First tests for in-beam proton and carbon therapy treatment monitoring with a planar PET system at CNAO

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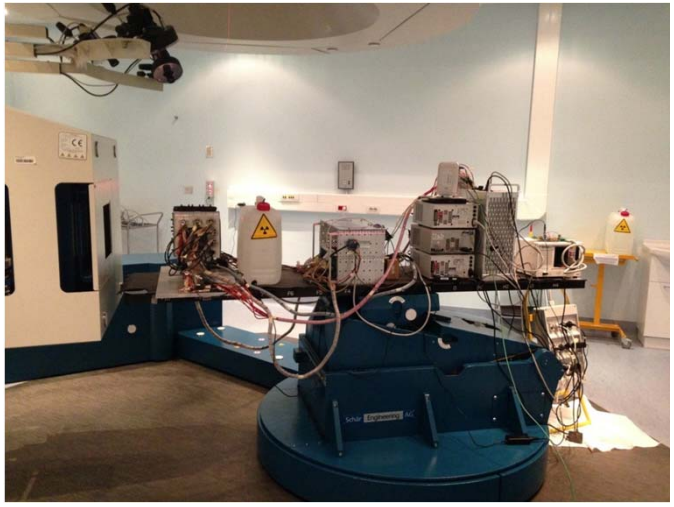
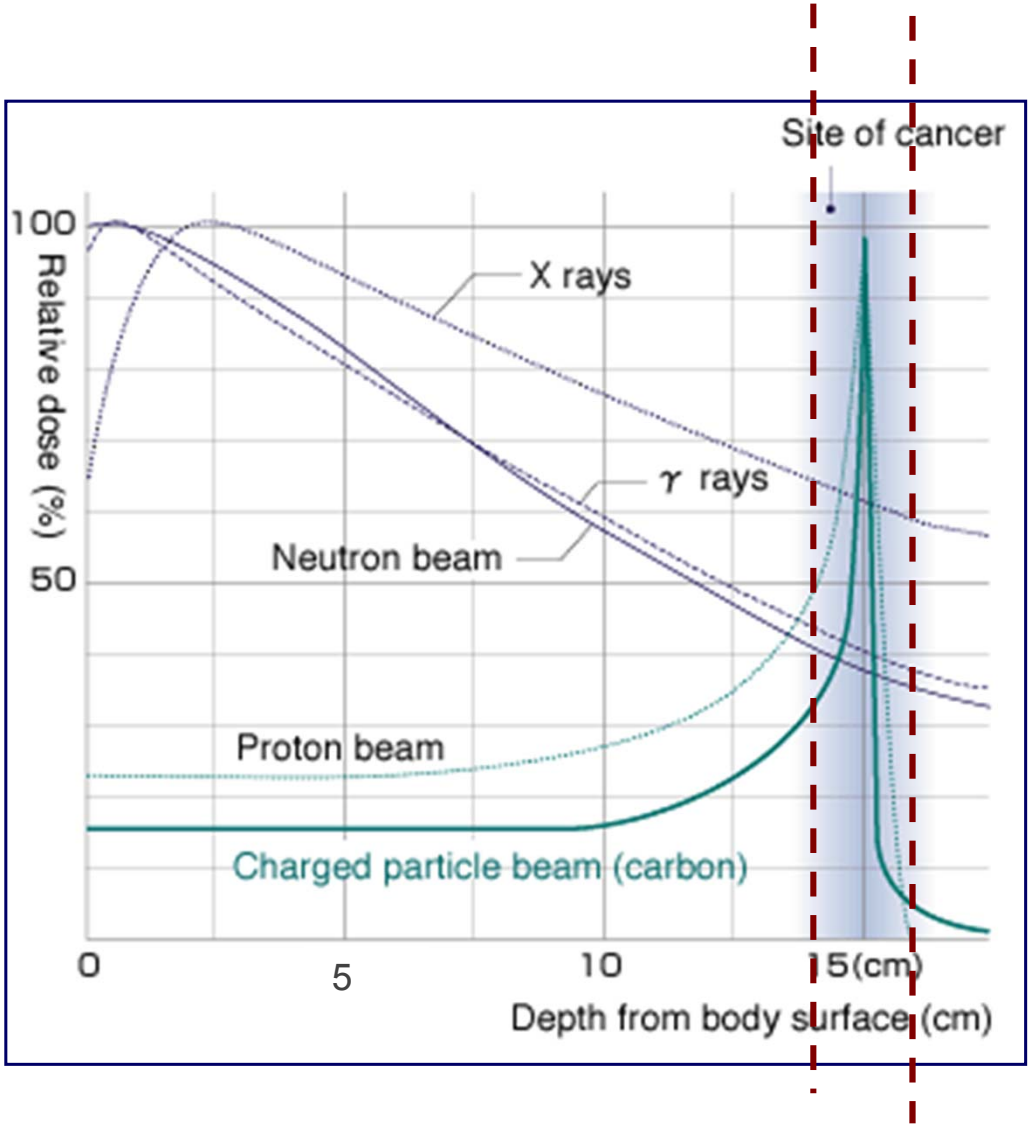


Frontier Detectors for Frontier Physics
13th Pisa meeting on advanced detectors
La Biodola, May 24-30, 2015

Dose profile in water

Charged particles have highly advantageous dose profile



- ❑ Relatively low entrance dose (plateau)
- ❑ Maximum dose at depth (Bragg peak)
- ❑ Rapid distal dose fall-off
- ❑ Energy modulation (Spread-out Bragg peak)
- ❑ Enhanced RBE

Uncertainties in particle therapy

Physics related

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

Patient related

- daily positioning on the coutch
- internal organ motion
- changes in air cavities
- tumour regression
- weight loss

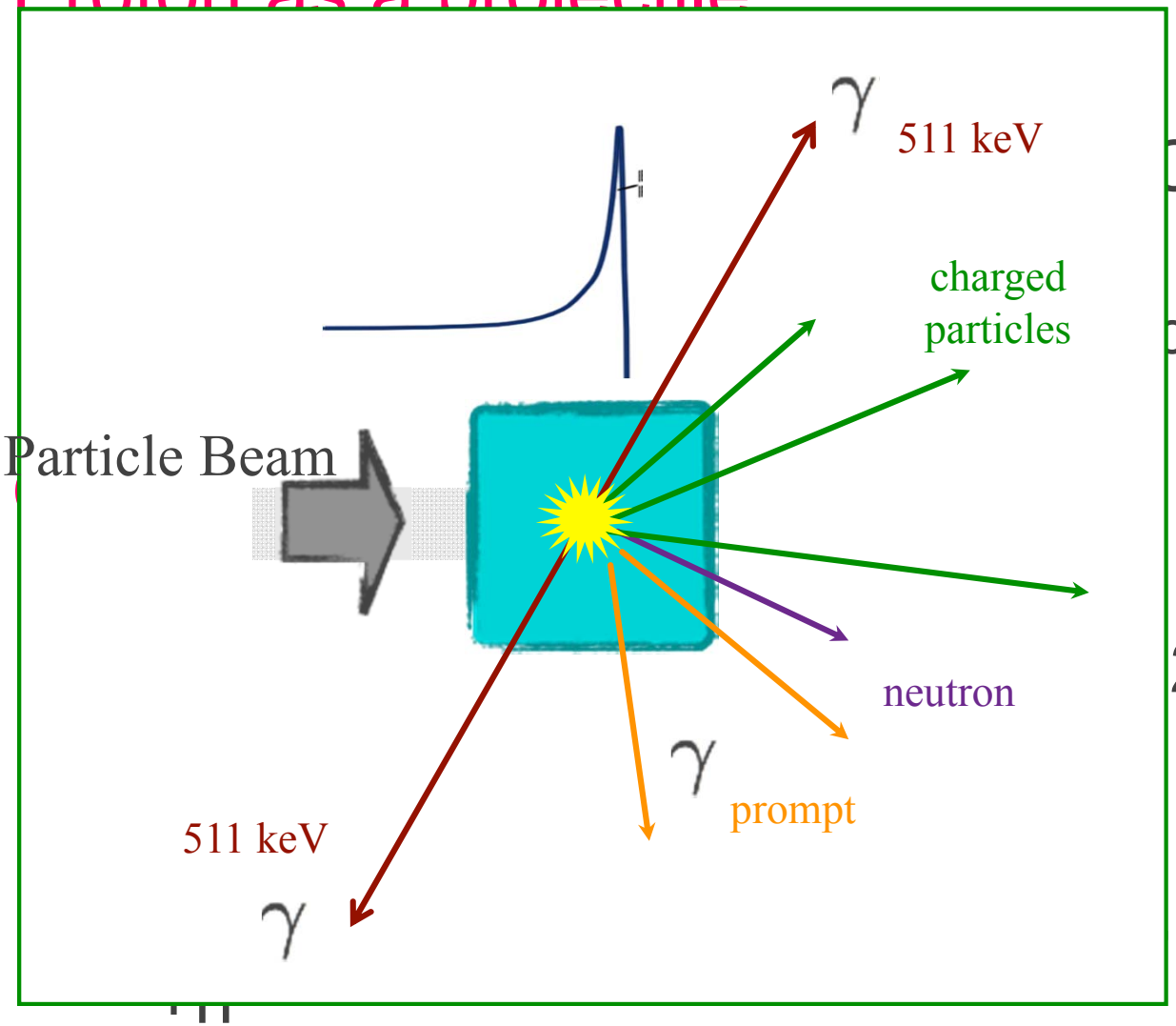
Other sources

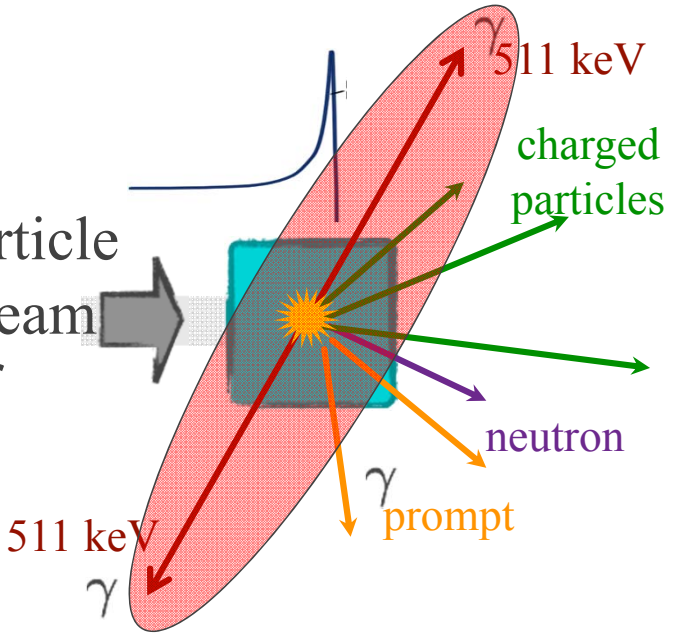
- RBE values
- Tumor heterogeneity
- Contouring uncertainties
- Reconstruction artifacts in CT
- Machine related

Monitoring is advisable

Particle Therapy monitoring

Proton as a projectile:





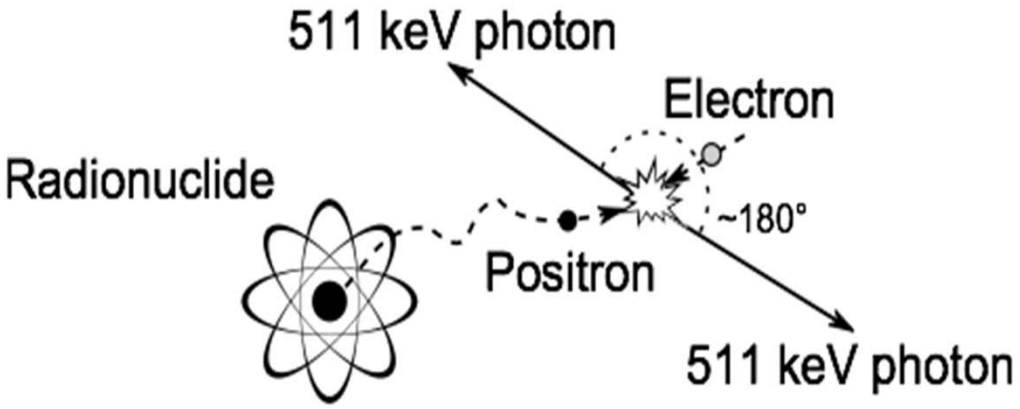
$\tau_{15\text{-}O}$=121.8 s $\tau_{11\text{-}C}$ =1222.8 s

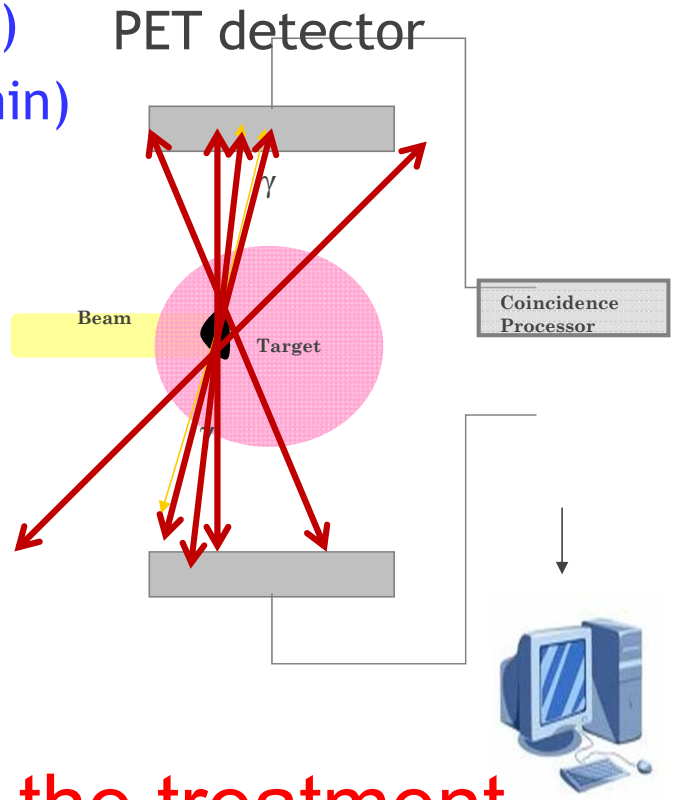
Positron Emission Tomography (PET) for Particle Therapy monitoring

- Protons and carbon produce β^+ emitters in living matter

$p + {}^{16}O \rightarrow (p,n) + {}^{15}O \rightarrow {}^{15}N + \beta^+ + \nu \quad \tau_{15\text{-}O} = 121.8\ s\ (2\ min)$

$p + {}^{12}C \rightarrow (p,n) + {}^{11}C \rightarrow {}^{11}B + \beta^+ + \nu \quad \tau_{11\text{-}C} = 1222.8\ s\ (20\ min)$

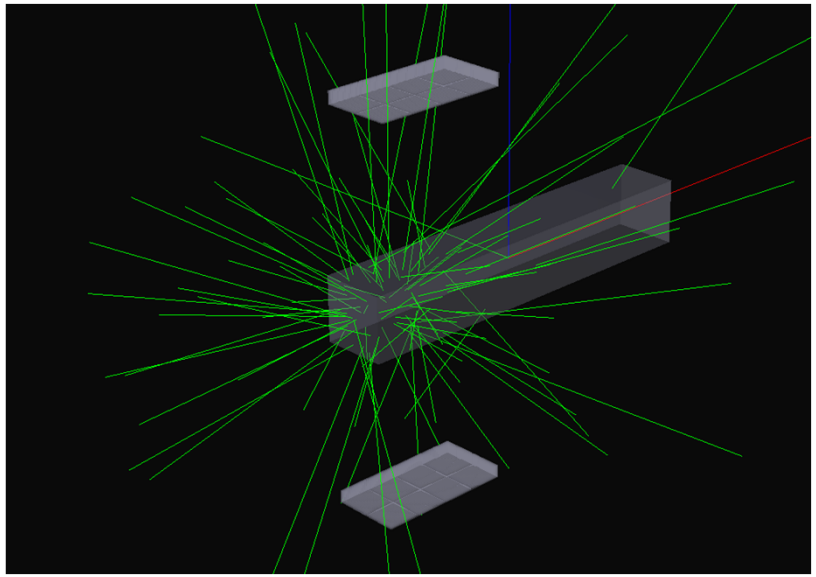




Measuring the β^+ activity we monitor the treatment

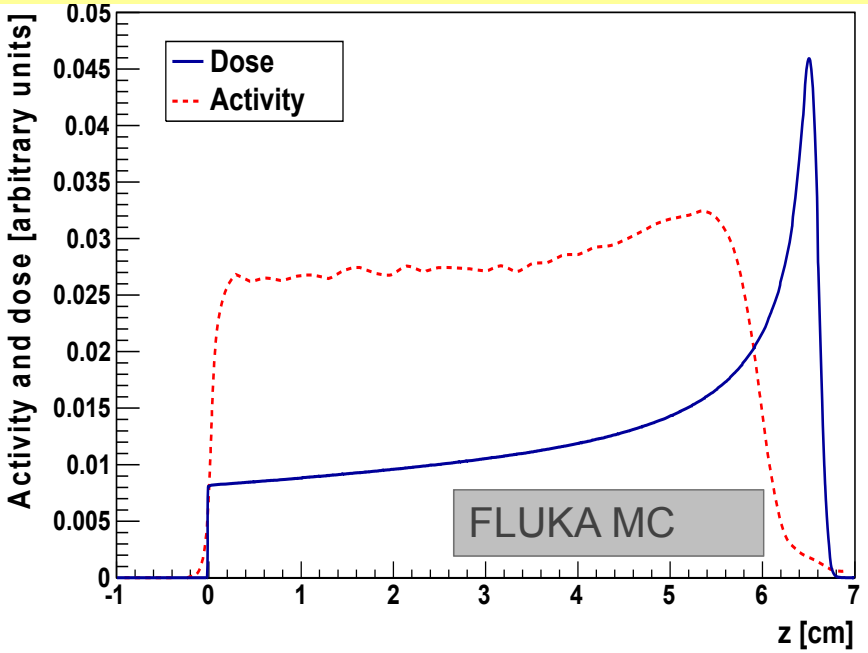
β^+-emitter	Half-life (min)	Reaction Channel	Threshold energy (MeV)
^{15}O	2.037	$^{16}O(p,pn)^{15}O$	16.79
^{11}C	20.385	$^{12}C(p,pn)^{11}C$	20.61
		$^{14}N(p,2p2n)^{11}C$	3.22
		$^{16}O(p,3p3n)^{11}C$	59.64
^{13}N	9.965	$^{16}O(p,2p2n)^{13}N$	5.66
		$^{14}N(p,pn)^{13}N$	11.44
^{30}P	2.498	$^{31}P(p,pn)^{30}P$	19.7
^{38}K	7.636	$^{40}Ca(p,2p2n)^{38}K$	21.2

Zhu, Theranostics (2013) 3(10):731-40



	Density	H(%)	C (%)	0 (%)
PMMA	1.18	8	60	32
H2O	1.0	11.19		88.81

95 MeV protons on PMMA

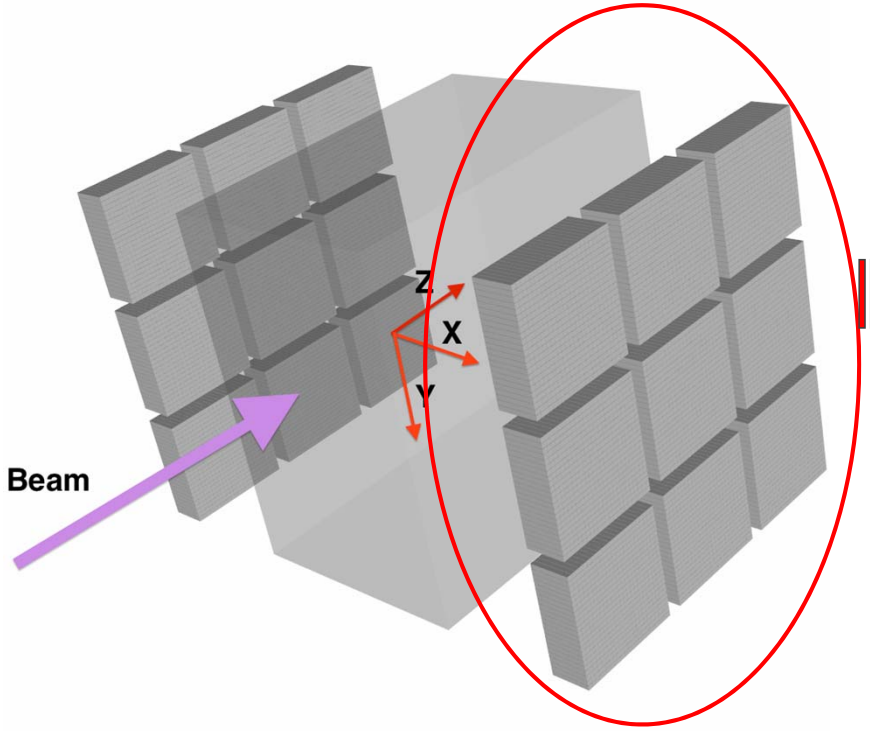


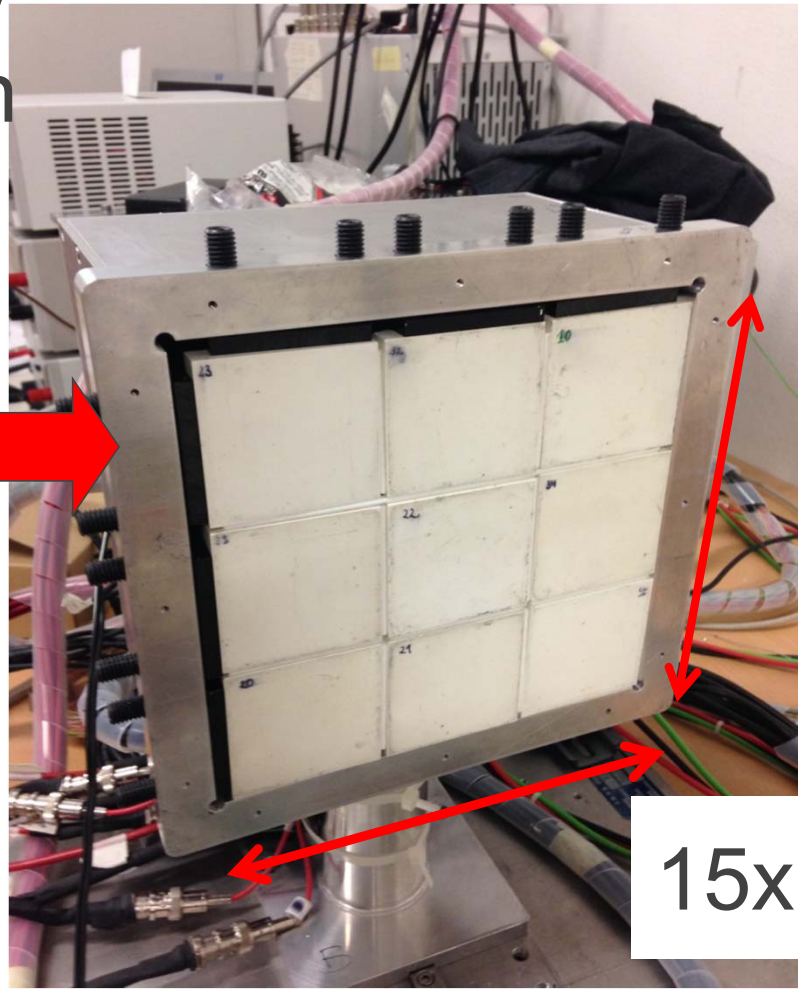
http://www.fluka.org

DoPET

DoPET is a stationary 2 heads tomograph

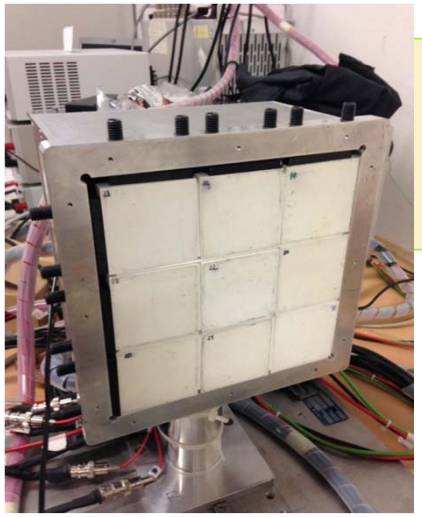
- gantry compatibility
- in-beam acquisition





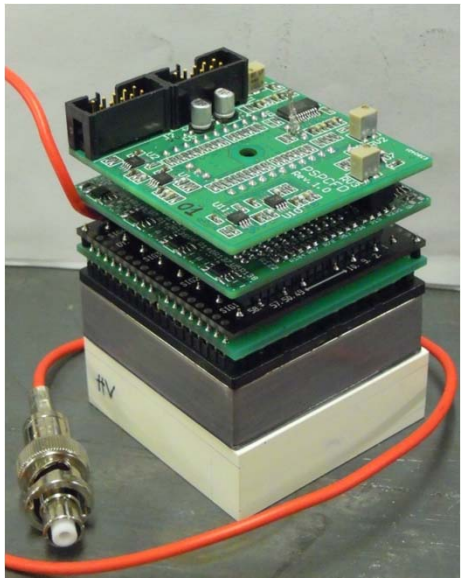
9 modules per head

15x15 cm^2



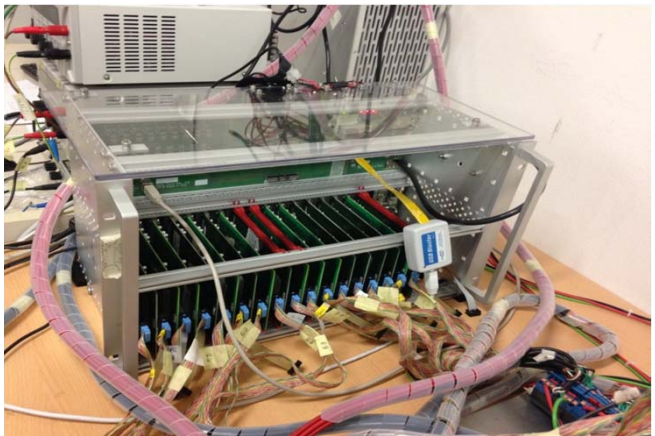
DoPET 9vs9

The current prototype is an upgrade of the 4x4 DoPET system



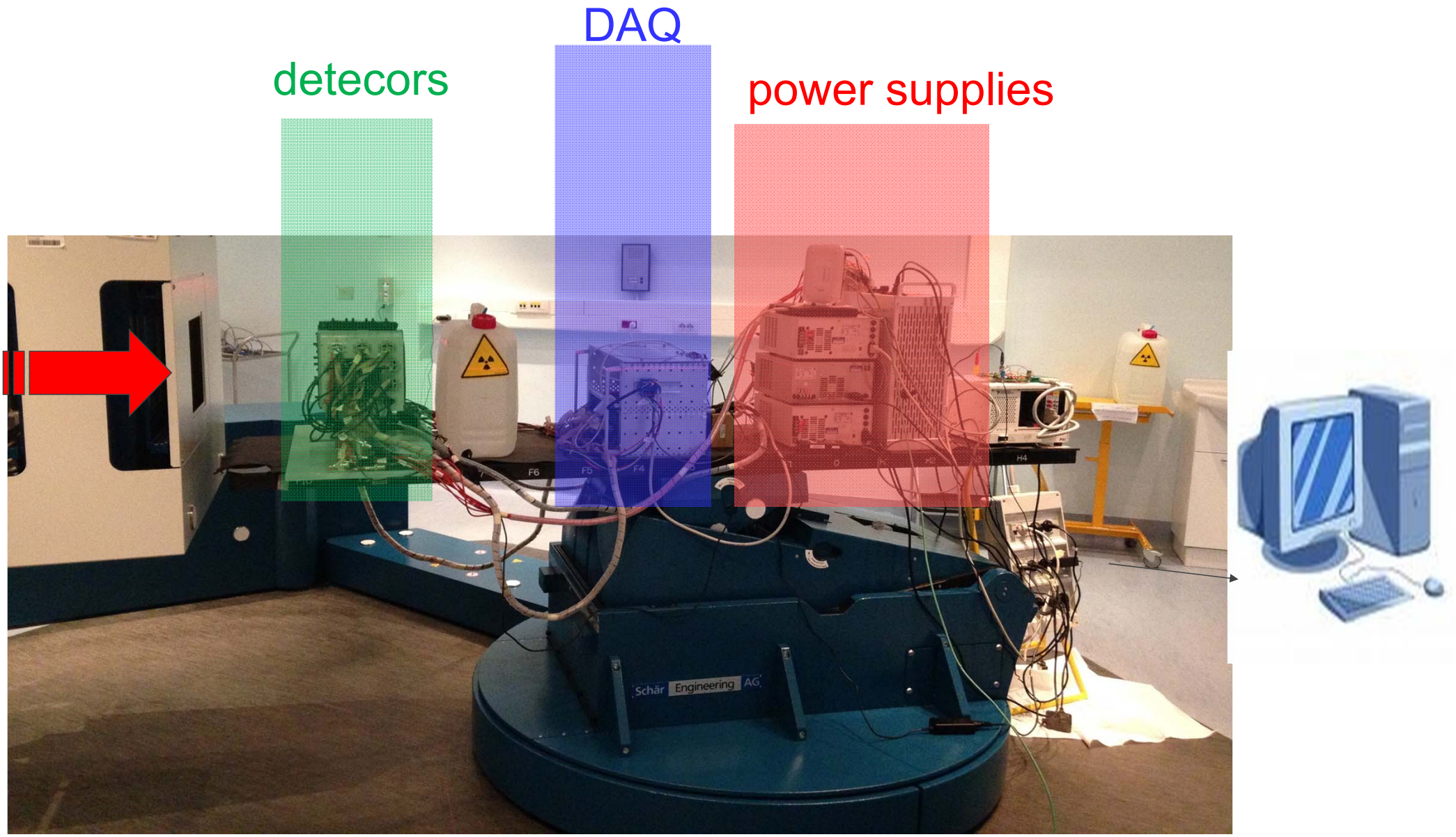
Vecchio, IEEE Trans. Nucl. Science, 56 (1), (2009)
Sportelli, IEEE Trans. Nucl. Science 58 (3) (2011)

- Detecting module (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 ~5 ns.



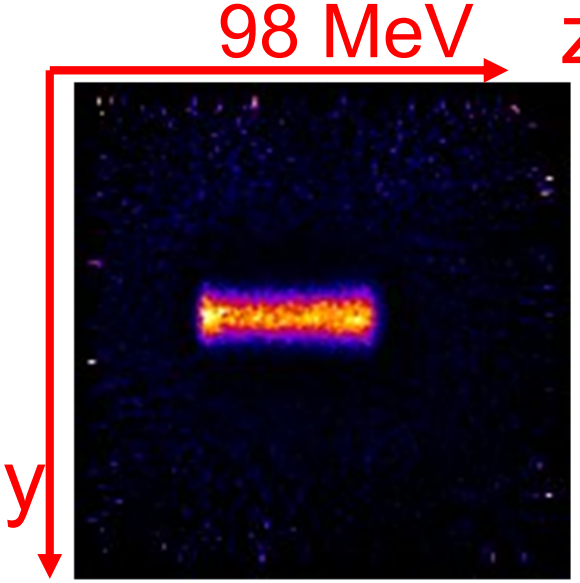
- ➢ Activity is reconstructed with Maximum Likelihood Estimation Maximization (MLEM)
- ➢ Iterative algorithm
  - ➢ Reconstruction transforms acquired data in a 3D-activity distribution
- ➢ The reconstruction is performed in few minutes

the DoPET system @ CNAO

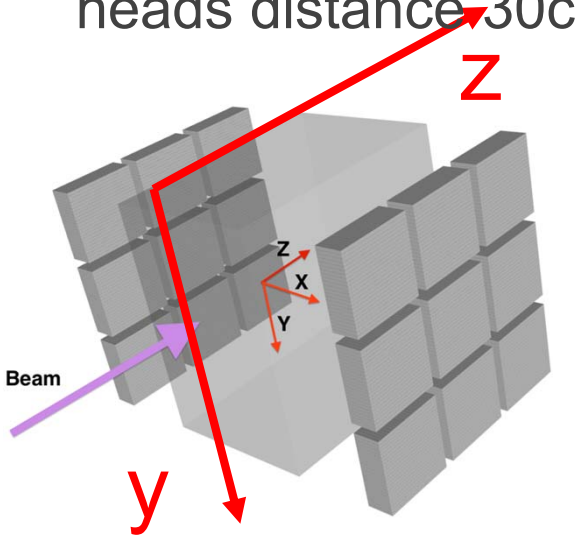


Protons and carbon ions on PMMA phantoms: activity images

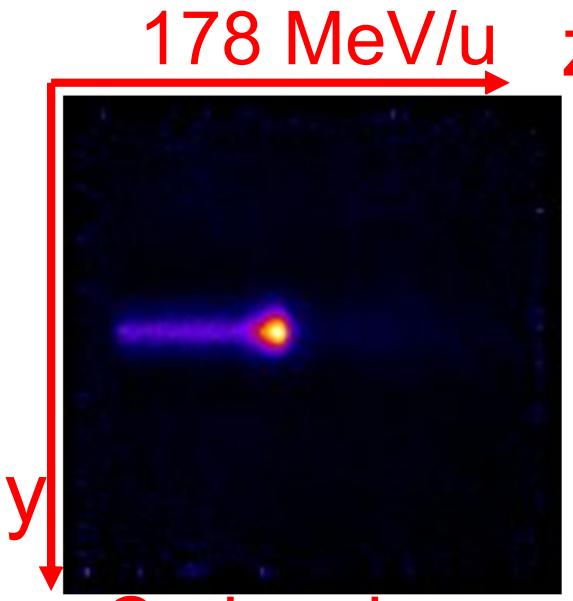
Proton beam
98 MeV

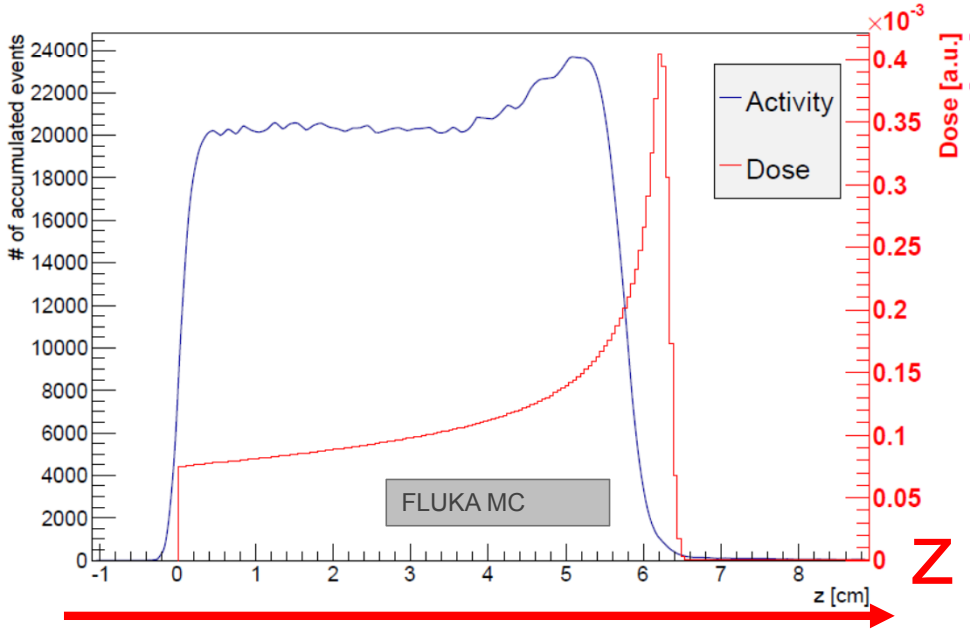


heads distance 30cm

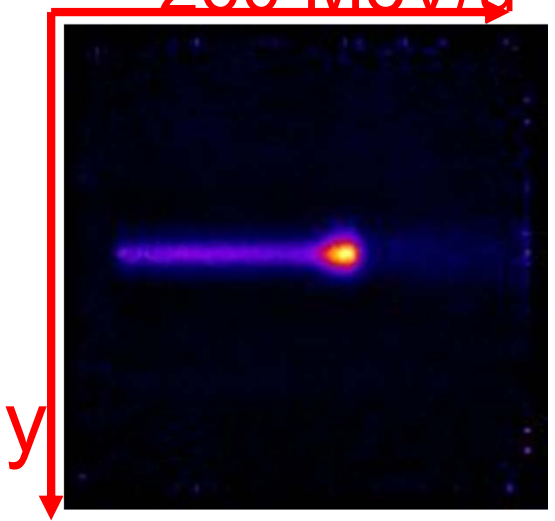


Carbon beam
178 MeV/u

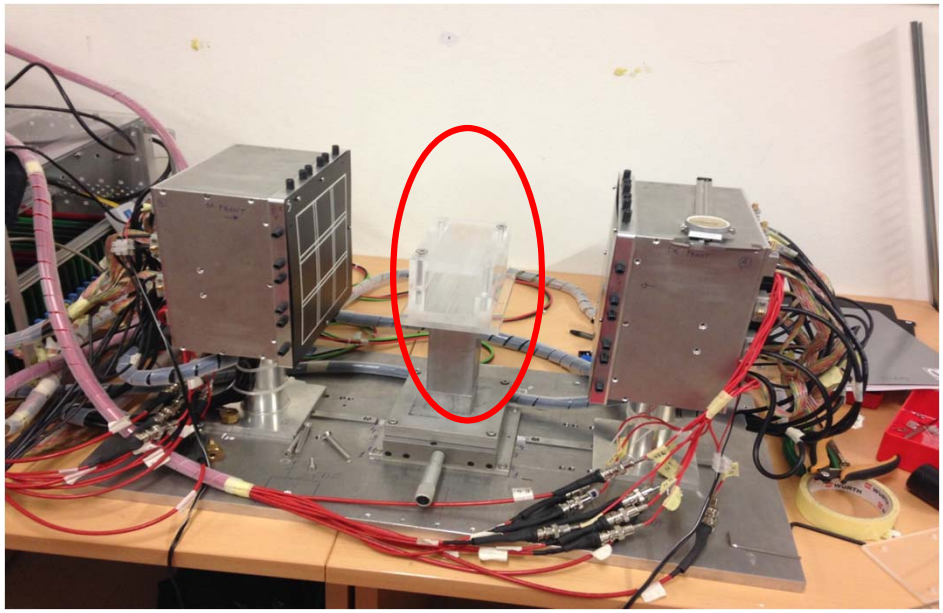




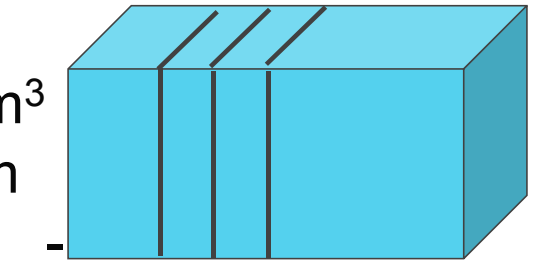
Carbon beam
260 MeV/u

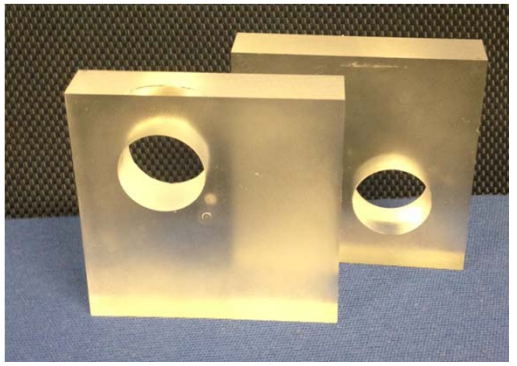


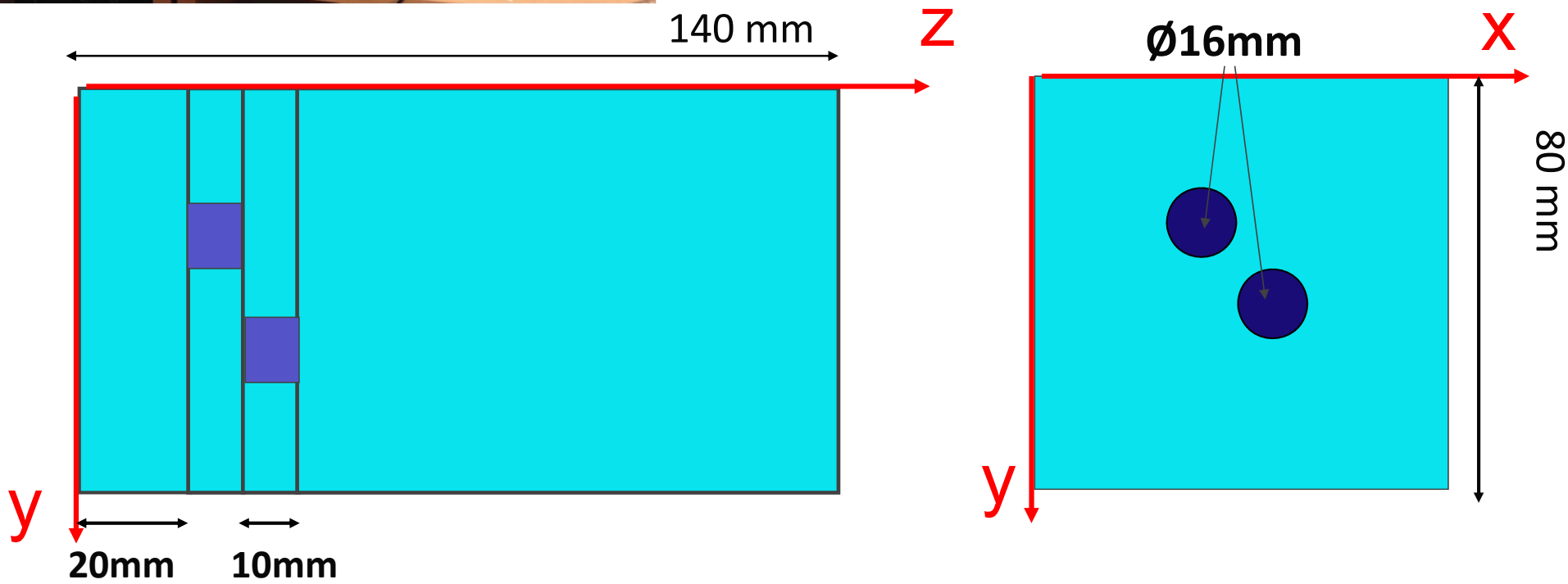
Heterogeneous PMMA phantom: 2 air cavities



-80x80x140 mm^3 PMMA phantom
-2 cavities:
z=10mm
Ø=16mm





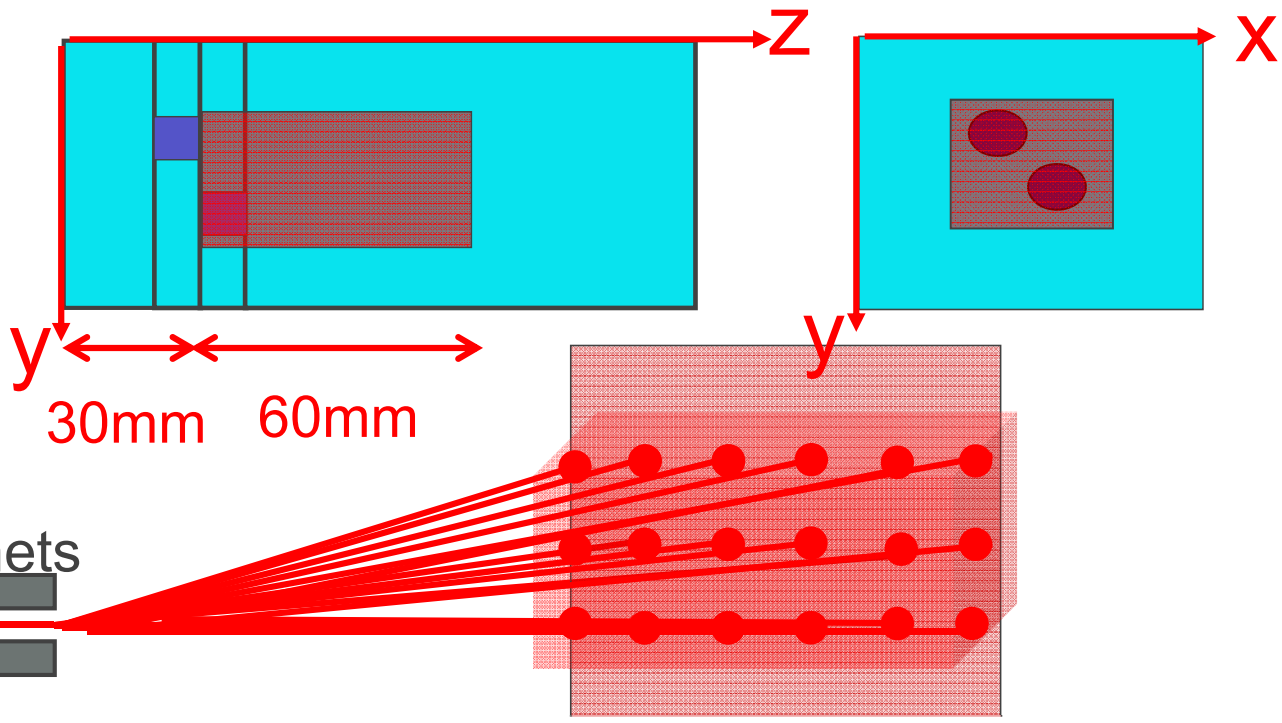


Pencil Beam Scannining Treatment Delivery

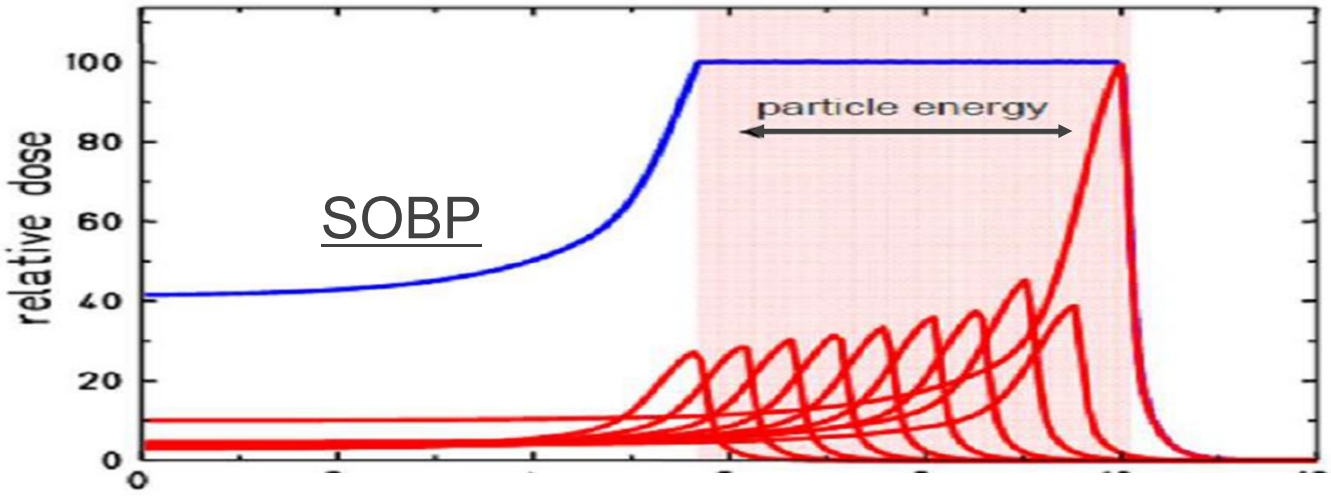
Planning-Target-Volume

PTV: 40x40x60 mm^3

from 30 to 90 mm in z



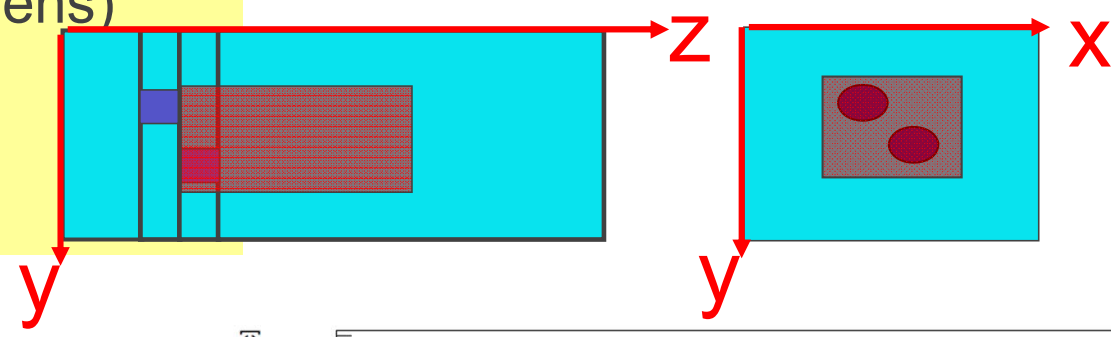
Uniform 2 Gy dose: the Treatment Planning System (TPS) chooses ions energies and their intensisties (SOBP)



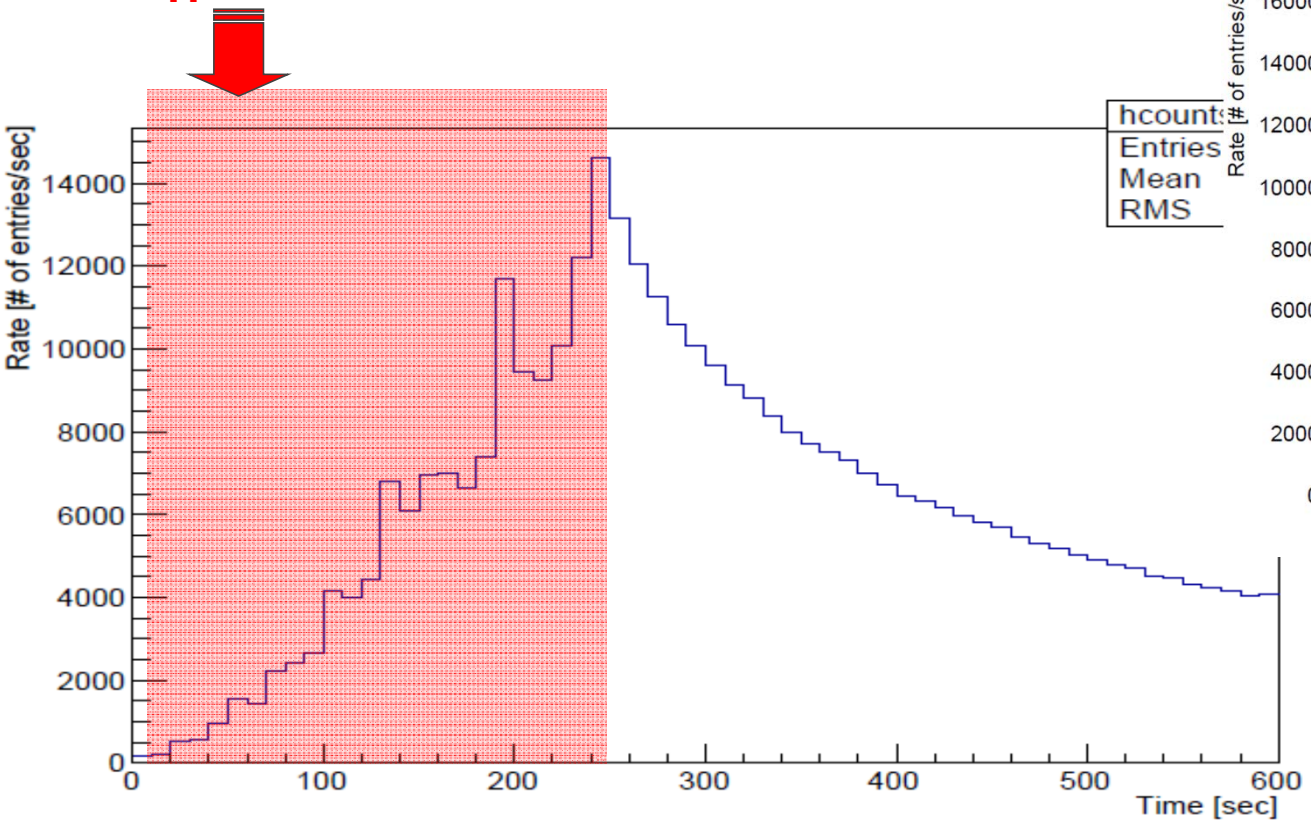
Proton 2Gy: Activity events time profiles

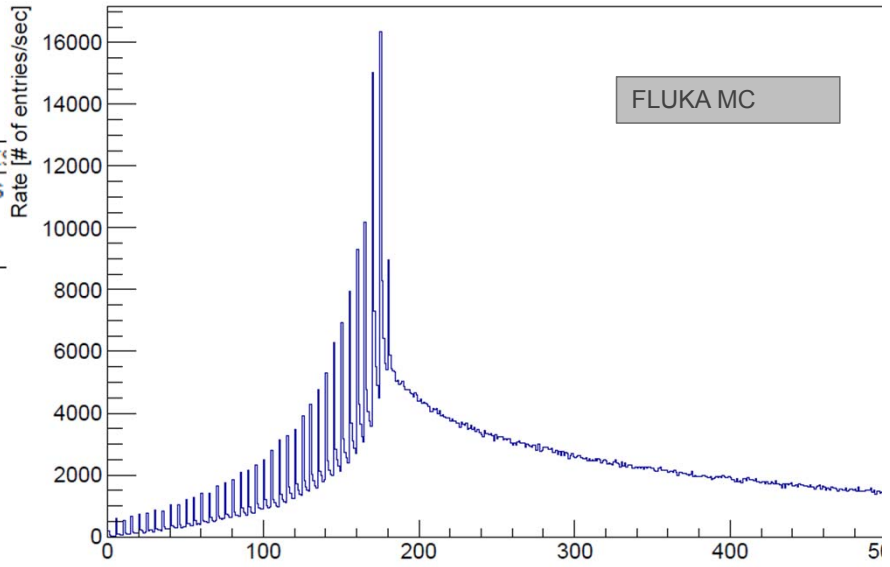
TPS: Syngo PT Planning VC12, Siemens)

- 2 Gy on PTV: 40x40x60 cm^3
- 62.3 MeV - 116 MeV (35 EL)



ΔT_{TP} = 230 s



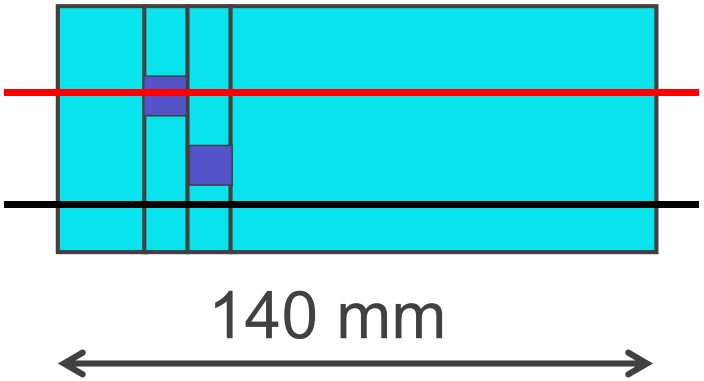


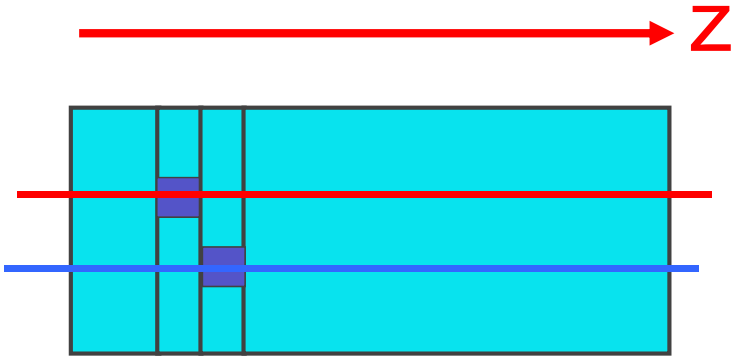
Exp. activity events time profile [0, 600 s]

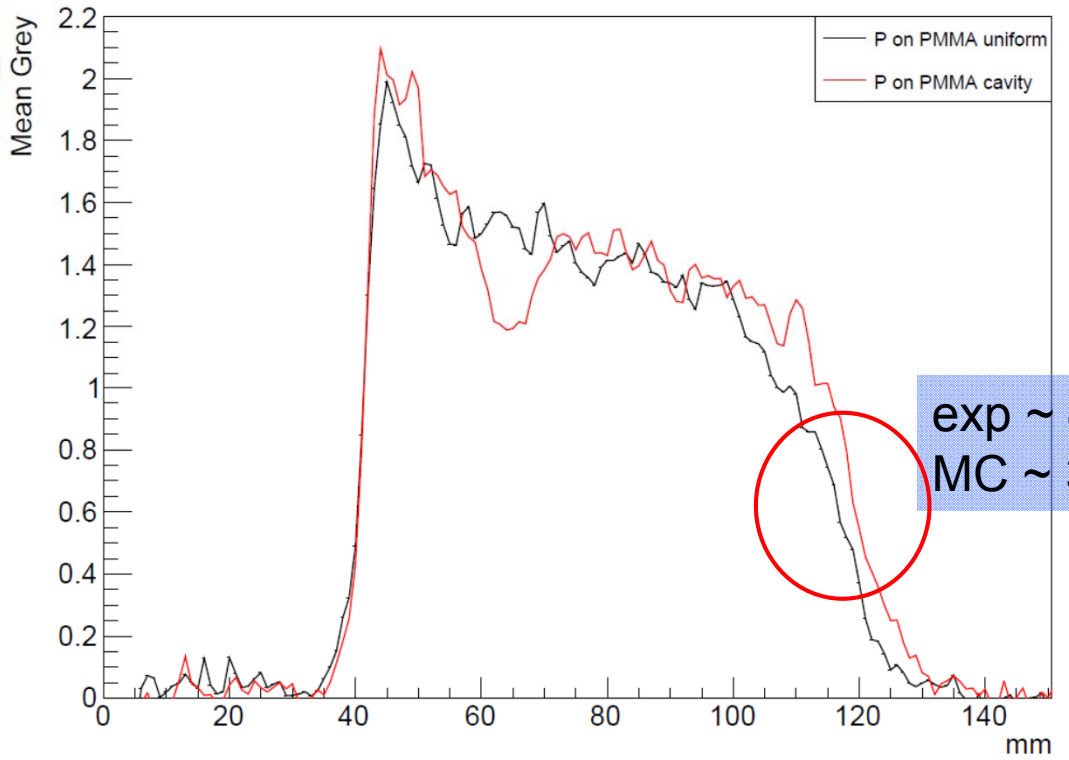
DoPET is partially paralized during the TP deliver

Proton 2Gy

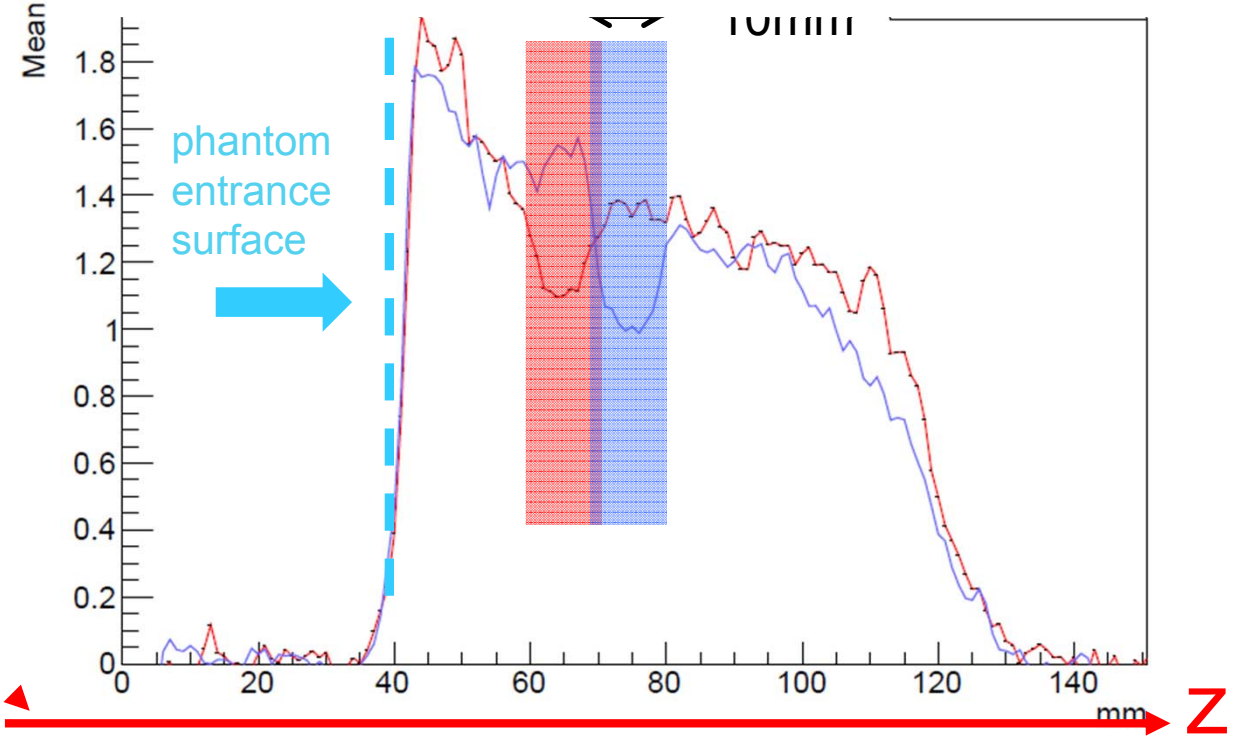
Activity: z profile [0, 600 s]





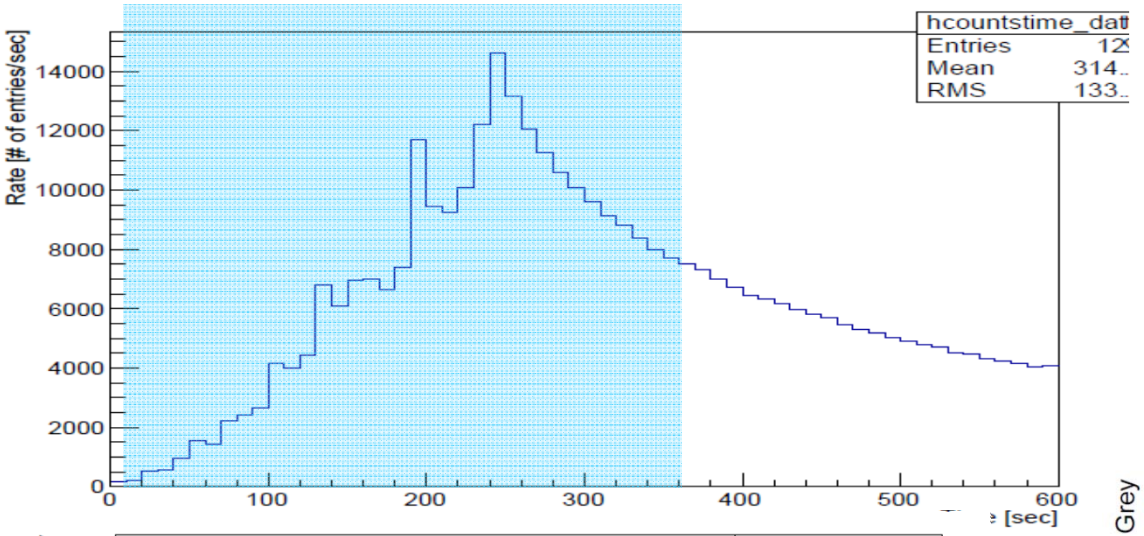


exp ~ 4 mm
MC ~ 3mm



Protons 2Gy:
can we reduce the acquisition time?

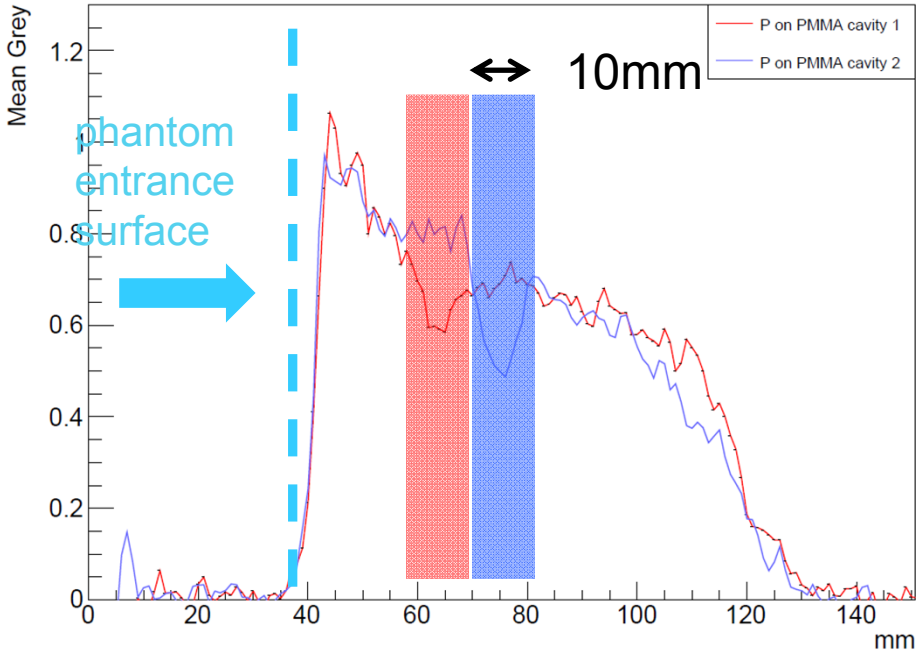
reducing acquisition time will reduce the room occupancy

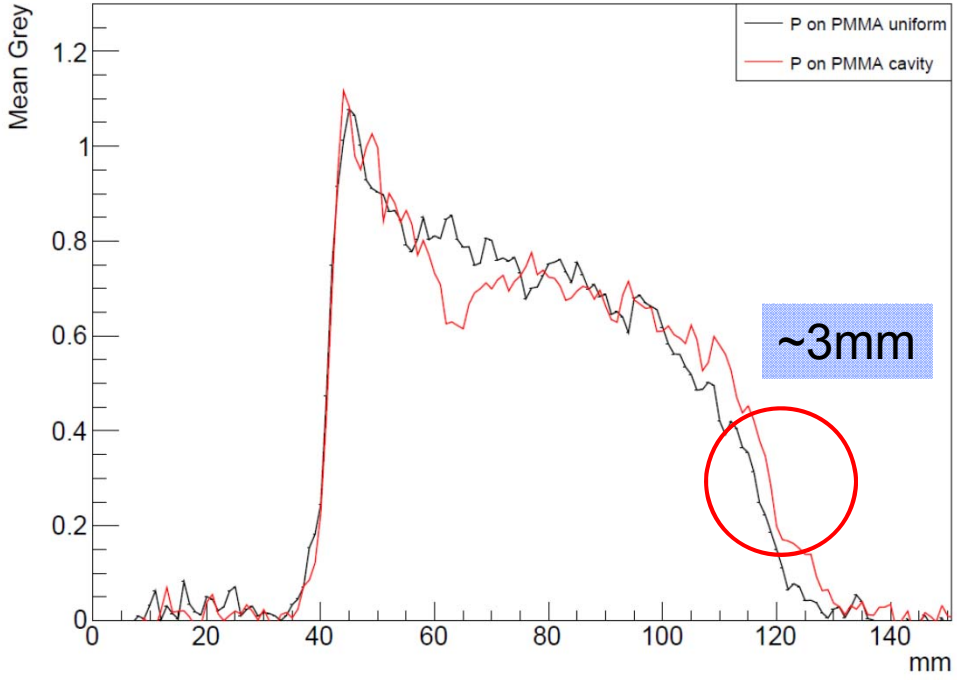


ΔT_{tot}= 360 s

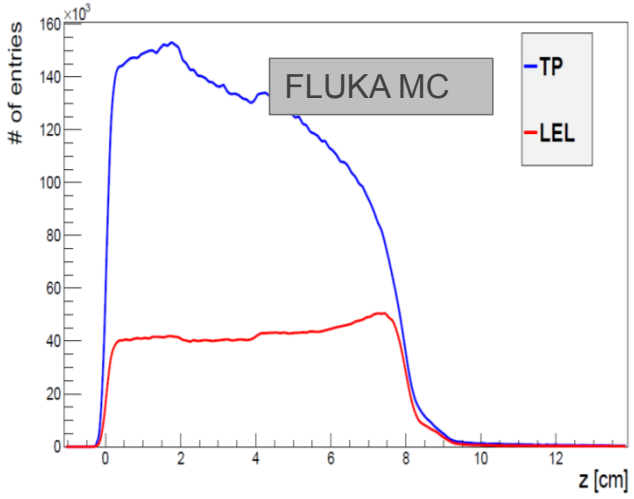
4' TP-delivery + 2'

more noisy profiles



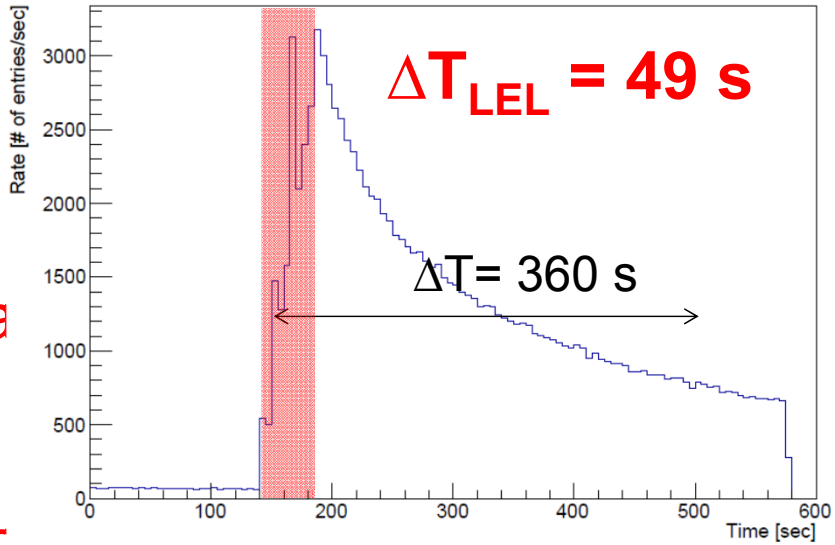


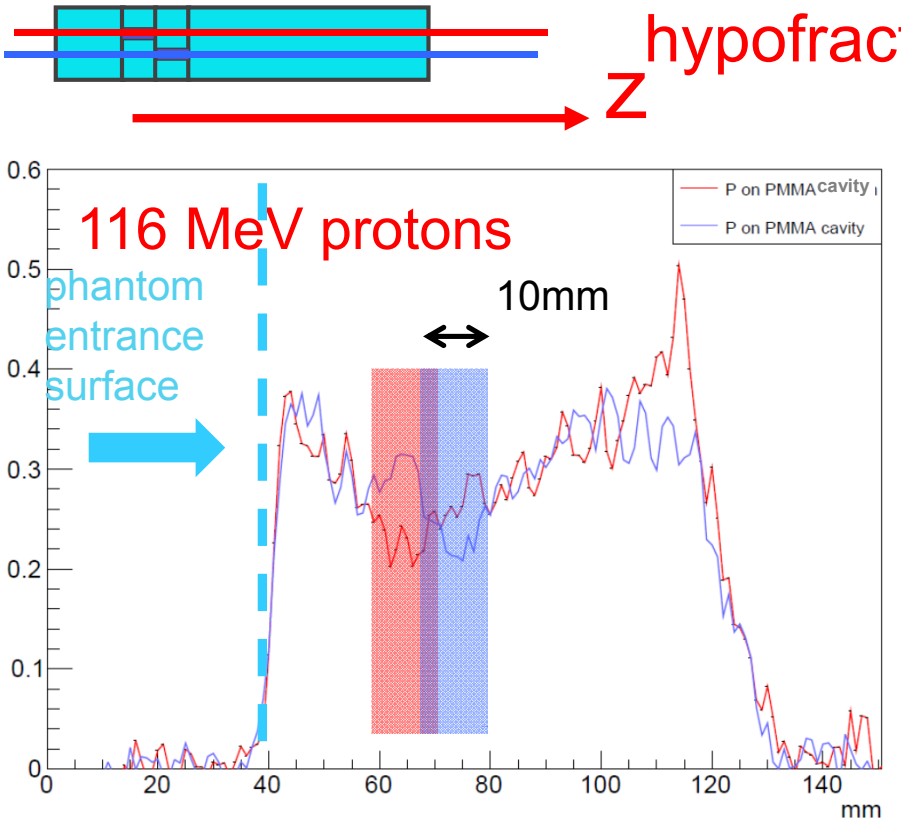
Last Energy Layer

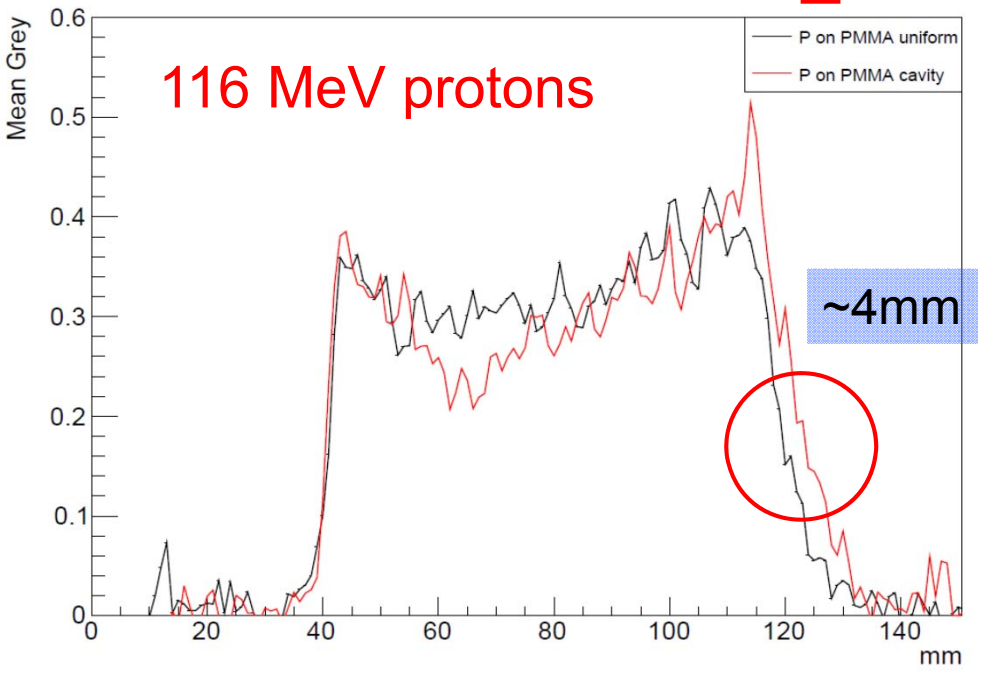


only LEL protons

The same information (still more noisy) with a smaller dose: helpful for hypofractionation?





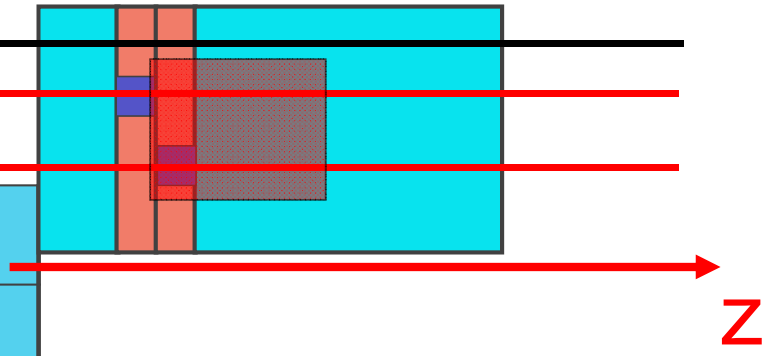


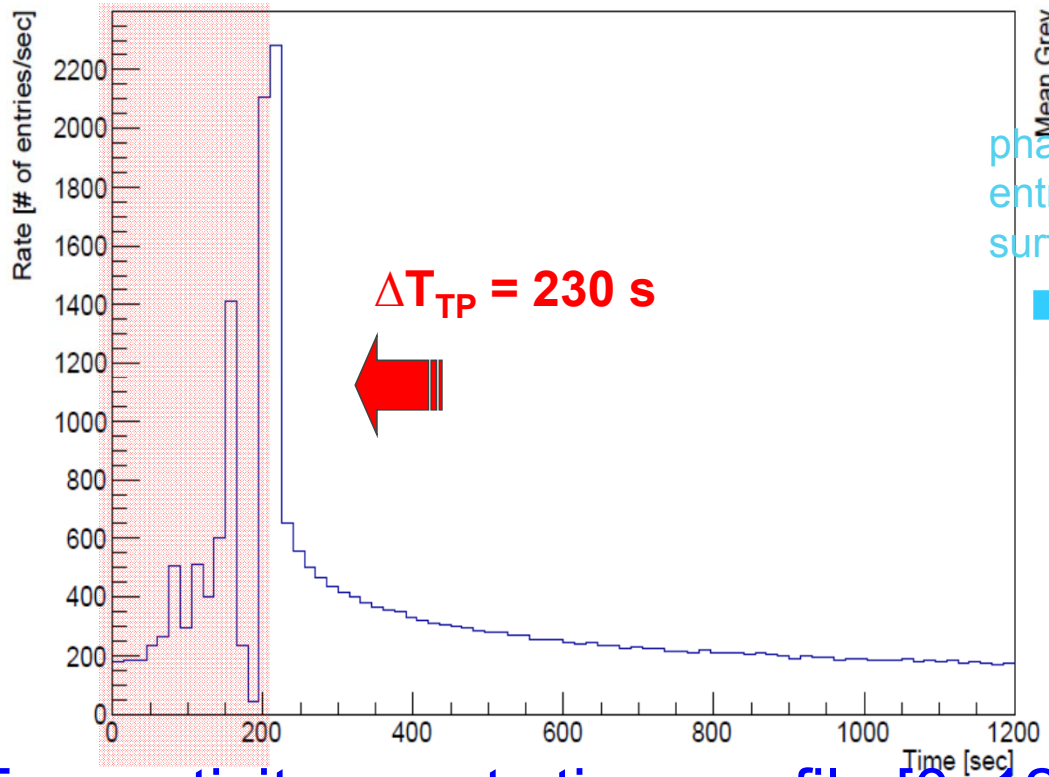
^{12}C TP, 2Gy on PMMA phantom with 2 cavities

TPS: Syngo PT Planning VC12, Siemens)

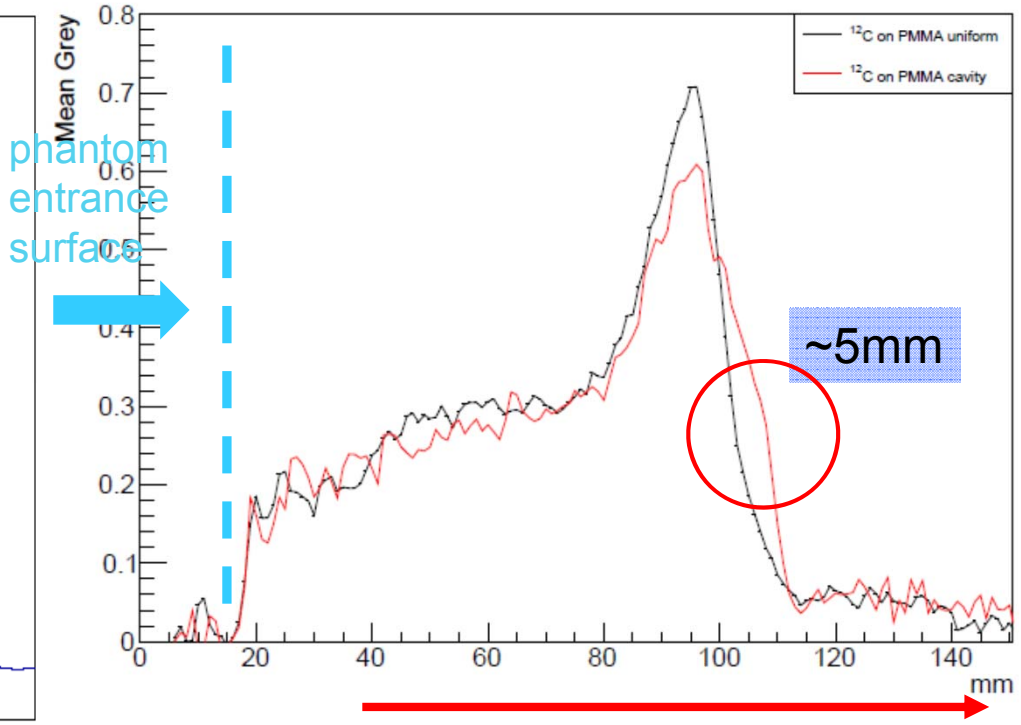
- 2 Gy uniform dose on PTV: 40x40x60 mm^3
- 123 MeV/u – 224/u (35 EL)

p	**12.7 10^4**	ΔT=600s 45.9 10^4
12-C	**2.4 10^4**	ΔT=1200s 8.3 10^4





Exp. activity events time profile [0, 1200 s]



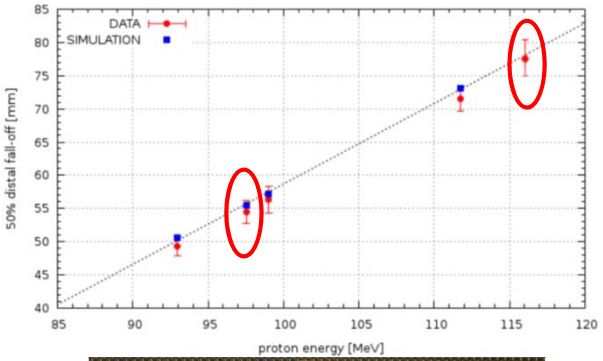
Exp. activity events z profile

Conclusions

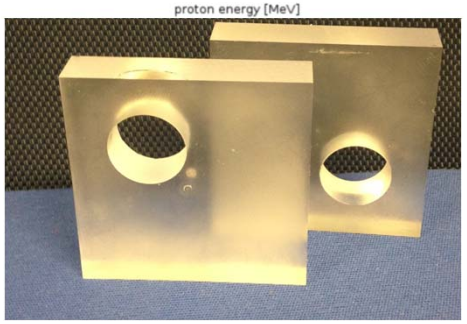
-the DoPET 9x9 prototype is able to acquire data also in-treatment

reduce room occupancy

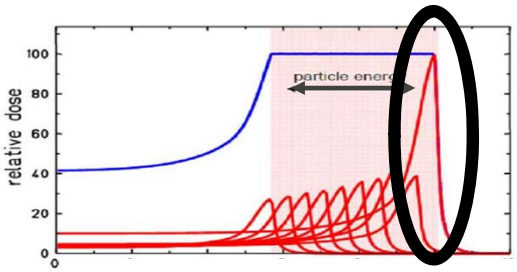
data are not affected by wash-out process



-the activity measurements are reproducible (see plot exp. data with **4x4 prototype and data 9x9 prototype)**



-the system is able to detect the precence of small cavities using 2Gy TP (protons and carbon ions)



-using LEL protons we can monitor the treatment (hypofractionation)

-anthropomorphous phantom irradiations have been performed: the data will soon be analyzed