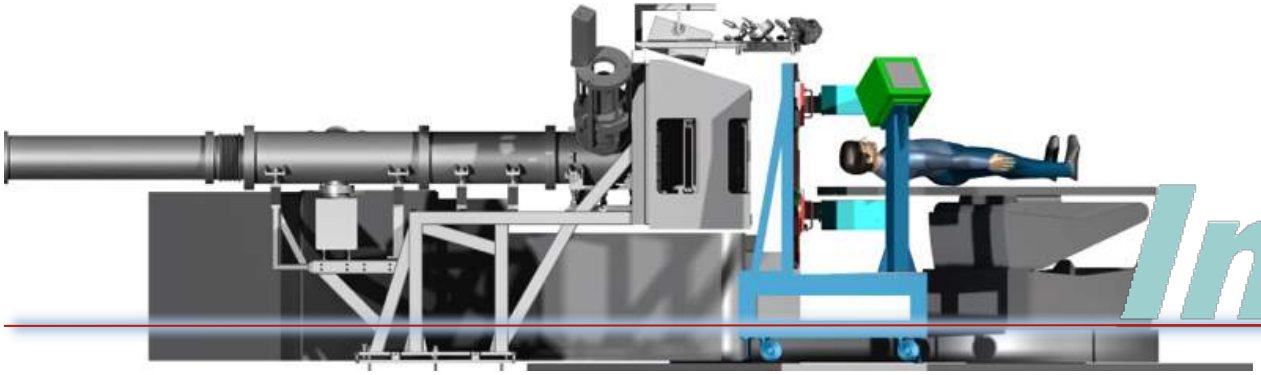


An integrated system for the on-line monitoring of particle therapy treatment accuracy

Elisa Fiorina
(Universita' di Torino and INFN, TORINO)
on behalf of the INSIDE collaboration

N. Belcari, N. Camarlinghi, A. Del Guerra, S. Ferretti, E. Kostara, A. Kraan, B. Liu, 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

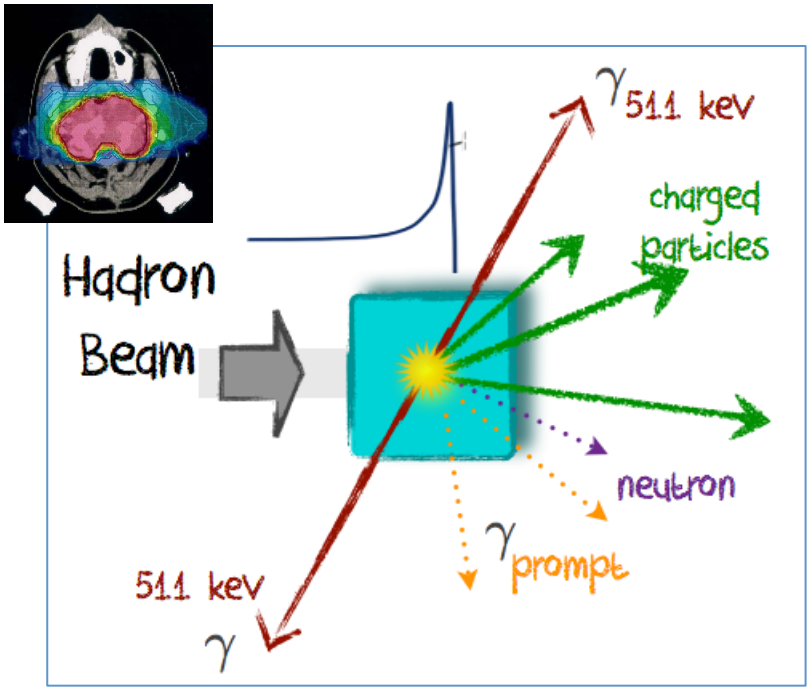
G. Battistoni, M. Cecchetti, F. Cappucci, S. Muraro, P. Sala

INSIDE coordinator: M. G. Bisogni

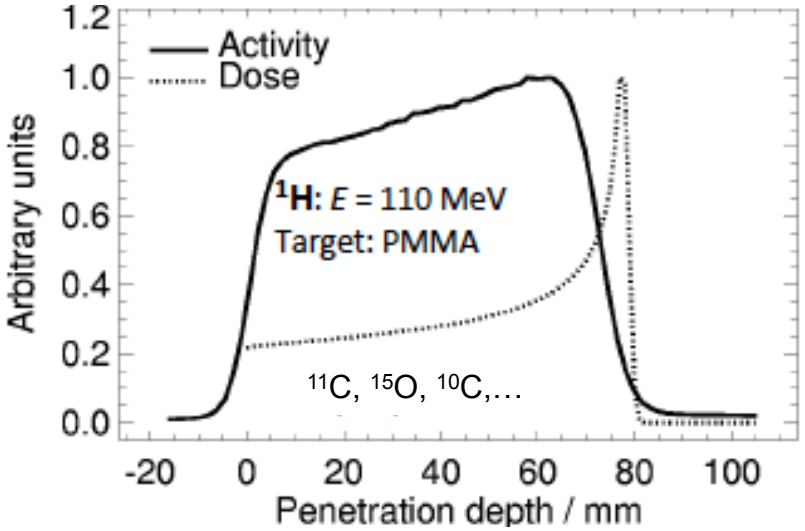
partners: CNAO M. Ciocca, M. Donetti, A. Mairani

Hadrontherapy monitoring

Real time monitor of Bragg Peak depth with passive signals by secondary particles

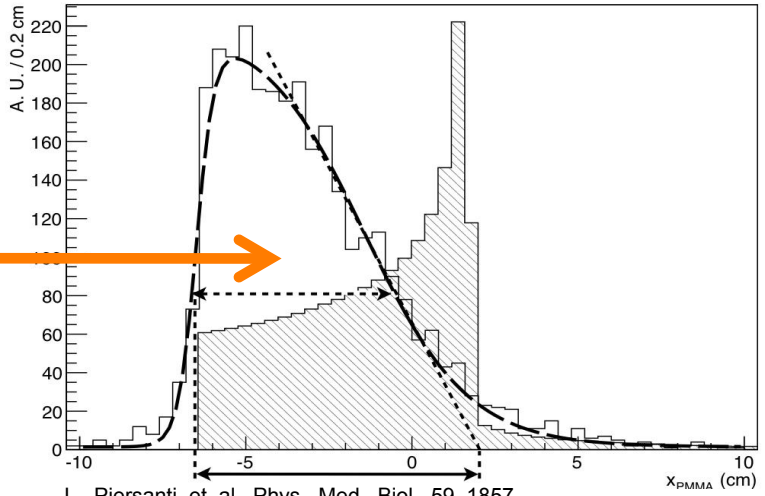


β⁺ activity distribution



J Pawelke et al., Proceedings IBIBAM, 26.-29.09.2007, Heidelberg

prompt secondary particles emission

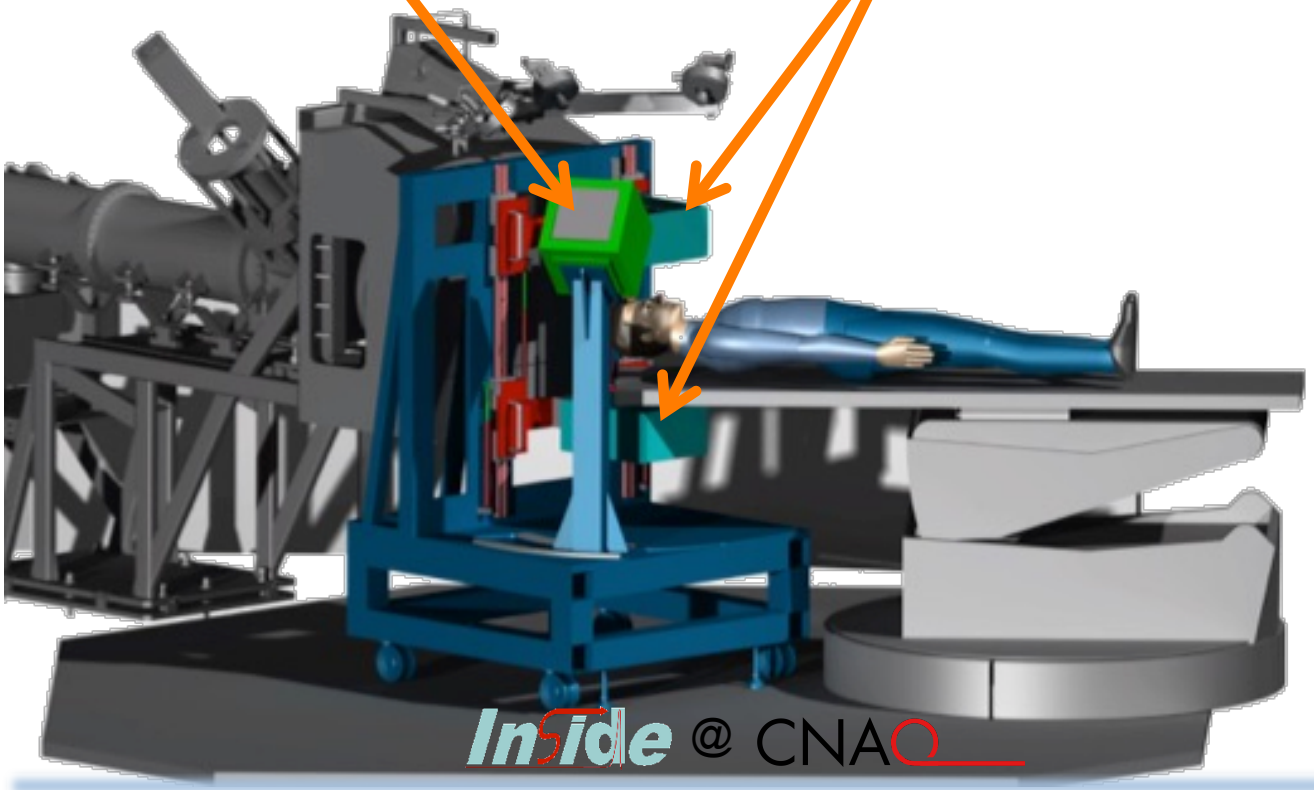


L. Piersanti et al. Phys. Med. Biol. 59 1857

The InSIDE Project

Prompt secondary particles emission?
Tracker + Calorimeter = DOSE PROFILER

β^+ activity distribution?
IN-BEAM PET HEADS

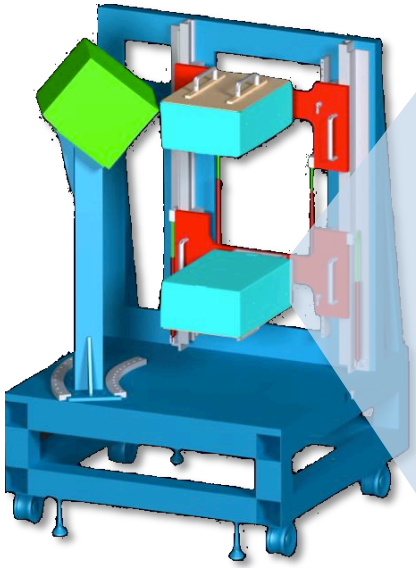


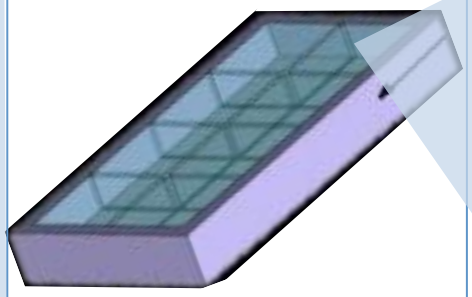
INnovative **S**olutions for **I**n-beam **D**osim**E**try in Hadrontherapy

Designed to:

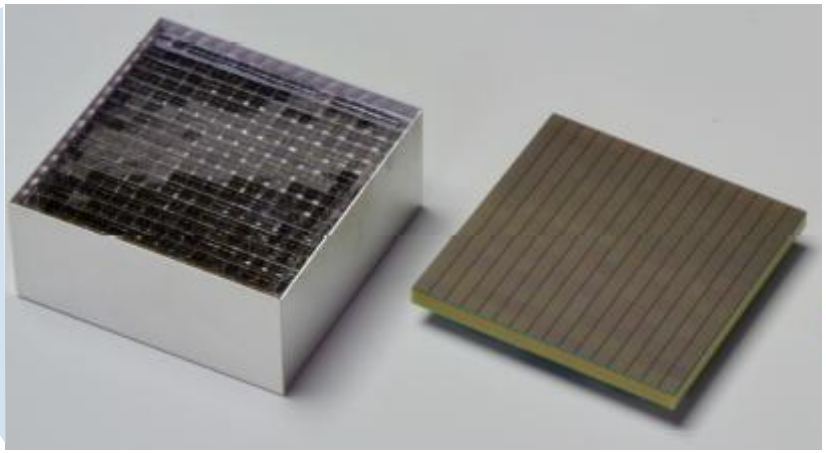
- be integrated in the gantry
- be operated in-beam
- **provide an IMMEDIATE feedback on the particle range**

In-beam PET heads

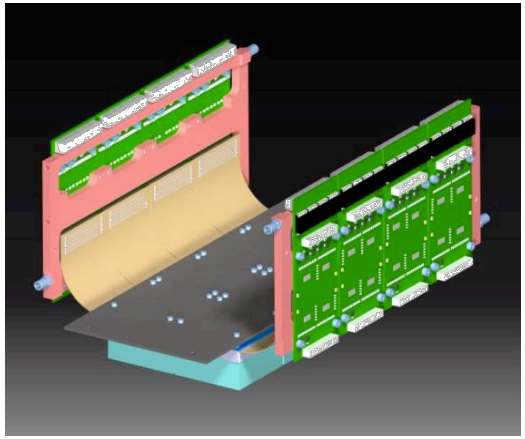


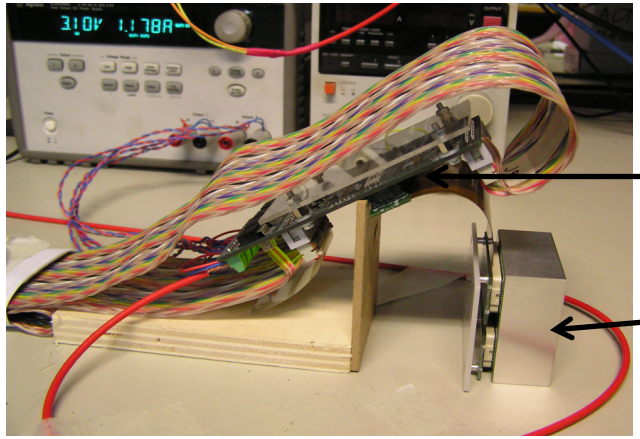


10x 20 x 5 cm^3
Distance from the isocenter=25 cm



256 LFS pixel crystals ($3x3x20mm^3$) coupled one to one to MPPCs (Multi Pixel Photon Counters, SiPMs).



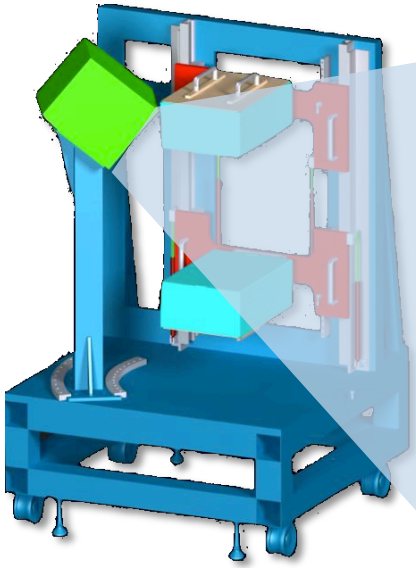


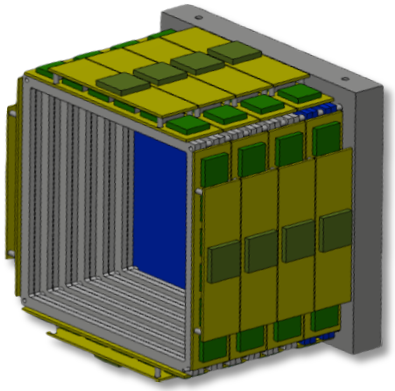
FE board (Tofpet ASIC[1])

In-beam PET module

[1] Work partly funded by the European Union 7th Framework Program (FP7/ 2007-2013) under Grant Agreement No. 256984 EndoTOFPET-US and supported by a Marie Curie Early Initial Training Network Fellowship of the European Union 7th Framework Program (PITN-GA-2011-289355-PicoSEC-MCNet).

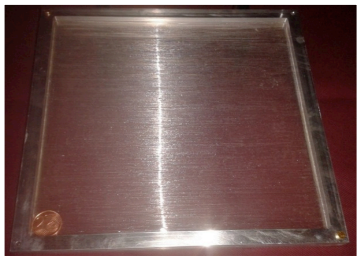
Dose Profiler

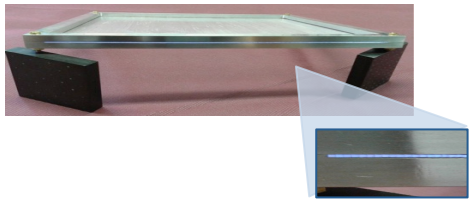


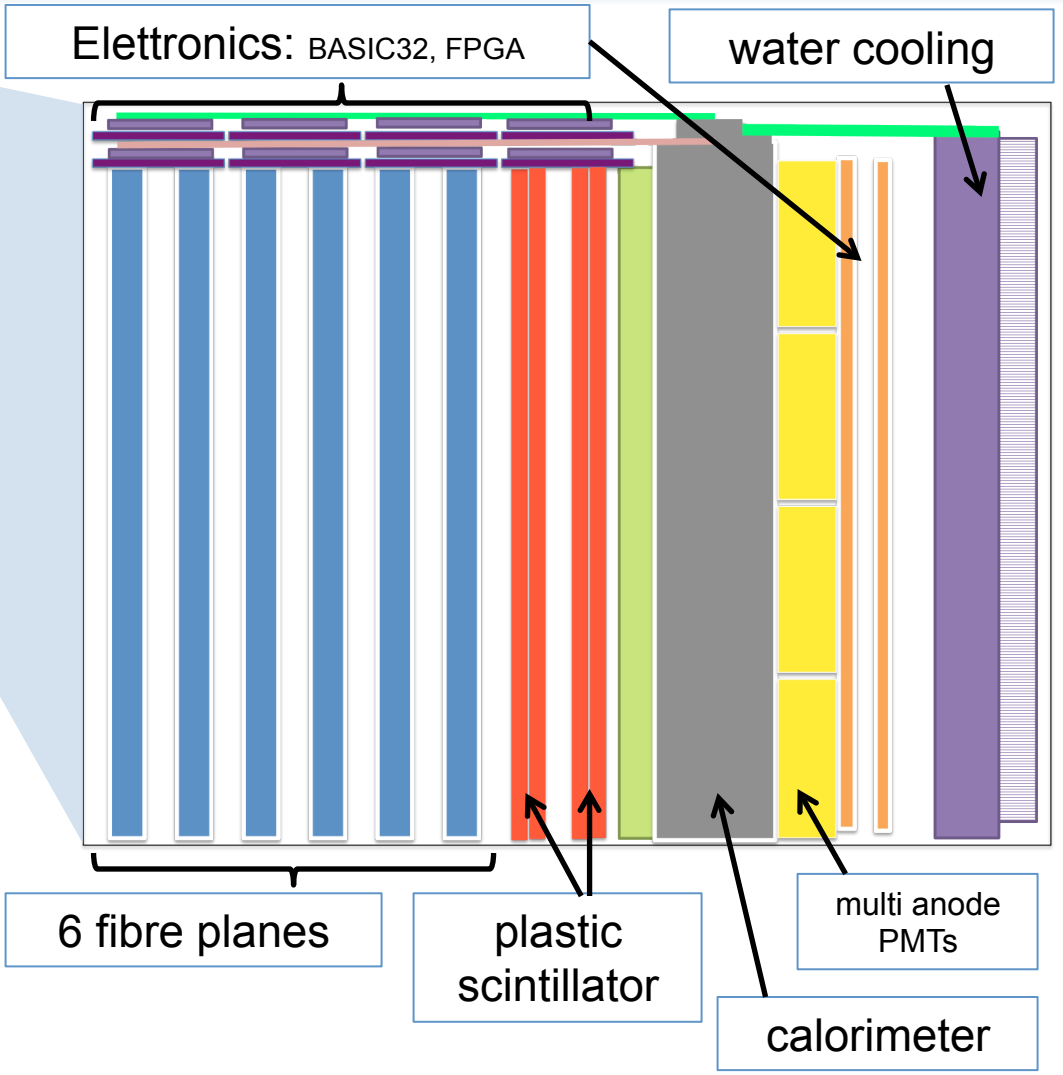


28 x 28 x 35 cm^3

- 6 planes of orthogonal squared scintillating fibers coupled to SiPMs
- an electromagnetic calorimeter coupled to Position Sensitive PMTs.







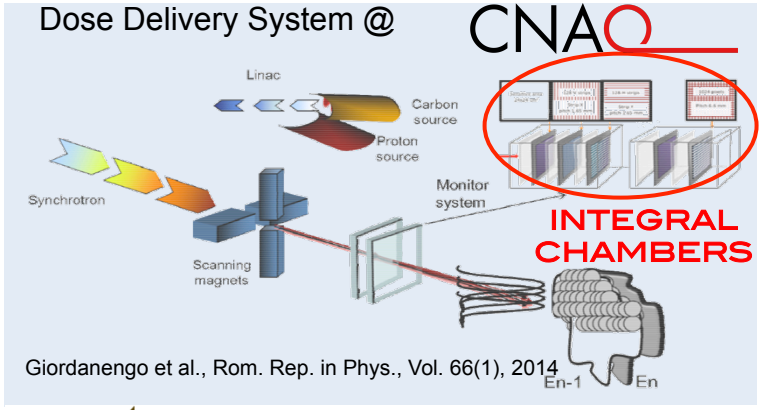
The InSide System Specifications

	IN-BEAM PET HEADS	DOSE PROFILER
Signal	β+ decay	Prompt secondary particles
Acquisition phases	In-spill, inter-spill and after-treatment	In-spill
Position	❑ heads face to face ❑ perpendicular to the beam axis ❑ fitted position wrt the isocenter	❑ forward direction ❑ 60^{o} angle wrt the beam axis
Distance from beam isocenter	25 cm	about 40 cm
Output	3D PET image	Emission point distribution

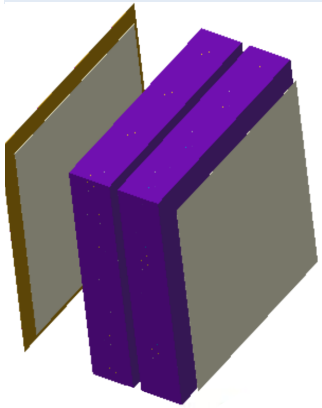
Bragg Peak depth online check before patient irradiation with the complete treatment session.

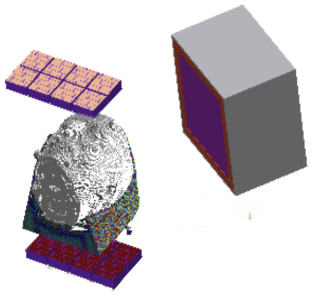
MC simulations

Essential for system design, development and operation planning.



Giordanengo et al., Rom. Rep. in Phys., Vol. 66(1), 2014





FLUKA http://www.fluka.org

BEAM SIMULATION	PHANTOM/PATIENT SIMULATION
❑ CNAO beam pipe and nozzle ❑ beam space and time structure (from the beam monitoring system)	❑ phantom: different materials ❑ patient: Computed Tomography
PET SIMULATION	**DOSE PROFILER SIMULATION**
❑ two-steps approach ❑ detector response	❑ full ^{12}C beam simulation ❑ detector response

PET simulations (I)

STEP 1:
Beam simulation

FLUKA

About 1/100 of primary hadrons

Time-tagged activity scoring

- Annihilation time and position (gold standard)
- Isotope production map:
  ^{11}C ($t_{1/2}$=1220.04s)
  ^{15}O ($t_{1/2}$=122.4s)
  ^{10}C ($t_{1/2}$=19.290s)

100x

STEP 2:
PET simulation

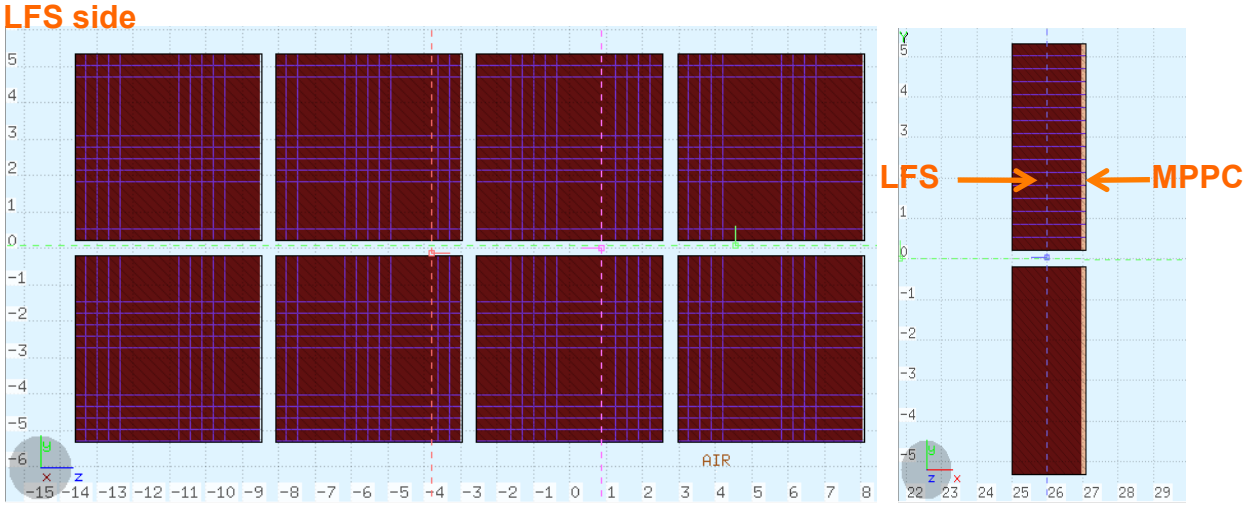
FLUKA

All positrons are simulated.
Detector simulation.

Data analysis & PET image reconstruction

Same as real data:
- Line Of Response (LOR) list extraction
- Image reconstruction (MLEM algorithm, 5 iterations)

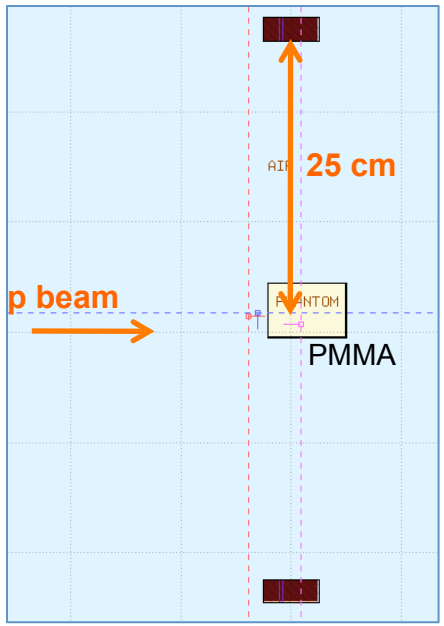
In-beam PET heads simulated geometry



- Simulated detector:
  - 10% σ ΔE/E
  - 460 ps σ time resolution
- 2.5 ns coincidence time window

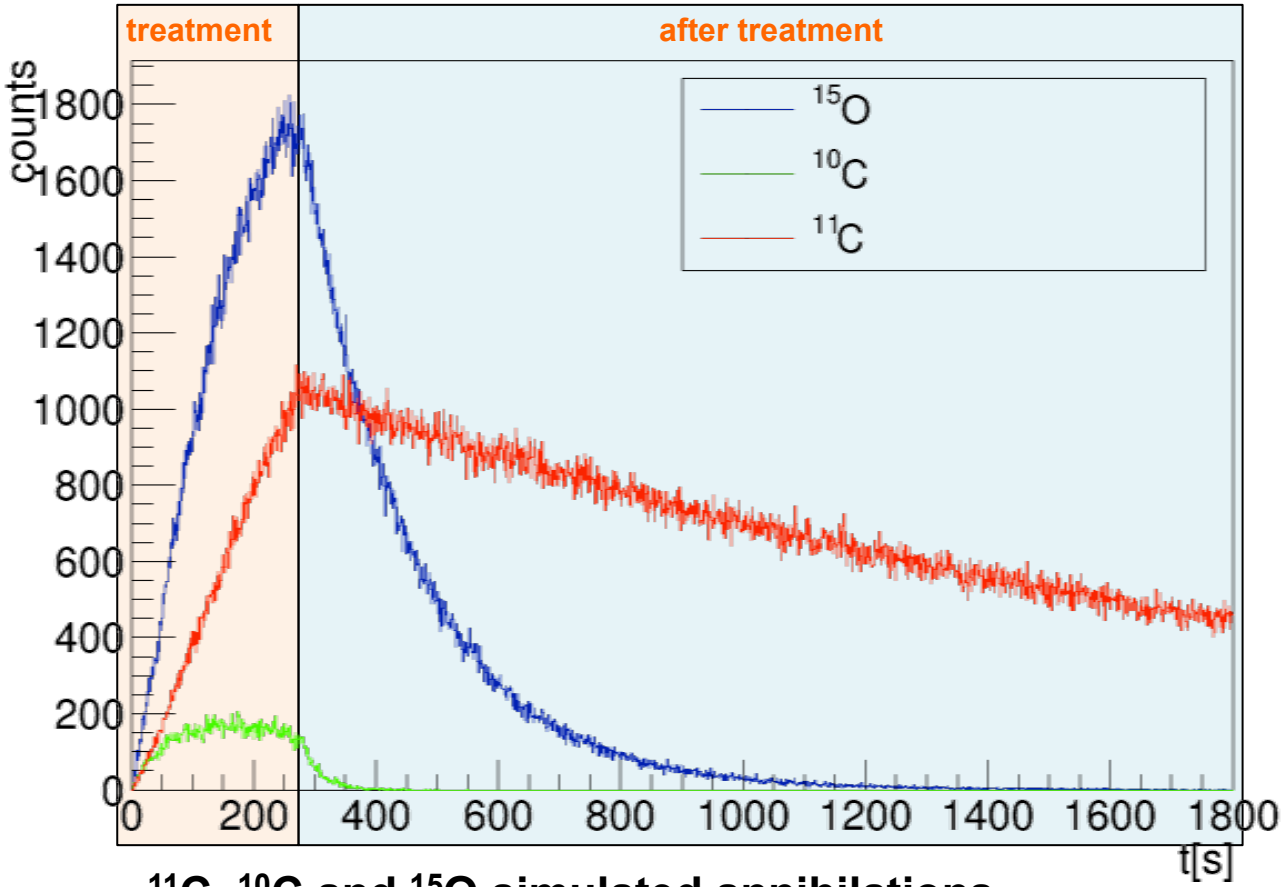
PET simulations (II)

ANNIHILATION DISTRIBUTION



Monoenergetic 2D proton treatment:

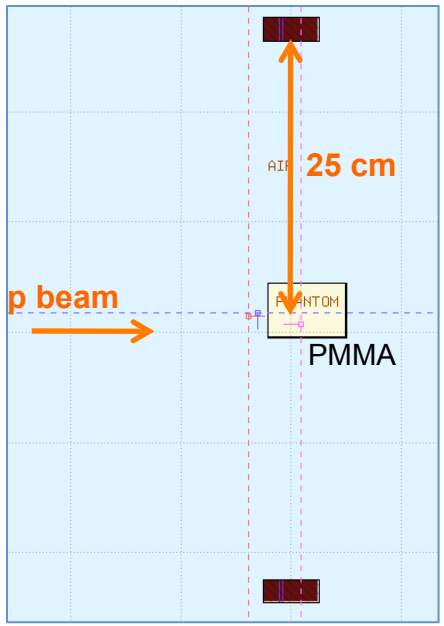
- uniform irradiation
- 4.5x4.5x0.3cm^3 slice @ E=66.34 MeV
- 4.50E+10 protons
- 59 spill
- 7.63E+8 average protons/spill



^{11}C, ^{10}C and ^{15}O simulated annihilations for the whole treatment plan = 3.2E+8 in 1800s.
Simulated isotopes: 86% during treatment, 95% after treatment

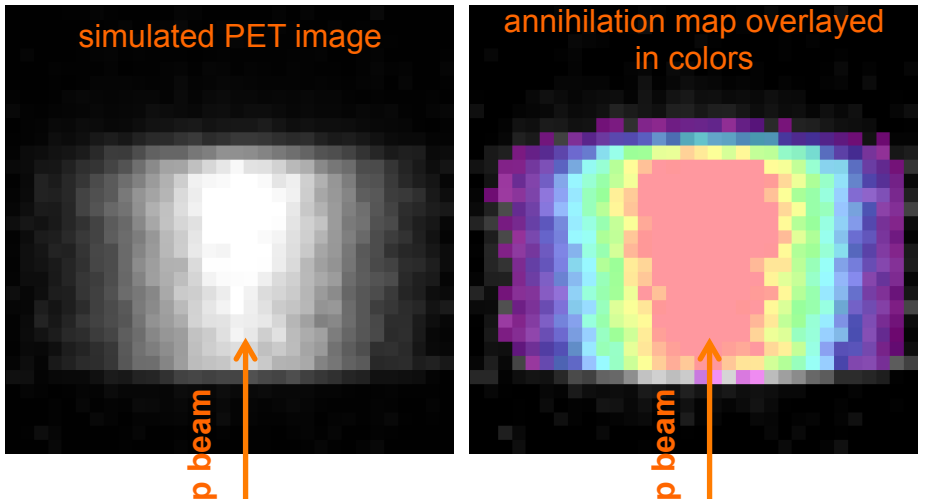
PET simulations (III)

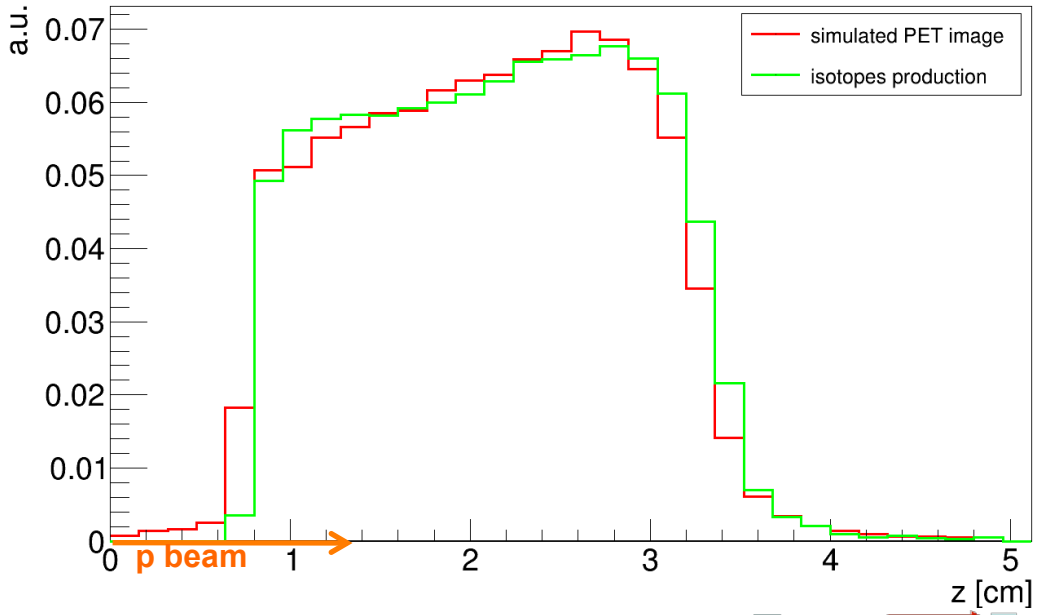
ACTIVITY PROFILE ANALYSIS



Monoenergetic 1D proton treatment:

- single spot @ E=68.3 MeV
- 2.E+11 protons
- 102 spill
- 1.96E+9 average protons/spill





Dose profiler simulation (I)

Dose Profiler simulation

- ^{12}C beams
- Detector simulation
- Phantom and patient

→

Simulation output postprocessing

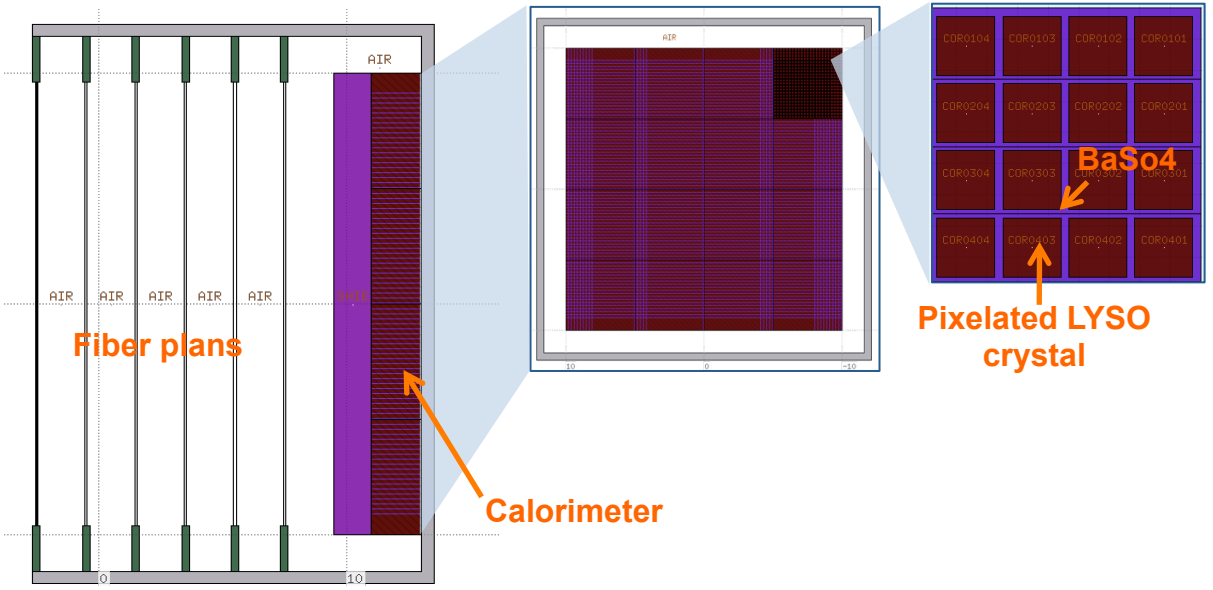
Necessary for reconstruction and data analysis

→

Track reconstruction and data analysis

Same as real data.

Dose profiler simulated geometry



Each LYSO crystal matches with 4 MAPMT anodes

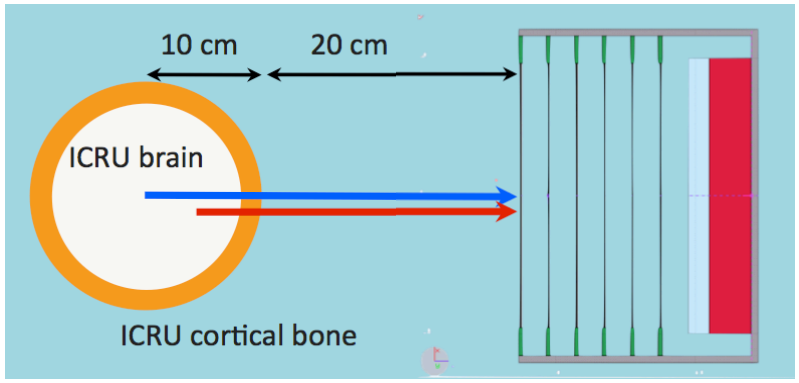
↓

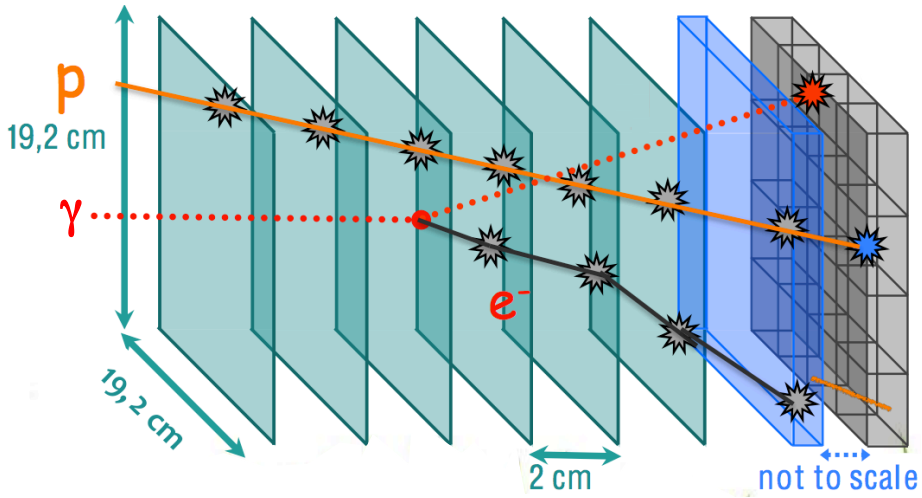
Lookup tables for energy correction

Dose profiler simulations (II)

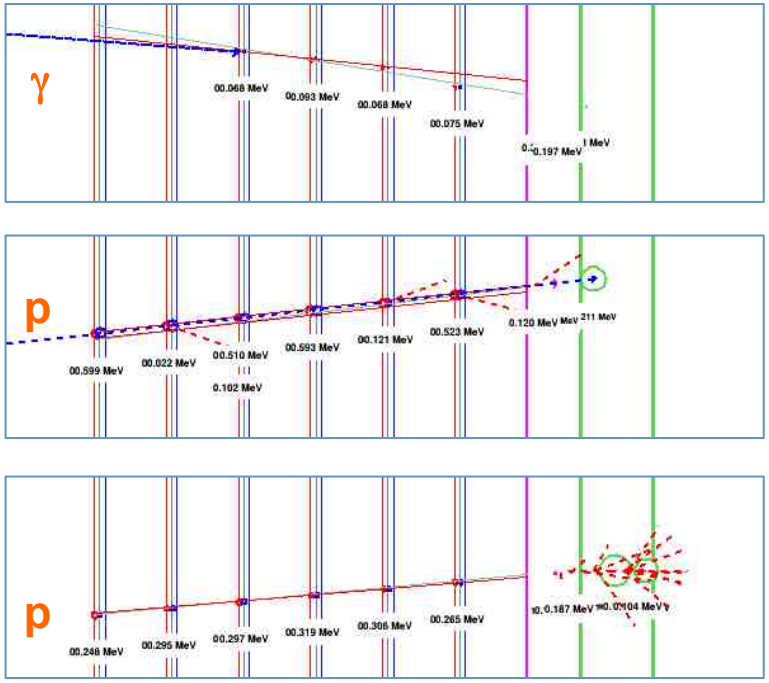
PHANTOM CASE

Single spot ^{12}C beam @ 220 MeV/u

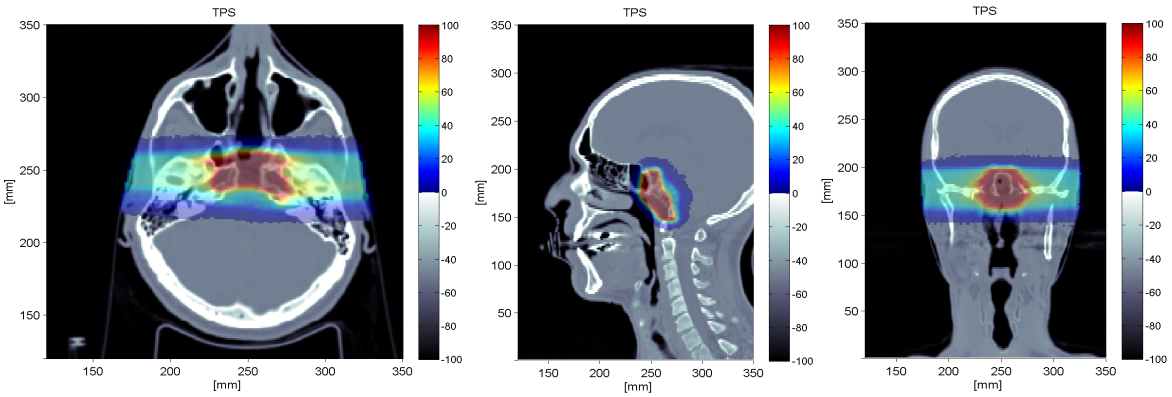




Simulated tracks inside the Dose Profiler



Dose profiler simulations (III)

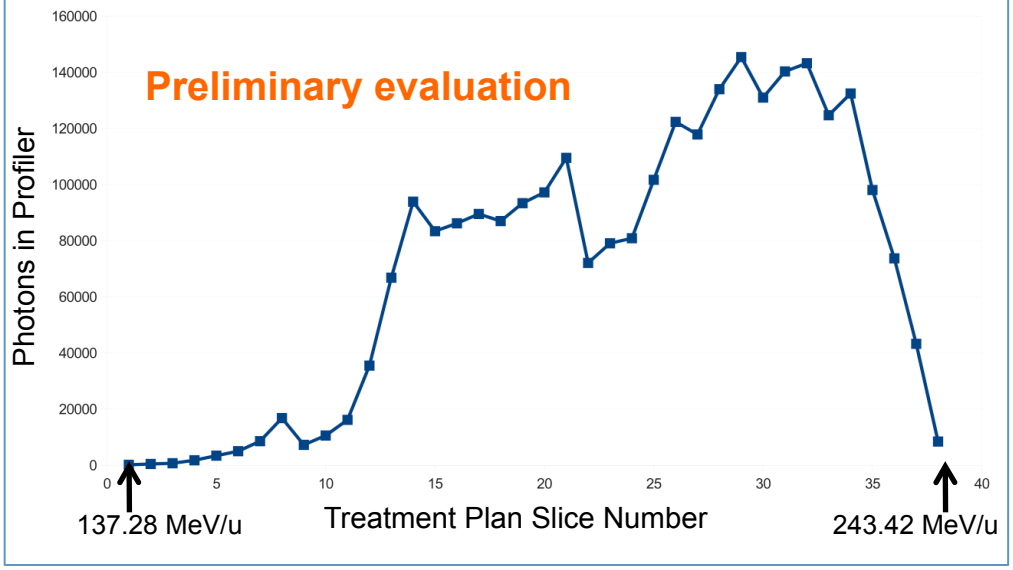


PATIENT CASE

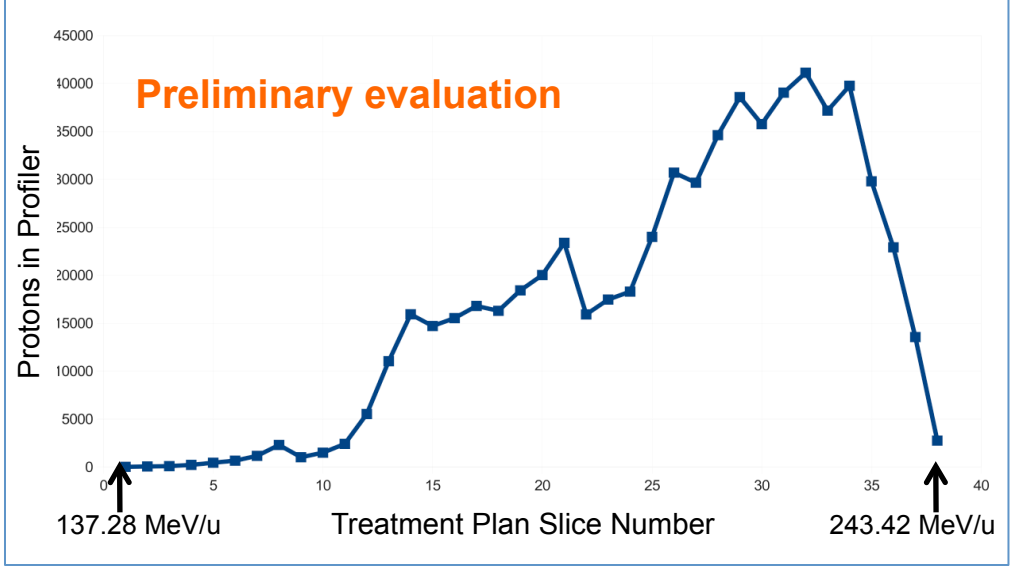
One beam, 2.7 10^8 ^{12}C

Energy in [137.28, 243.42] MeV/u range.

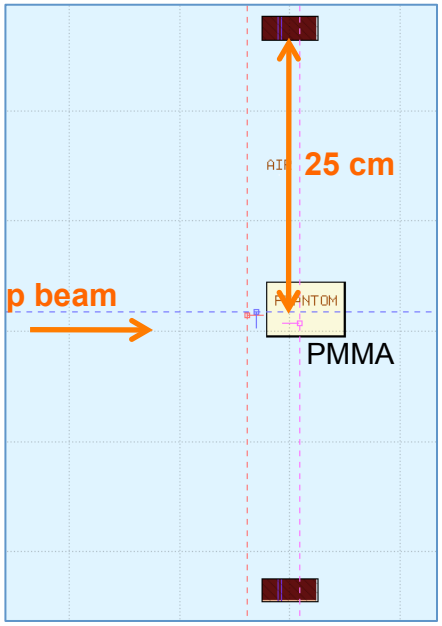
Photons (>1 MeV) = 2.66 10^6

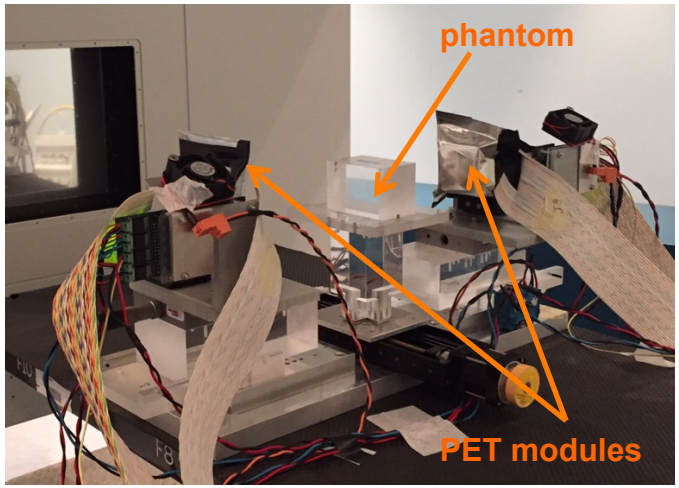


Protons (>20 MeV) = 6.39 10^5



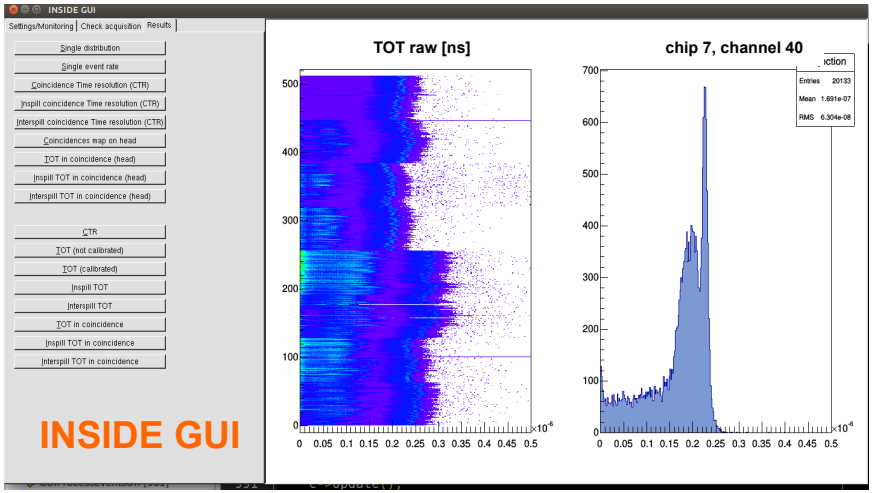
PET beam test May 2015 @ CNAO (I)





Monoenergetic 1D proton treatments
Single spot, 2E+11 protons

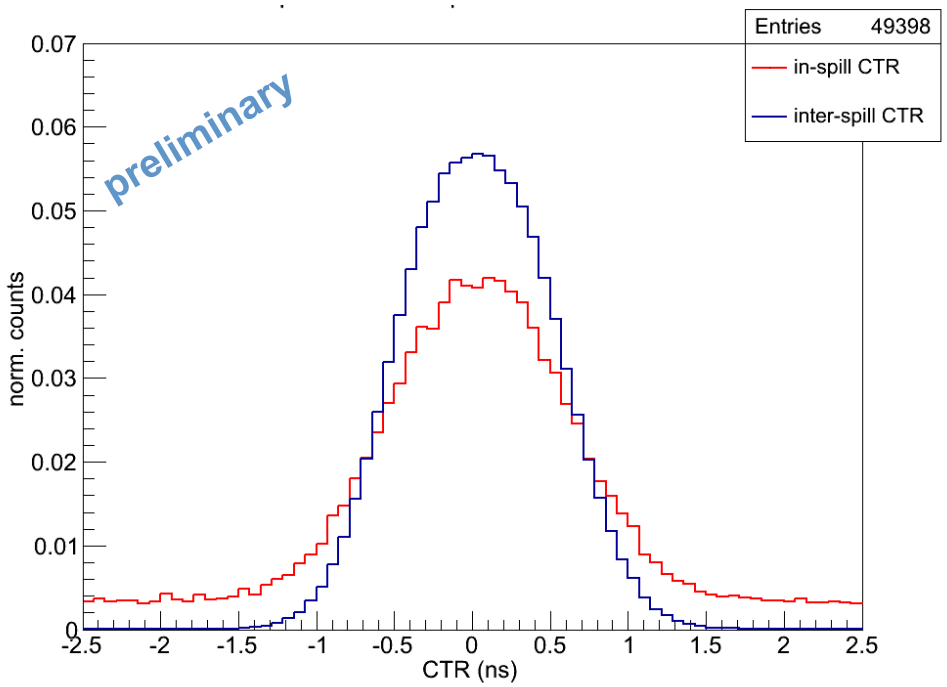
Energy [MeV]	68.3	72.03	84.3
spill	102	98	183
average protons/spill	1.96E+9	2.04E+9	1.09E+9



DATA ANALYSIS:
- Online/offline analysis
- For each channel, automated:
  - energy window selection
  - time delay calibration
- 3D PET image reconstruction
- Profile analysis

PET beam test May 2015 @ CNAO (II)

p @ 68.3 MeV



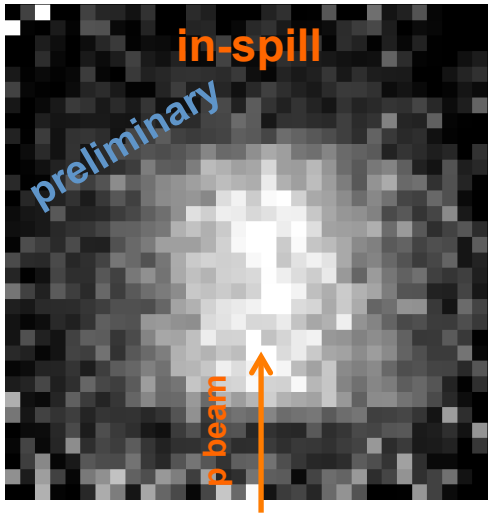
Coincidence Time Resolution (CTR)*

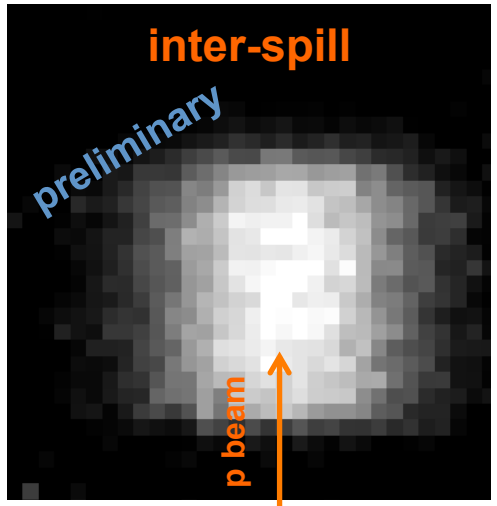
Interspill = 699 ps σ (blue)

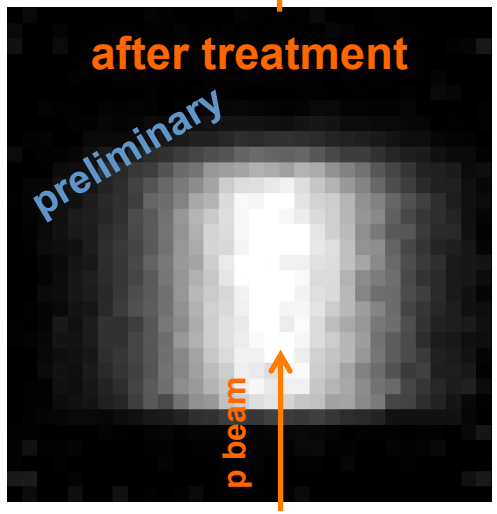
Inspill = 851 ps σ (red)

***detector calibration to be optimised**

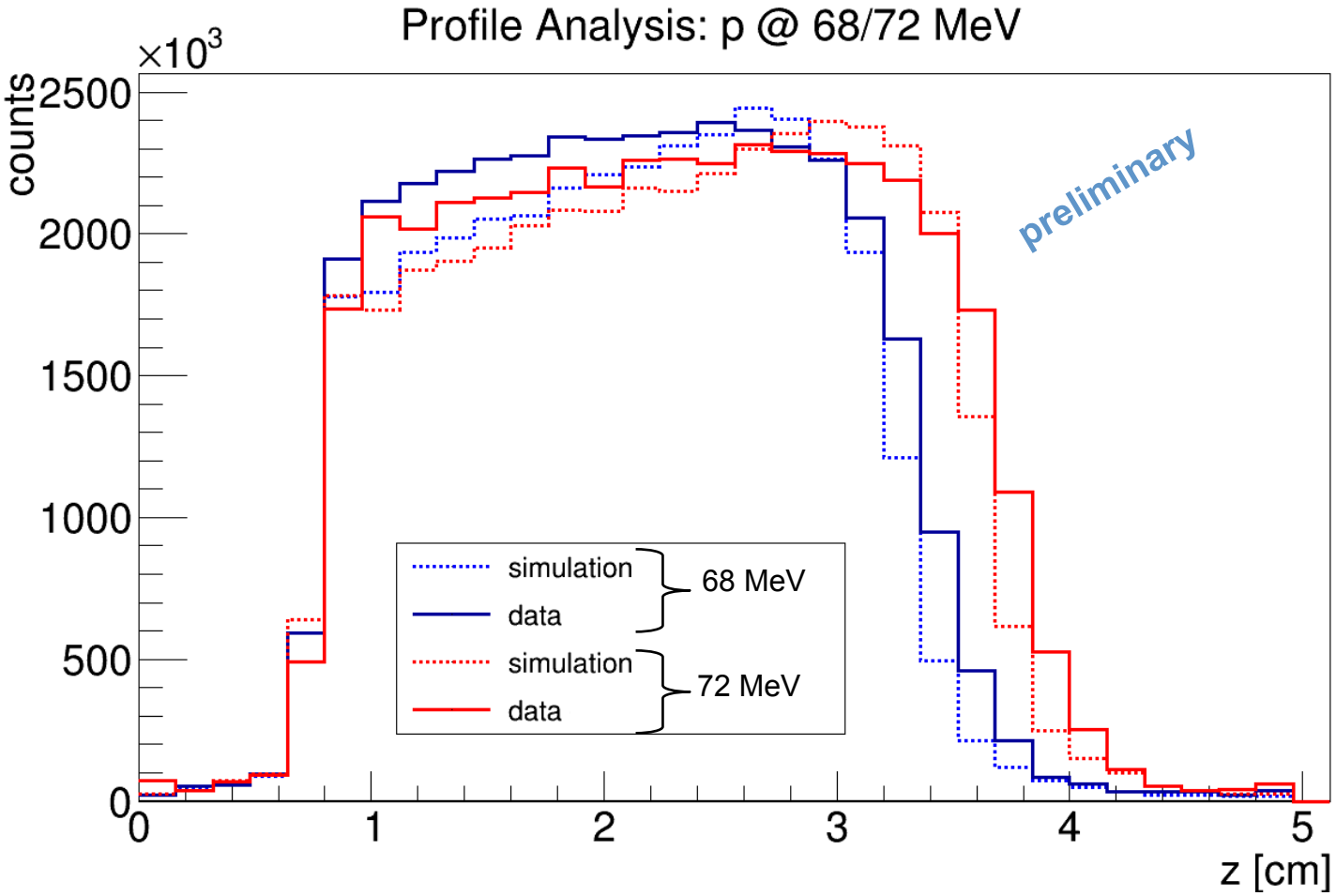
PET reconstructed images







PET beam test May 2015 @ CNAO (III)



Correction for isotopes not simulated
(14% during, 5% after treatment)

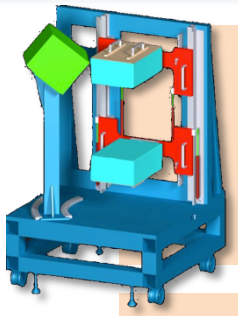
↓

Quantitative compatible simulation and real data profiles.
Distal fall off evaluation: simulation and real data difference < 1 mm

↓

The MC simulation is a reliable tool to evaluate the performance of the full in-beam PET system.

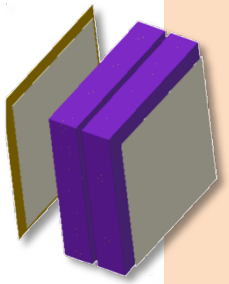
Conclusions & Prospects



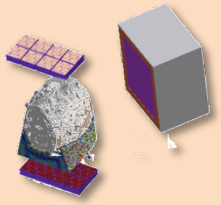
The INSIDE Project combines:

- β^+ activity detection: **IN-BEAM PET HEADS**
- secondary particle tracking: **DOSE PROFILER**

to provide 3D real-time monitoring in hadrontherapy

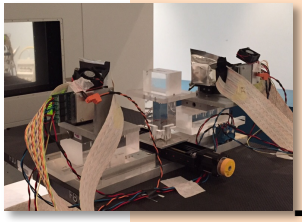


MC simulations:
essential for system design, development and operation



In-beam PET: two-steps technique reduces the simulation time (70x), validation on real data

Dose Profiler: secondary particle signal quantification with ^{12}C beam



In-beam PET first modules (tested at CNAO, May 2015):

- very satisfactory results
- both in-spill and inter-spill/after treat. PET images
- adequate coincidence time resolution

The INSIDE system commissioning at CNAO by the early of 2016.

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