lucia, R. Faccini, P.M. Frallicciardi, M. Marafini, C. Morone, V. Patera, L. Piersanti, A. Sarti, A. Sciubba, C. Voena

F. Ciciriello, F. Corsi, F. Licciulli, C. Marzocca, G. Matarrese

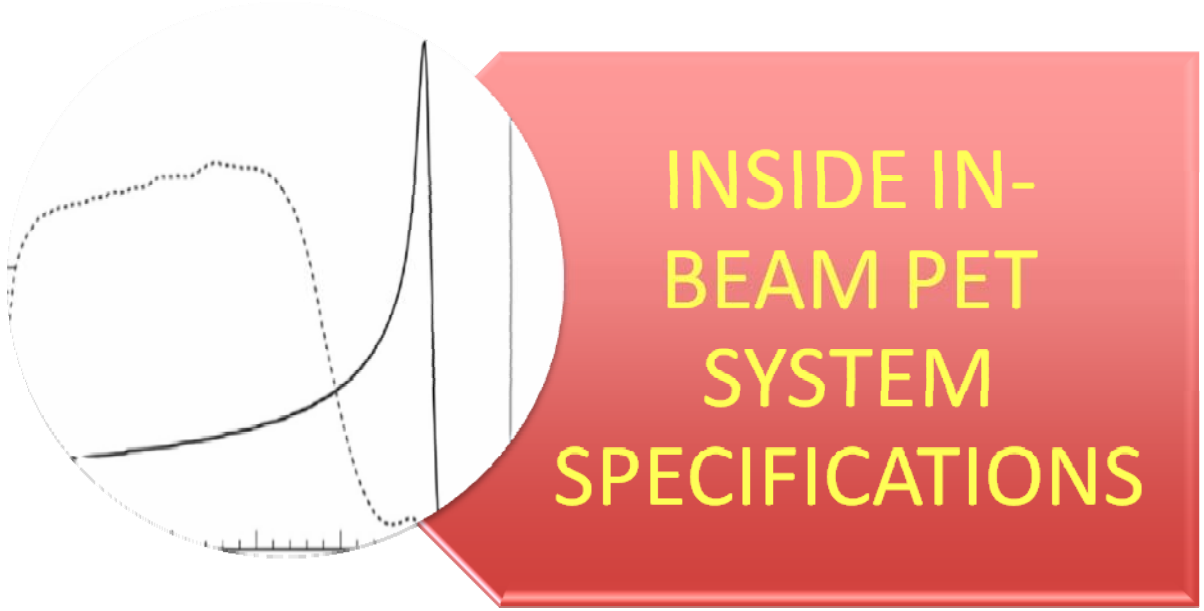
INSIDE at CNAO





	IN-BEAM PET HEADS	DOSE PROFILER
Signal	β+ decay	Secondary (charged) particles
Acquisition	In-spill, inter-spill, after-treatment	In-spill
Position	❑ heads face to face ❑ perpendicular to the beam axis ❑ fitted position wrt the isocenter	❑ forward direction ❑ 60° wrt the beam axis.
Distance from beam isocenter	25 cm	~ 40 cm
Output	3D activity map / profile	Emission point distribution

INSIDE



INSIDE IN-BEAM PET SYSTEM SPECIFICATIONS

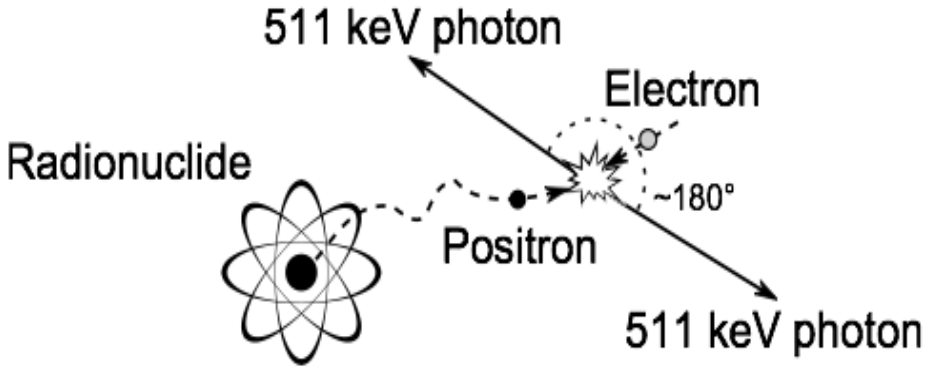
Proton therapy monitoring using PET

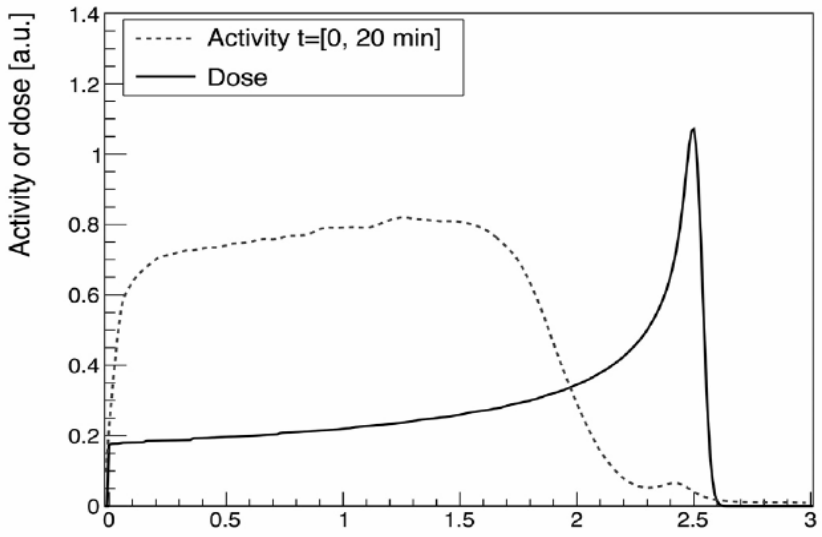
Proton as a projectile

$^{16}O\ (p,n)\ ^{15}O$ $T_{1/2\text{-}15\text{-}O}$=121.8 s

$^{12}C\ (p,n)\ ^{11}C$ $T_{1/2\text{-}11\text{-}C}$=1222.8 s

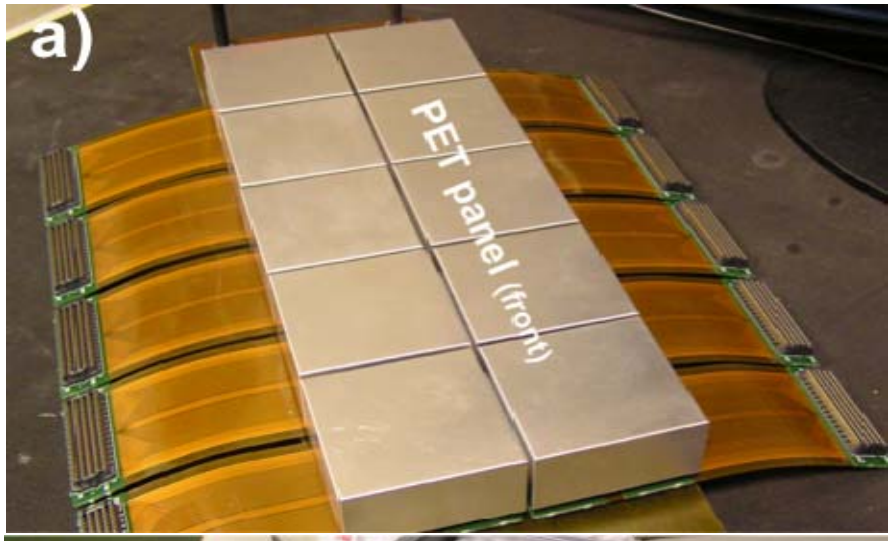
58 MeV p on PMMA

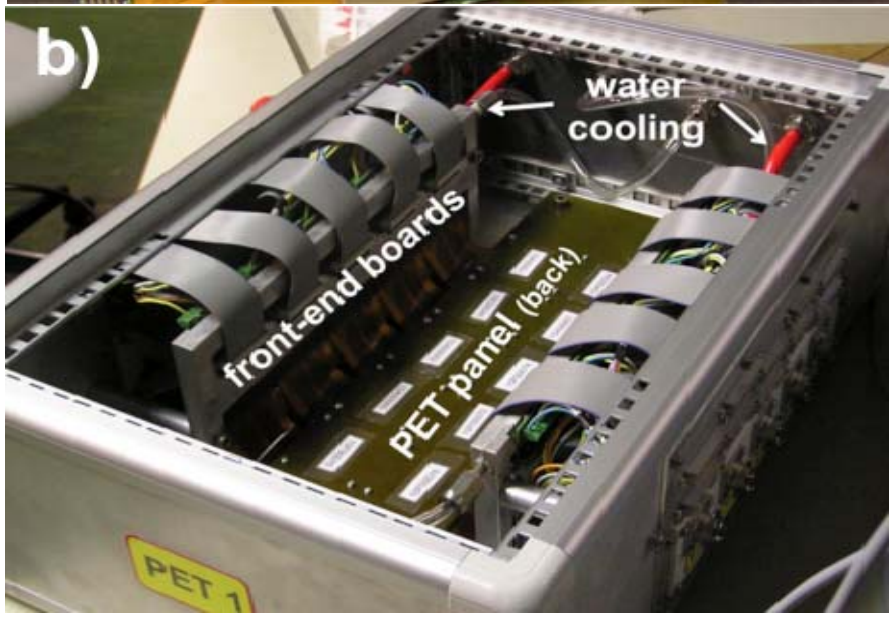




Measuring the β^+ activated volume it's possible to monitor the treatment

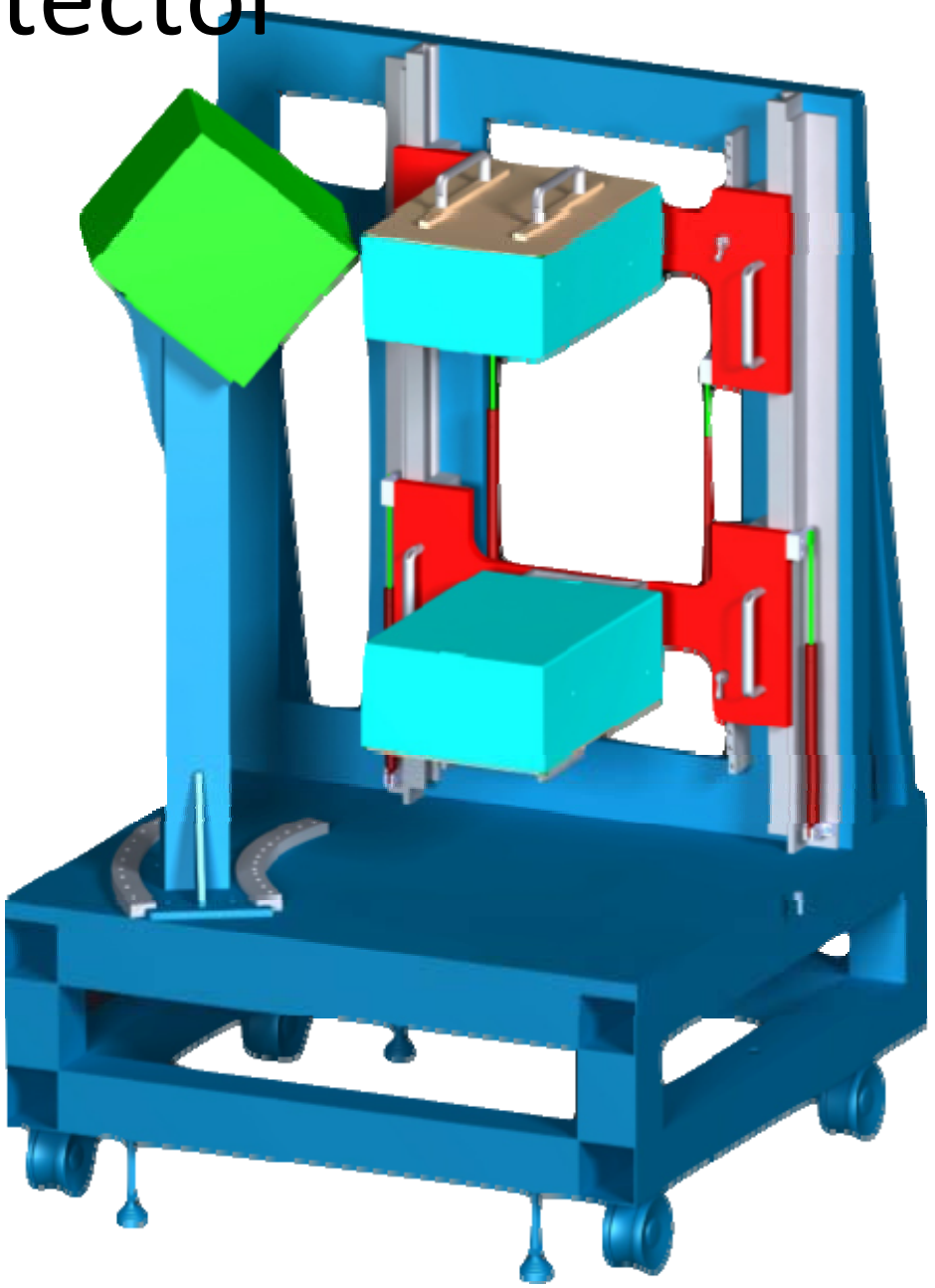
In-beam PET at CNAO





InSIDE PET Detector

- Full in-beam (full-beam) PET system ~20 MHz single event rate beam-on
- Two planar panels 10 x 25 cm wide. 2 x 5 detection modules.
- 5120 read-out channels
- pixelated LFS array (16 x 16 pixels, 3 x 3 mm crystals, pitch 3,1 mm), sensitive area of 5 x 5 cm.
- SiPMs (16x16 pixels) coupled one-to-one to LFS crystals



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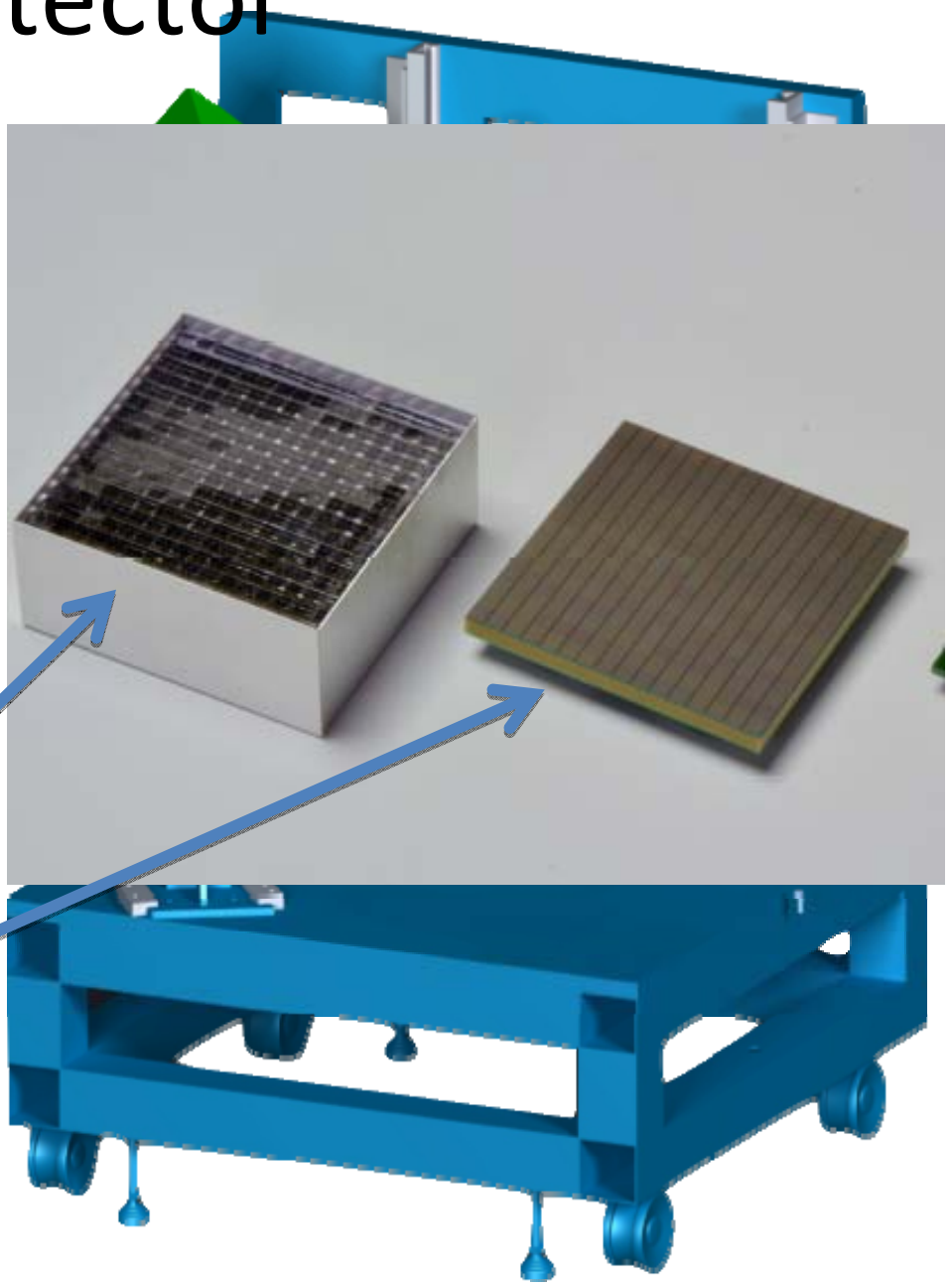
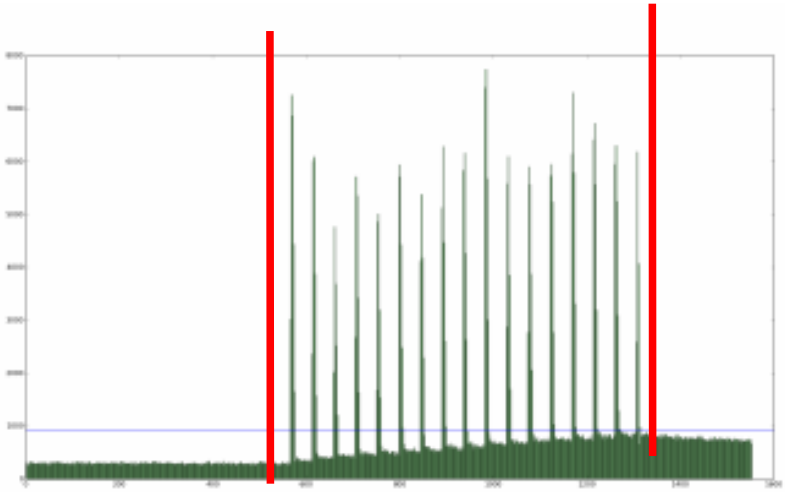
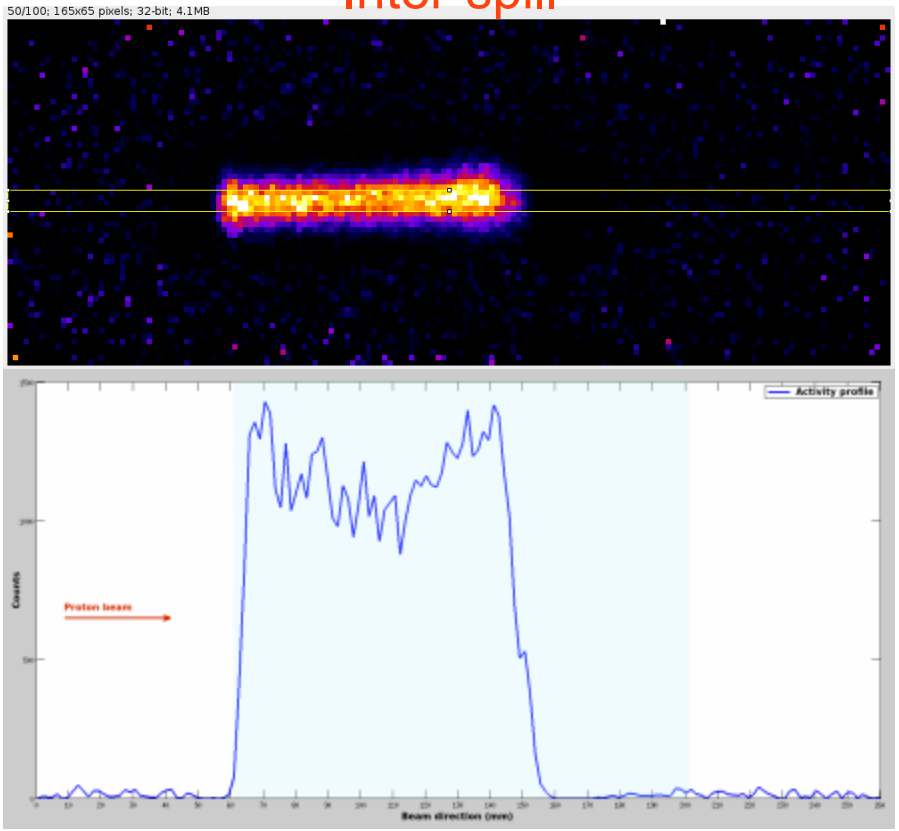


PET system at CNAO

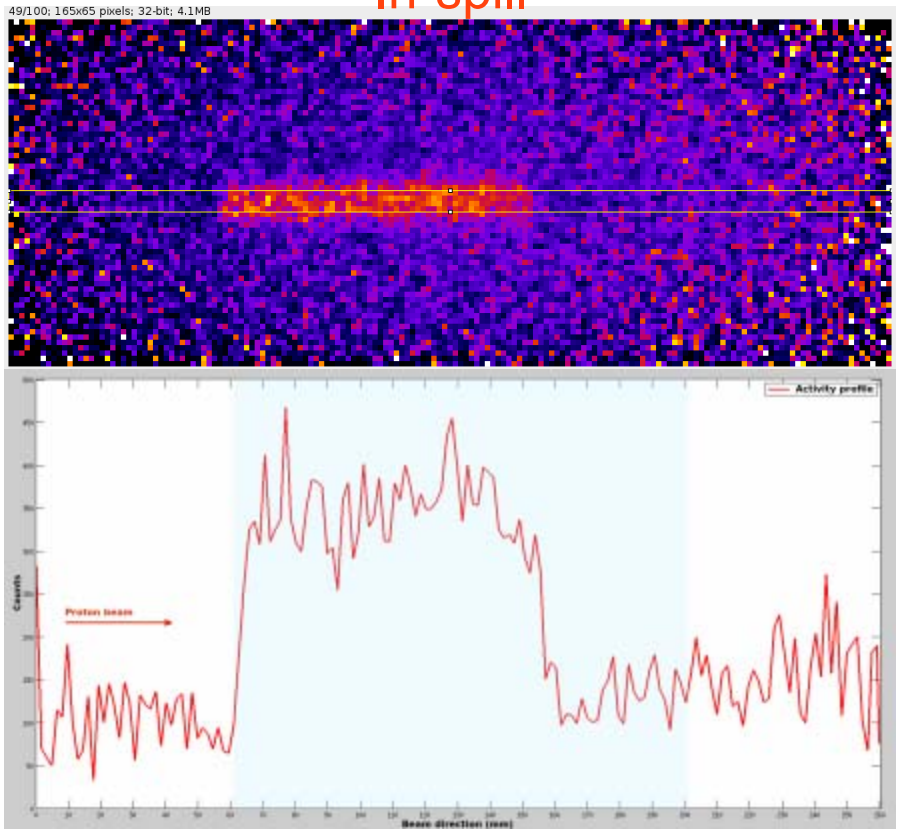


- Proton energy 124 MeV (111 mm in H_2O)
- $2*10^{10}$ particles
- 50 x 50 x 140 mm3 homogeneous PMMA phantom
- 17 spills

Inter-spill



In-spill

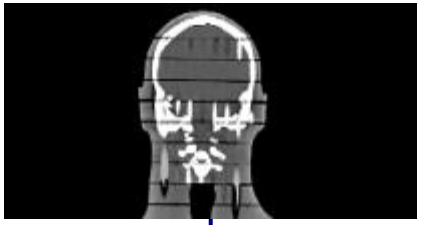


PET system at CNAO
antropomorphic phantom

Treatment plan information	
Radiation type	Proton
Target prescription dose	55.8 Gy
Number of fraction planned	31
Fraction dose	1.8 Gy
Number of beam	2 (B1 and B2)

Measurements information	
Beam	B1
Dose delivered	0,9 GyRBE
Nominal beam energy range	73.93 ÷ 134.12 MeV

Rando CT



PET image

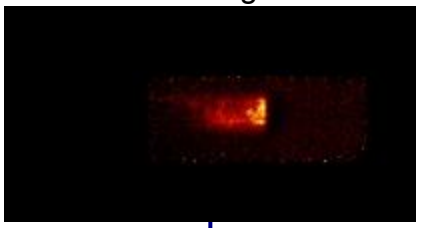
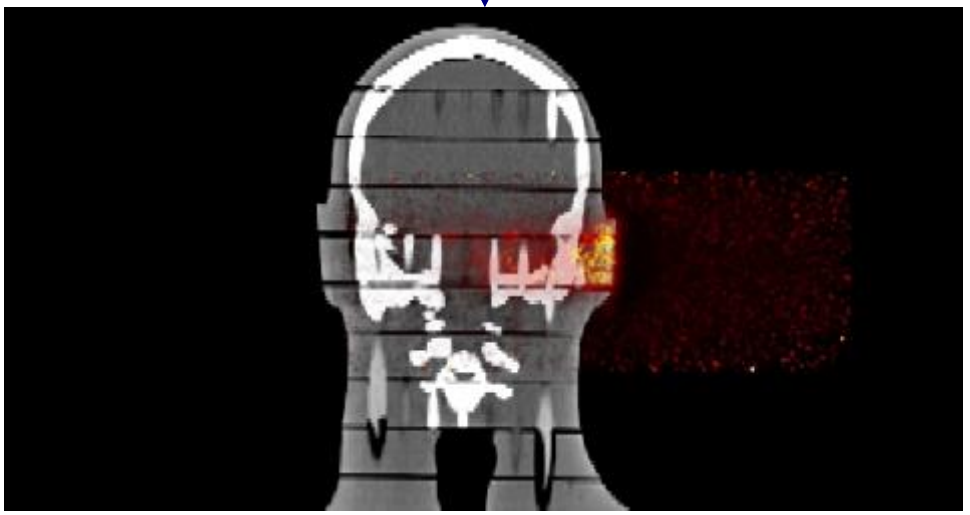
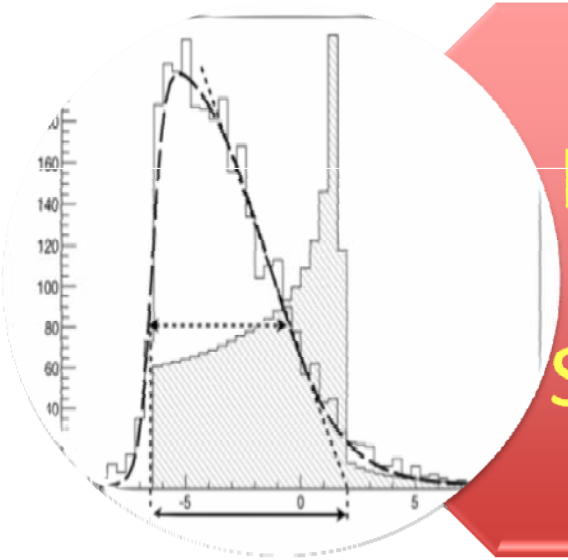
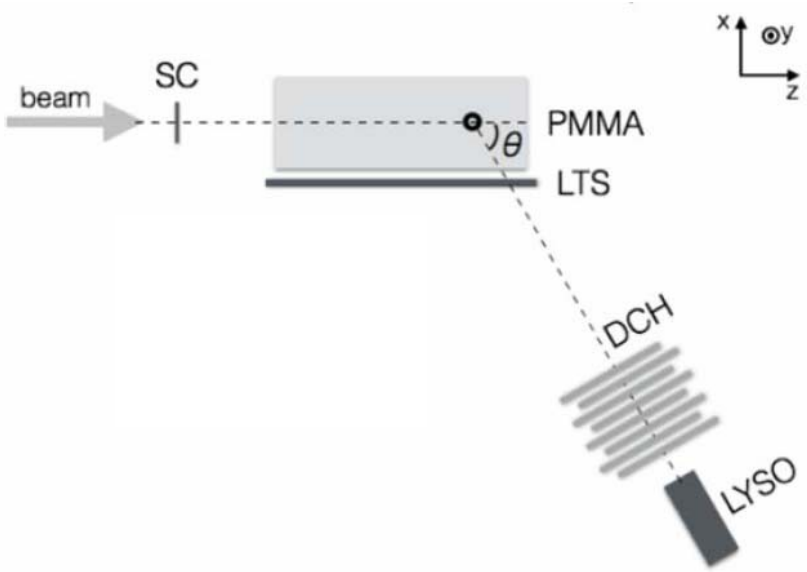


Image fusion



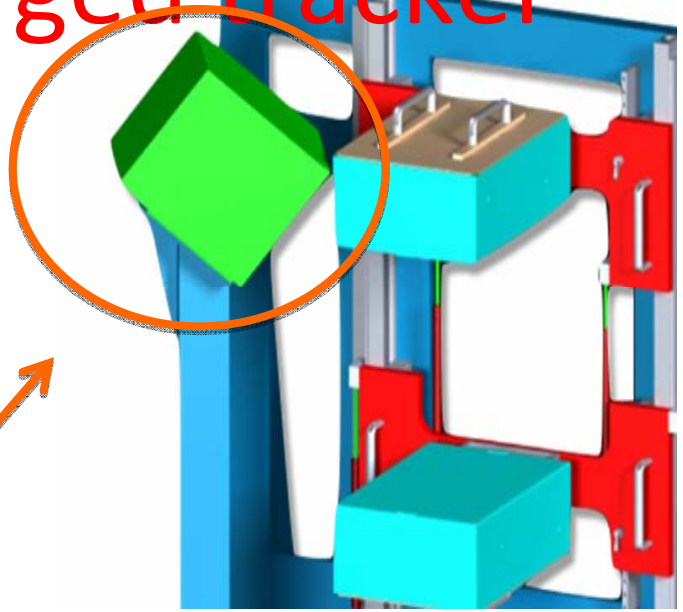


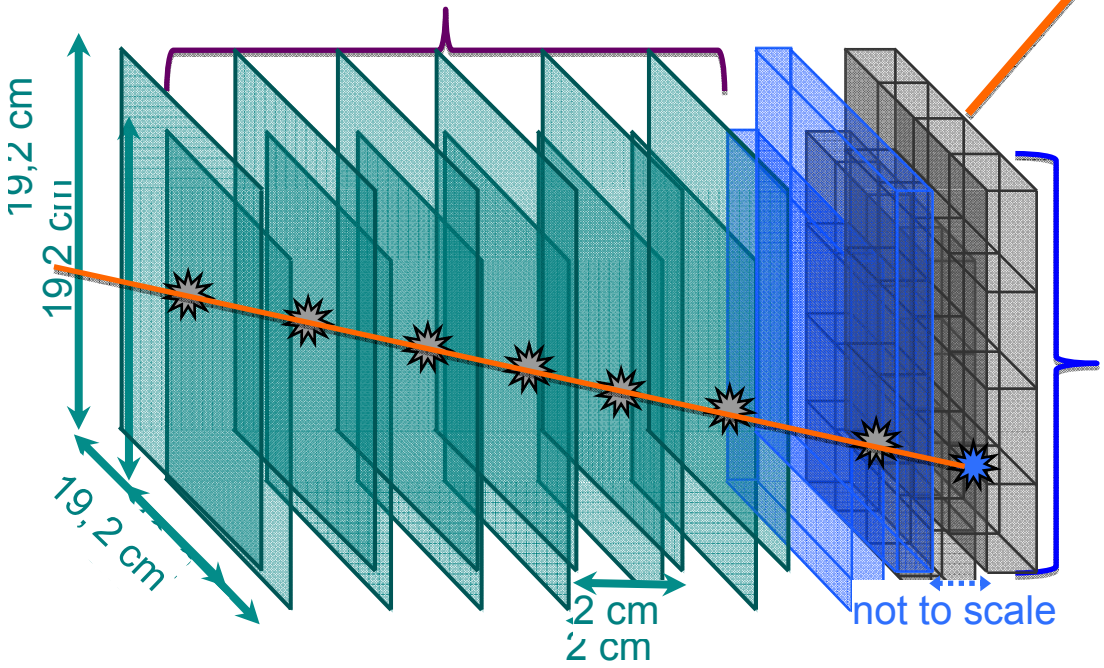
INSIDE CHARGE PROFILER SPECIFICATIONS



Profiler: charged tracker

- 6 XY planes with 2 cm spacing. Each plane made of 2 stereo layers of 192 0.5x0.5 mm^2 square scintillating fibers
- 2x0.5 mm squared fibers read out by Hamamatsu 1mm^2 SiPM : S12571-050P
- 32 SiPM feed a 32 ch ASIC BASIC32





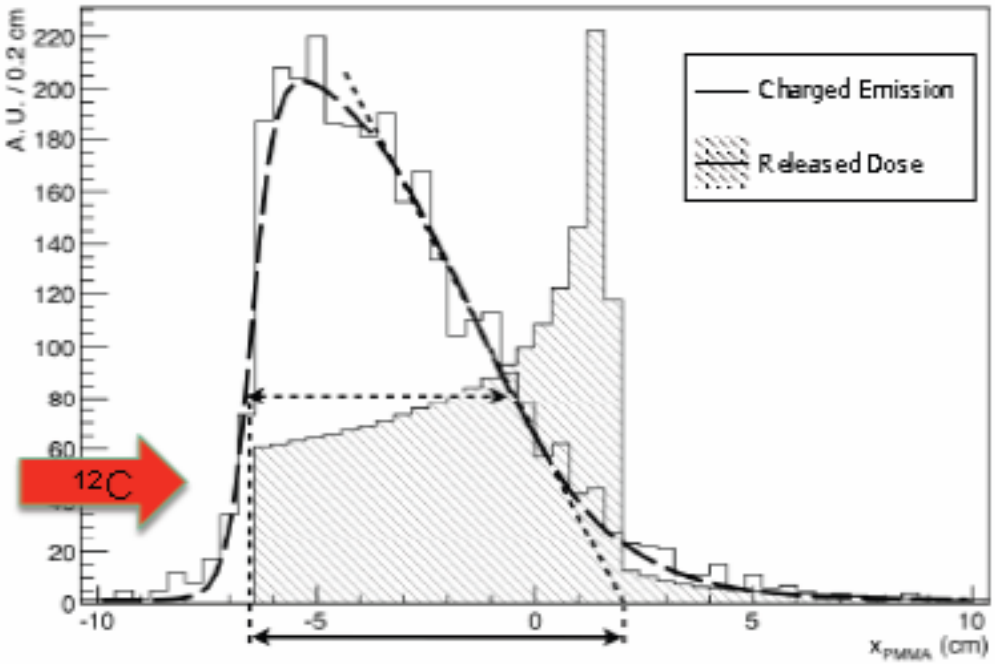
- 4x4 LYSO pixellated crystals tracking planes: 50 x 50 x 16 mm^3
- Plastic absorber 1.5 cm thick in front of LYSO to screen electrons
- Crystals read out by 64 ch Hamamatsu MultiAnode

Profiler: Fragmentation & dose monitoring

The method relies on the exp. knowledge of the abundance and on the energy spectrum of produced protons after the irradiadion with heavy particle beams (4-He, 12-C or 16-O)

Measured emission distribution shape of protons as detected outside a 5 cm thick PMMA at 90^0 wrt the direction of 220 AMeV ^{12}C beam
L. Piersanti et al Phys. Med. Biol 59 1857

Simulated emission distribution shape of protons as detected ouside different PMMA thickness at 30^0 wrt the direction of 95 AMeV ^{12}C beam
E. Testa et al Phys. Med. Biol. 57 4655



Create a parameter map:

- Simulae with FLUKA MC a parametric proton generator
- Cylindrical PMMA target with different thicnesses
- Fit the proton emission curve with an appropriate funcition

→ Parameter VS thickness relation

Profiler: Fragmentation & dose monitoring

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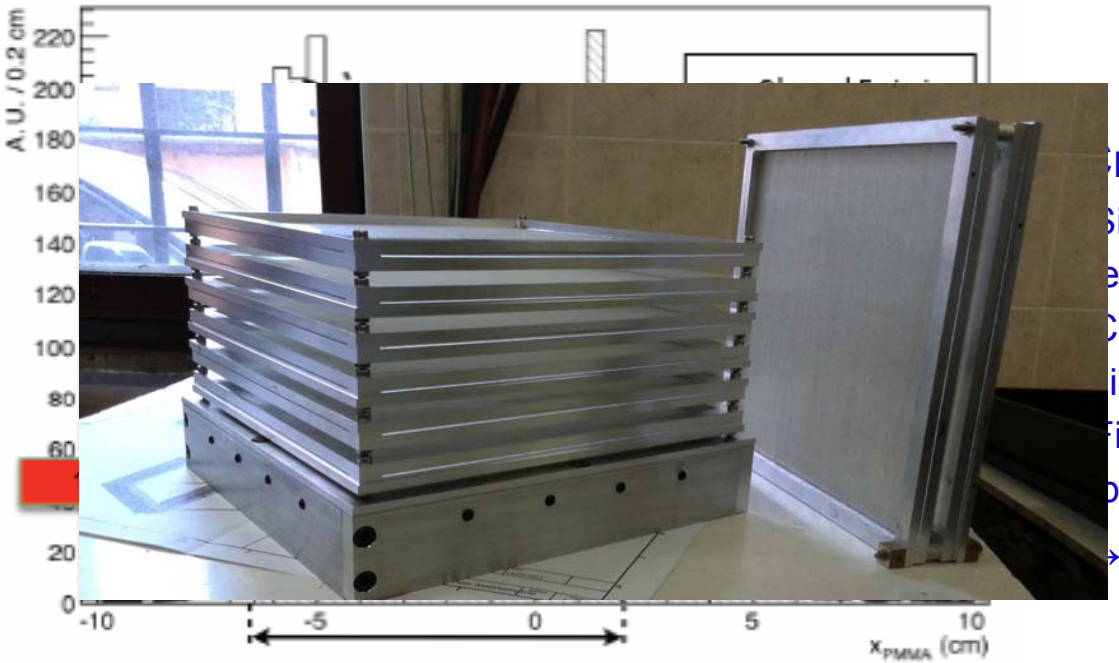

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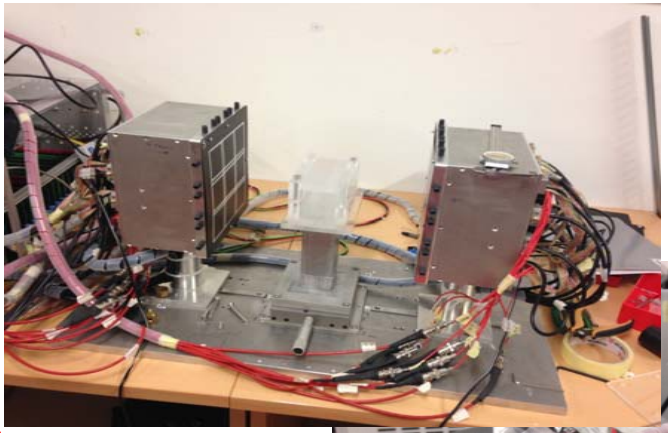
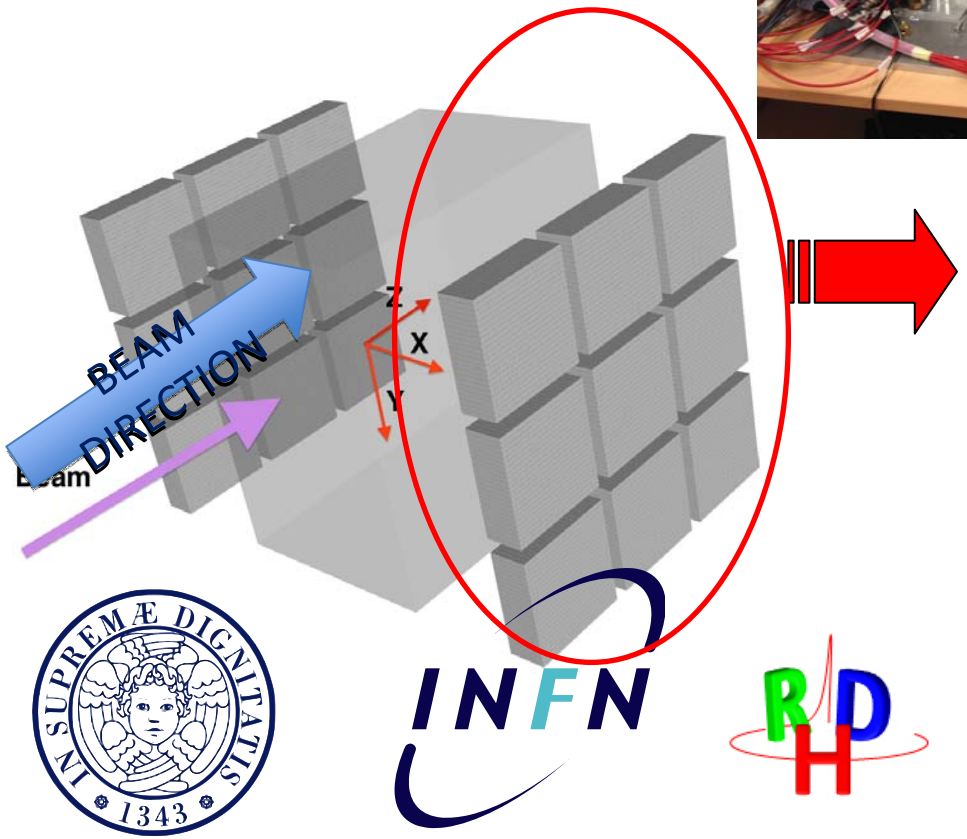
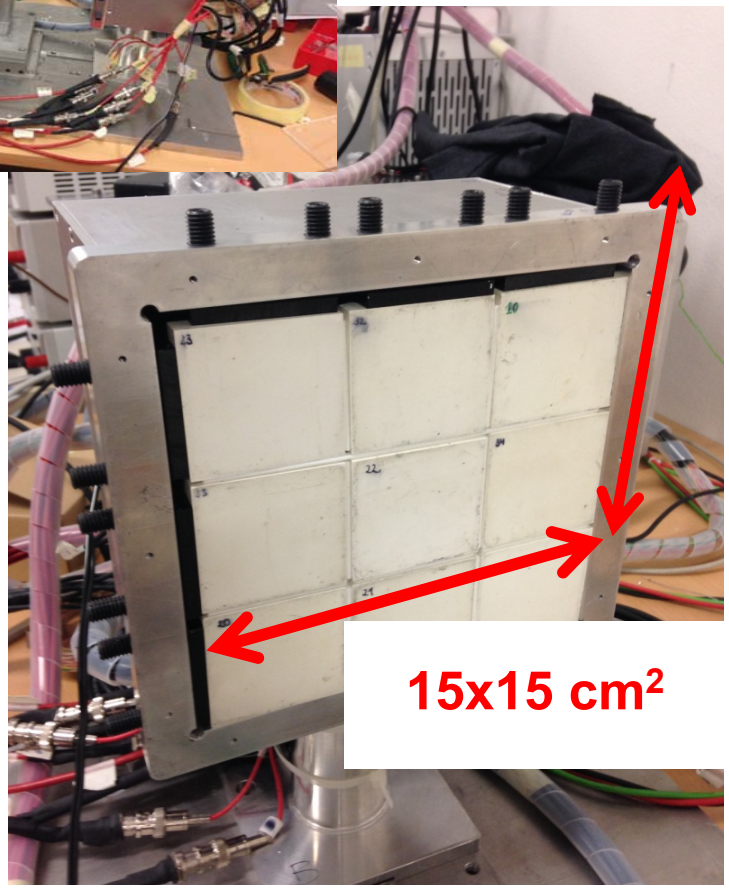
DoPET: 9 vs 9 prototype

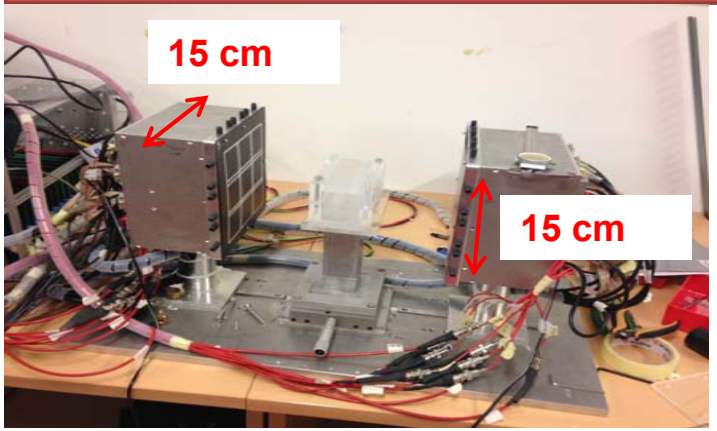
DoPET is a compact stationary 2 heads tomograph
-in-treatment acquisition



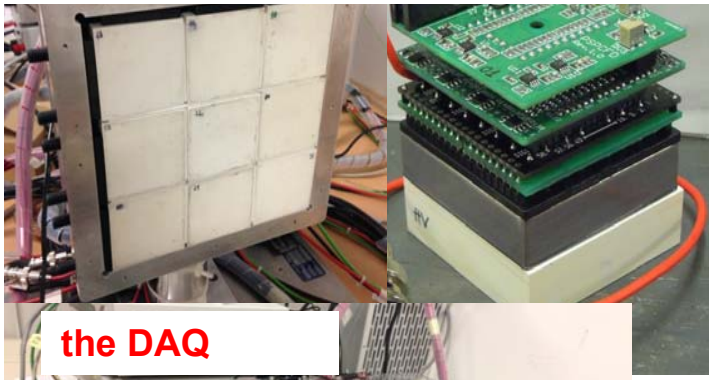


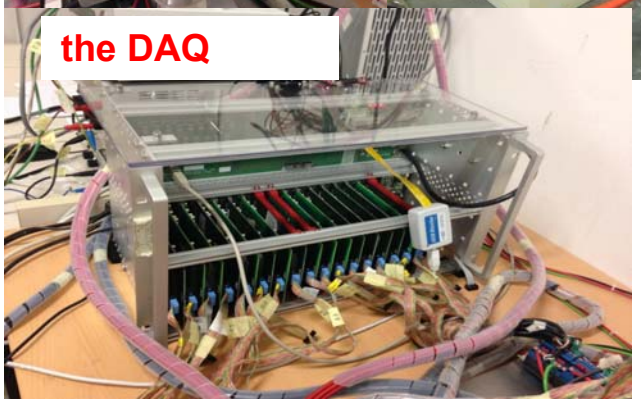


DoPET: 9 x 9 prototype



9 detecting modules the single module





Detecting module 5cm x 5cm

- LYSO matrices, each 23 x 23 crystals, 2mm pitch)
- PS-PMT 8500 Hamamatsu
- Dedicated front-end electronics

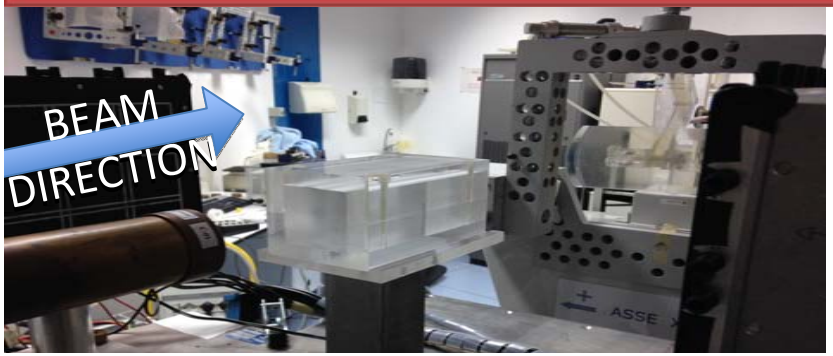
- Modularized acquisition electronics
  - FPGA based acquisition and coincidence processing
  - Coincidence time window ~3 ns

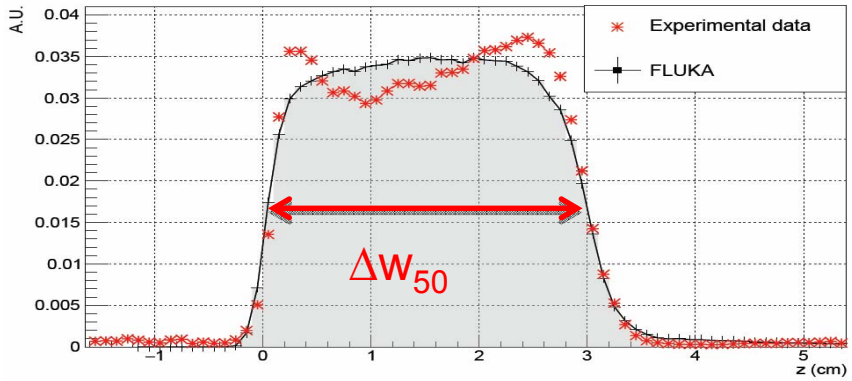
➢3D-activity distribution is reconstructed with Maximum Likelihood Estimation Maximization (MLEM) Iterative algorithm

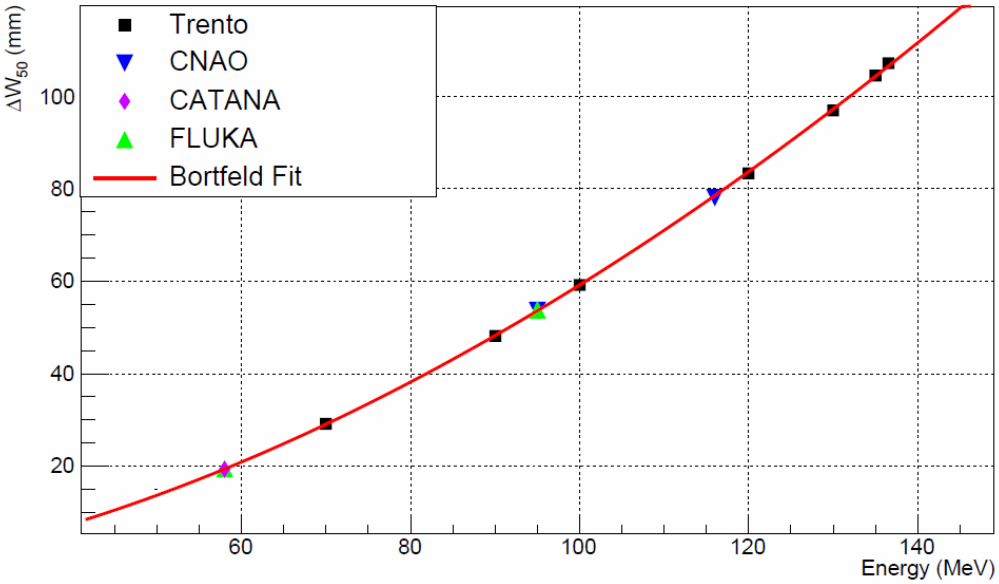
The reconstruction is performed in less than 1 minute (8 core Intel Xeon e5620 @2.4 GHz)

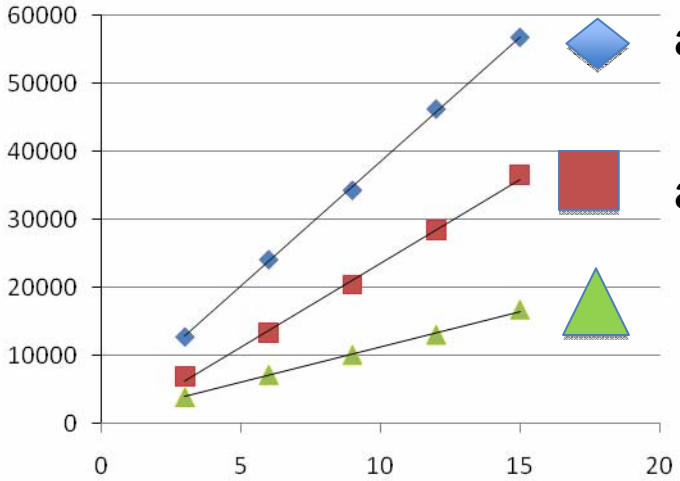
S. Vecchio et al., IEEE Trans. Nucl. Science 56 (2009) 51-56
G. Sportelli et al., IEEE Trans. Nucl. Science 58 (2011) 695-702
N. Camarlinghi et al., JINST 9 (2014) C04005 1-12

DoPET : spatial response (CATANA)



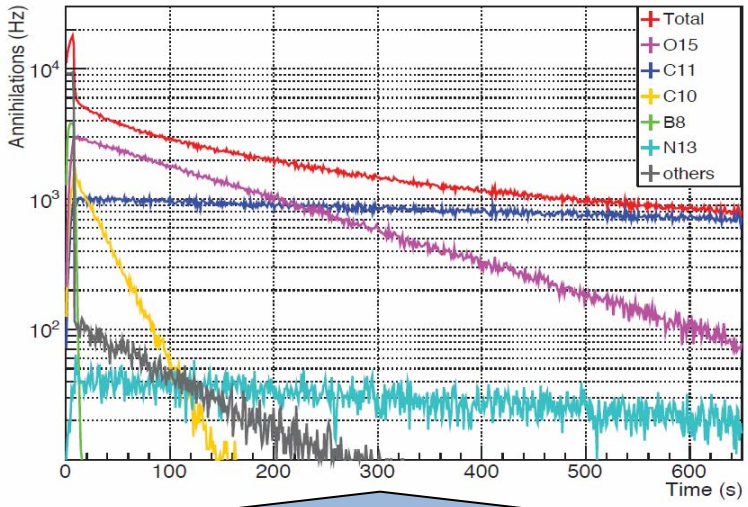




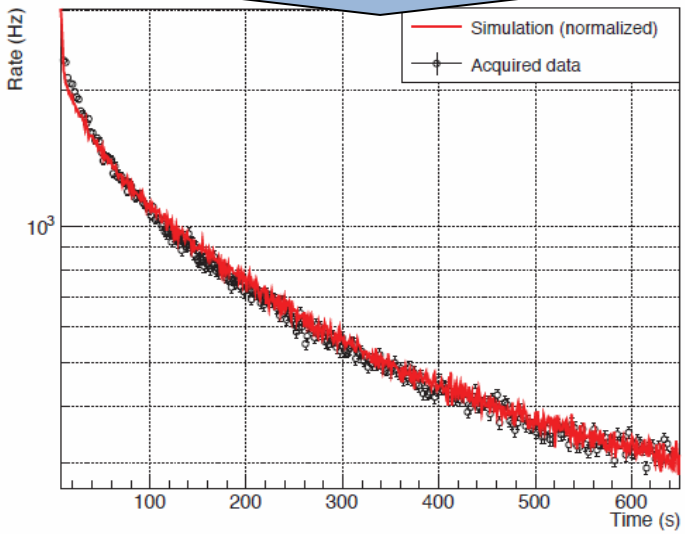


DOSE	treatment time [s]	Gy/min
3 Gy	16.3	11.04
6 Gy	30	12
9 Gy	48	11.25
12 Gy	56.4	12.77
15 Gy	72.9	12.35

DoPET: time analysis for isotopic contribution (TRENTO)



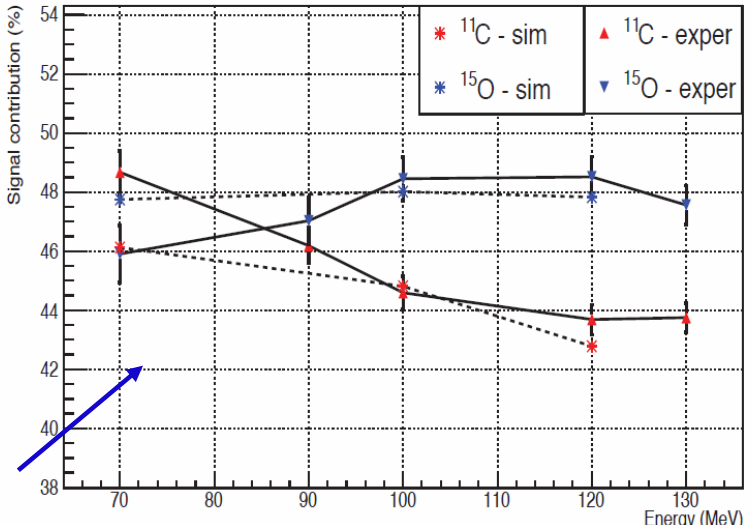
100 MeV protons on PMMA: MC and data



Protons on PMMA: **after-treatment (0-550 s) exp. data and MC simulations**

	11-C (%)	15-O (%)	10-C (%)	8-B (%)	other s(%)
MC-FLUKA	**44.81 ± 0.08**	**48.01 ± 0.08**	**4.06 ± 0.02**	**0.40 ± 0.01**	**2.72 ± 0.02**
exp-data	**44.59 ± 0.56**	**48.45 ± 0.74**	**6.56 ± 0.32**	**0.40 ± 0.05**	
$T_{1/2}$ [s]	**1220**	**122,2**	**19,3**	**0,770**	

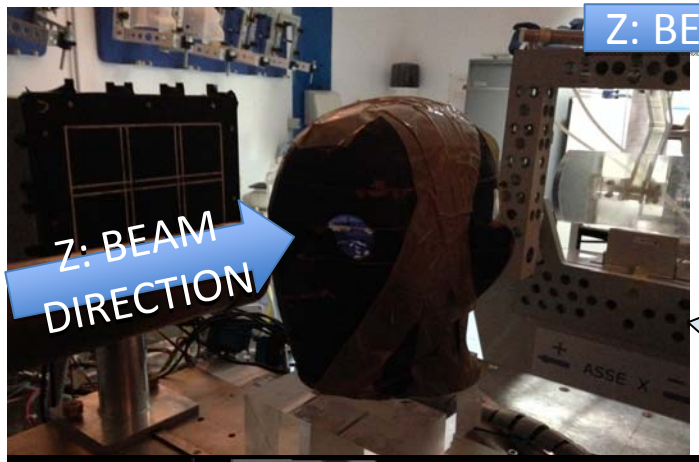
isotopes contributions /**5 energies** /ΔT =550 s only after-treatment data



the agreement is within 3%

DoPET: an example of an anthropomorphic phantom irradiation (CATANA)

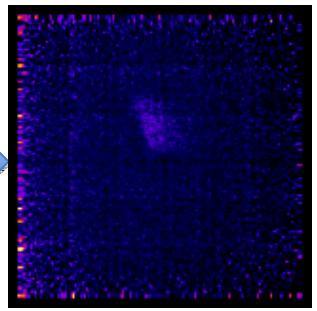
SOBP, collimator:Ø 3 cm, D= 15Gy
Δt in-treatment= 70s



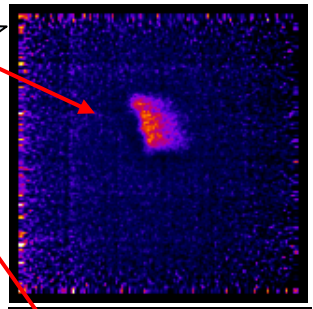
Z: BEAM DIRECTION

Eyelid is well visible

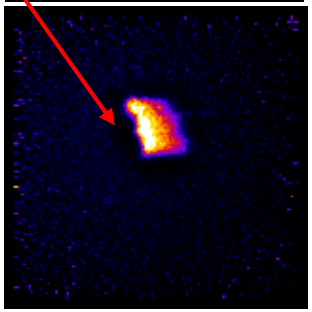
Z



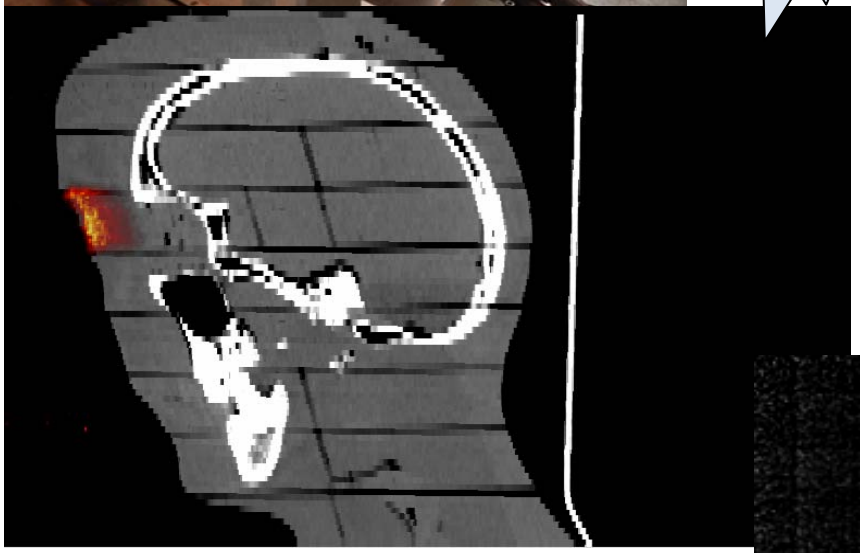
In-treatment
0-70 s



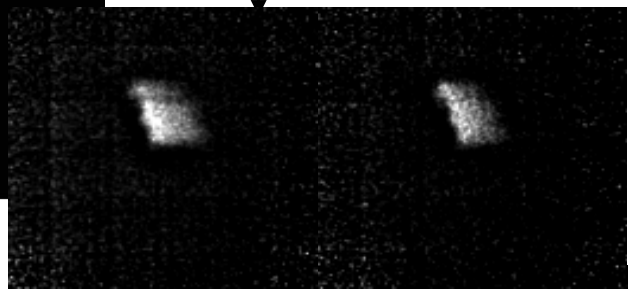
In + after treatment
0-190 s



after treatment
70-600 s



Y



left SOBP irradiation
right the SOBP + 3mm RS
Reconstructed data relative to acq. of 190 s

Conclusions

Different monitoring system were developed and are available:

- The systems are compact to be positioned close to the patient and to not interfere with the dose delivery
- in-treatment data taking
- along the beam direction they have a millimetric capability to detect changes in BP position
- the measurements are in agreement with the Monte Carlo previsions (FLUKA)
- the response is linear with respect to the delivered dose
- knowledge on the produced isotopes