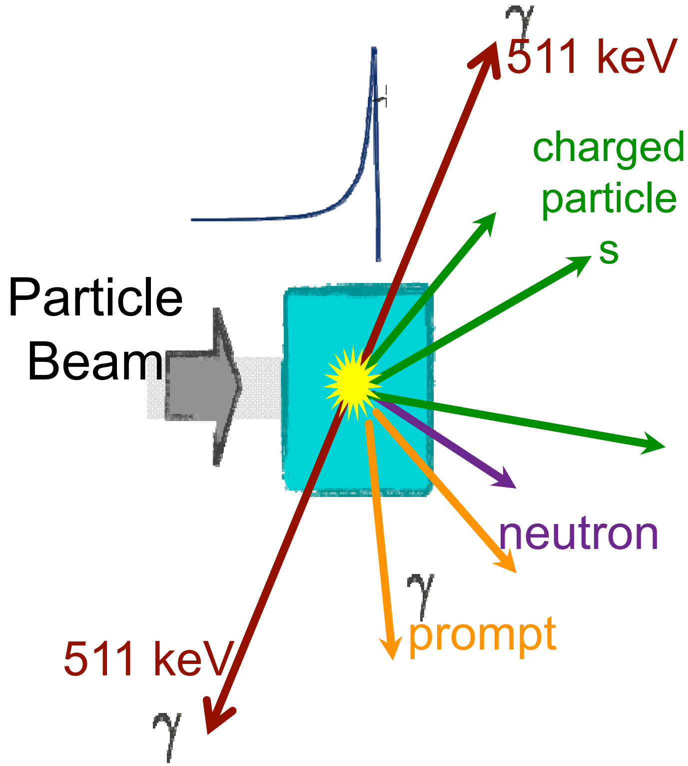
Proton therapy monitoring using PET

Proton as a projectile

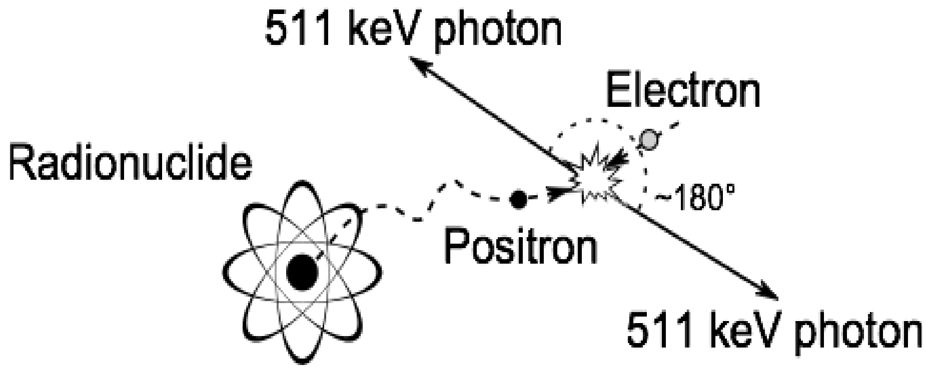


Fragmentation of the target:

^{16}O (p,n) ^{15}O ^{12}C (p,n) ^{11}C

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

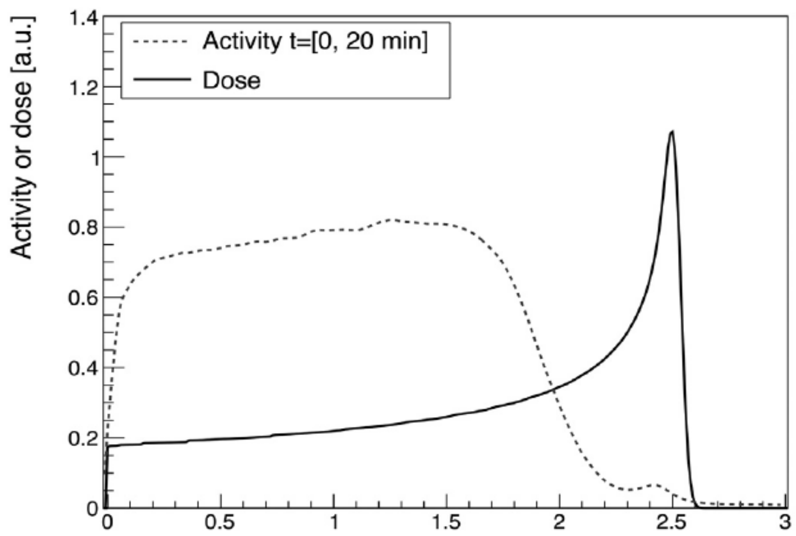
[15-20 MeV threshold for p-induced nuclear reactions]

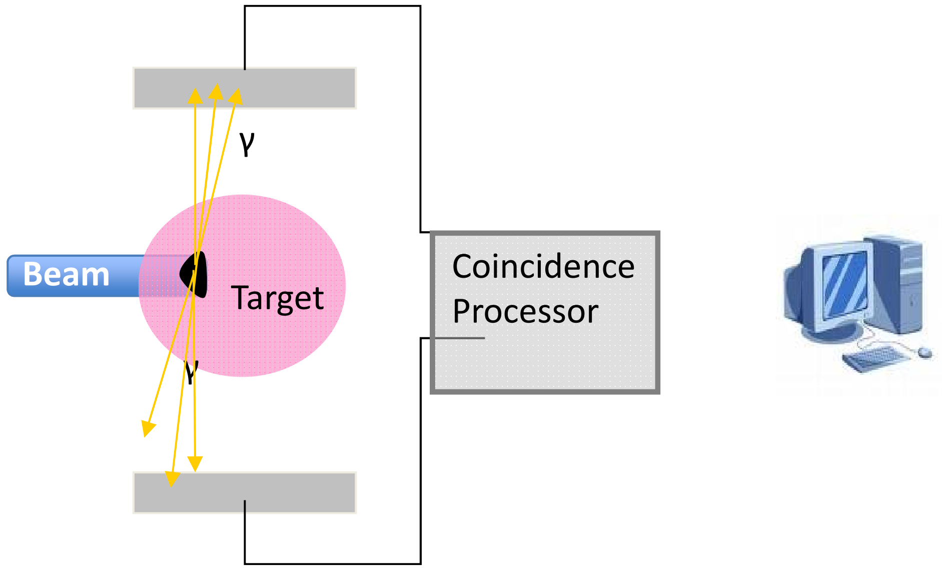


Measuring the β⁺ activated volume we monitor the treatment

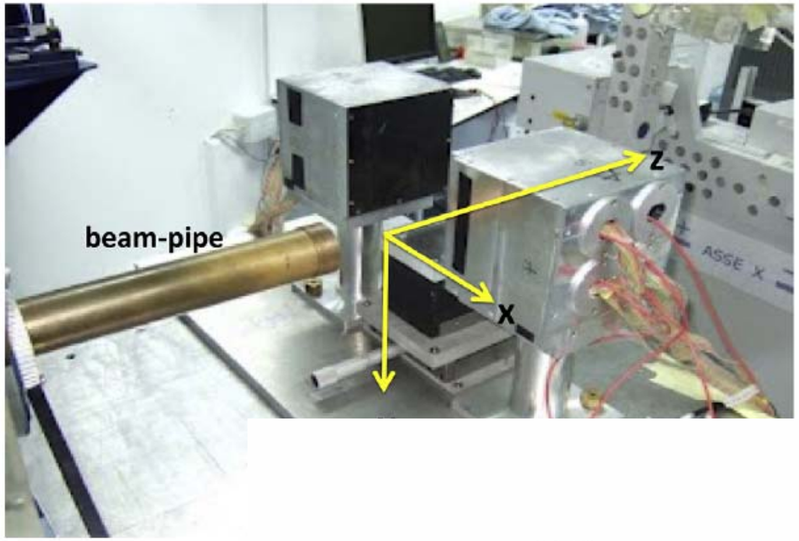
Dose and activity

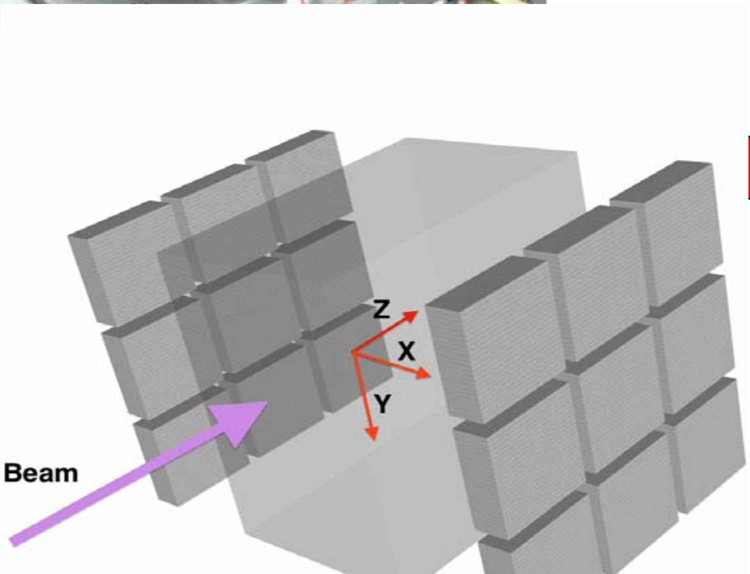
•Most consolidated way to verify the delivered dose is by means of PET
•Hadron beams induce β+ activity in patient
•Relation between activity and dose is indirect

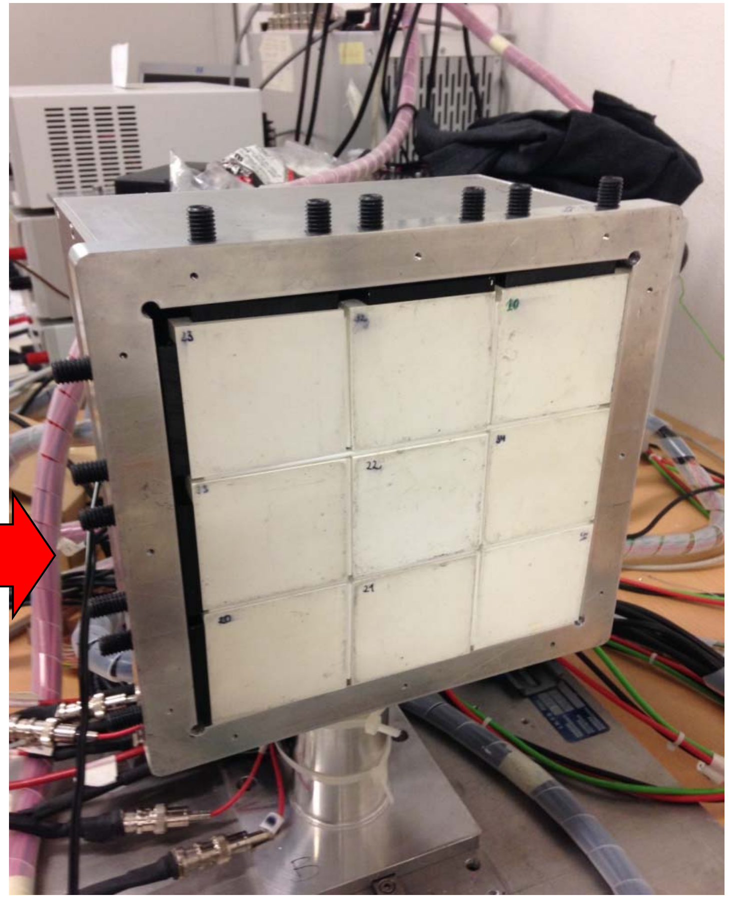




From the 4vs4 to 9vs9 prototype

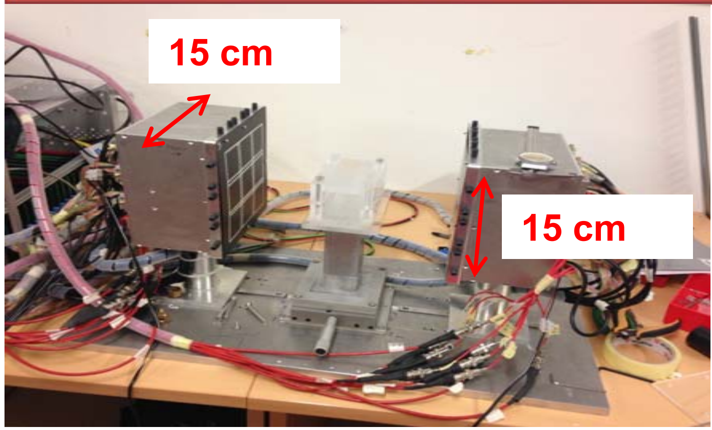




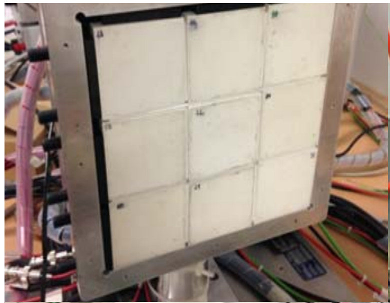


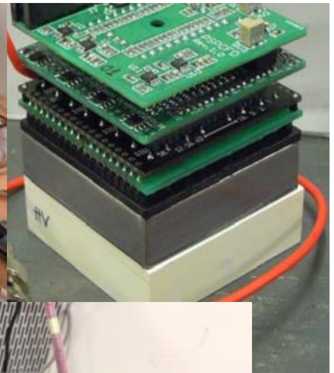
- Capability in beam-on data acquisition
- Advantages of beam-on data: no biological washout, less patient/organ movement, faster patient throughput

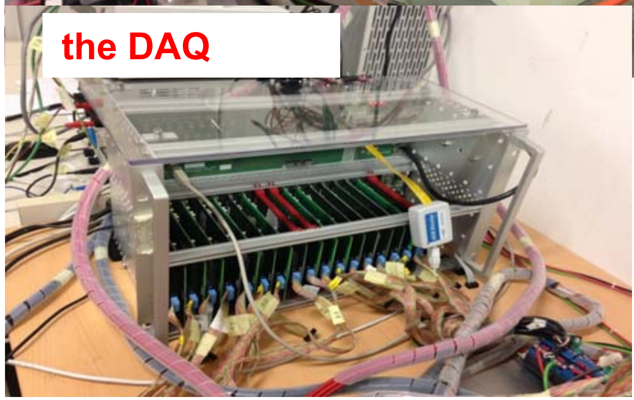
DoPET: 15 cm x 15 cm prototype



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

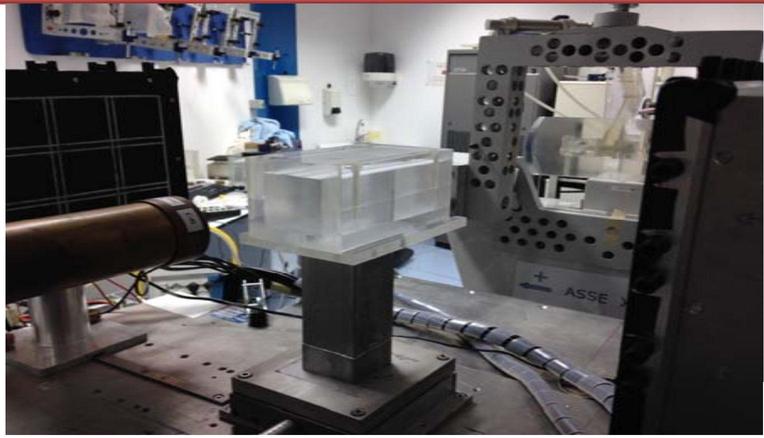
- Modularized acquisition electronics
  - FPGA based acquisition and coincidence processing
  - Coincidence time window ~5 ns

➢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

Several data taking were performed

CATANA

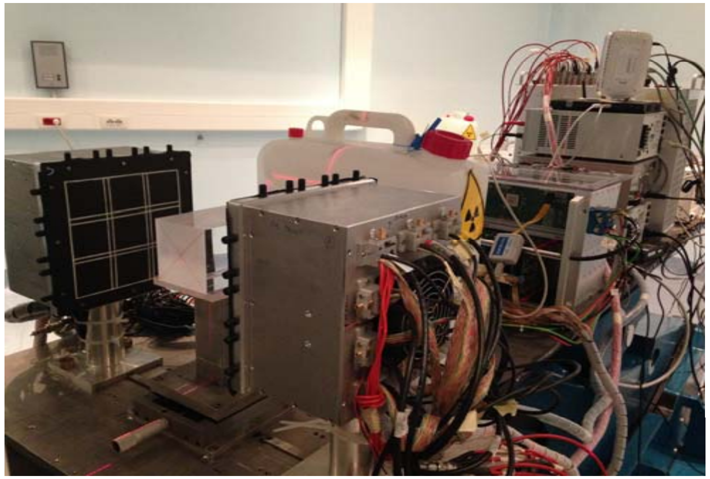


A. Kraan et al., Physica Medica 30 (2014) 559-569

V. Rosso et al., JINST, 11, C12029 (2016), 1-9

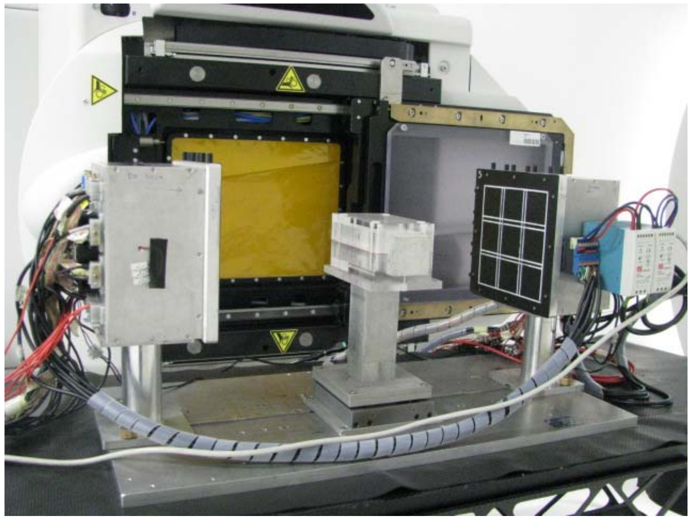
G. Sportelli et al., JINST, 10, C12029 (2015) 1-11

V. Rosso et al., Nucl Instr Meth, A824, (2016), 228-232



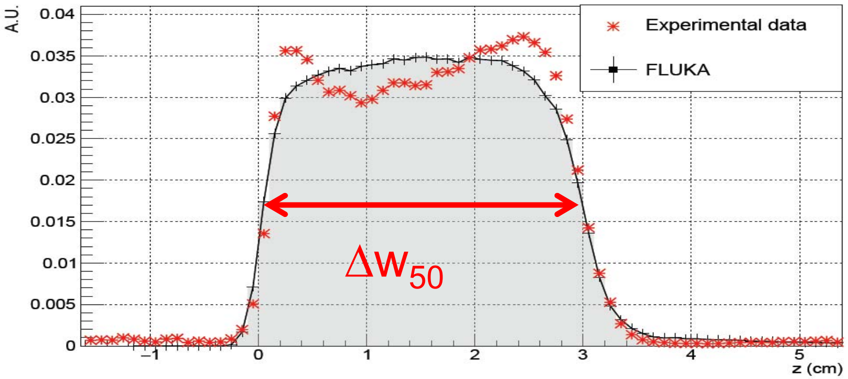
CNAO

TRENTO

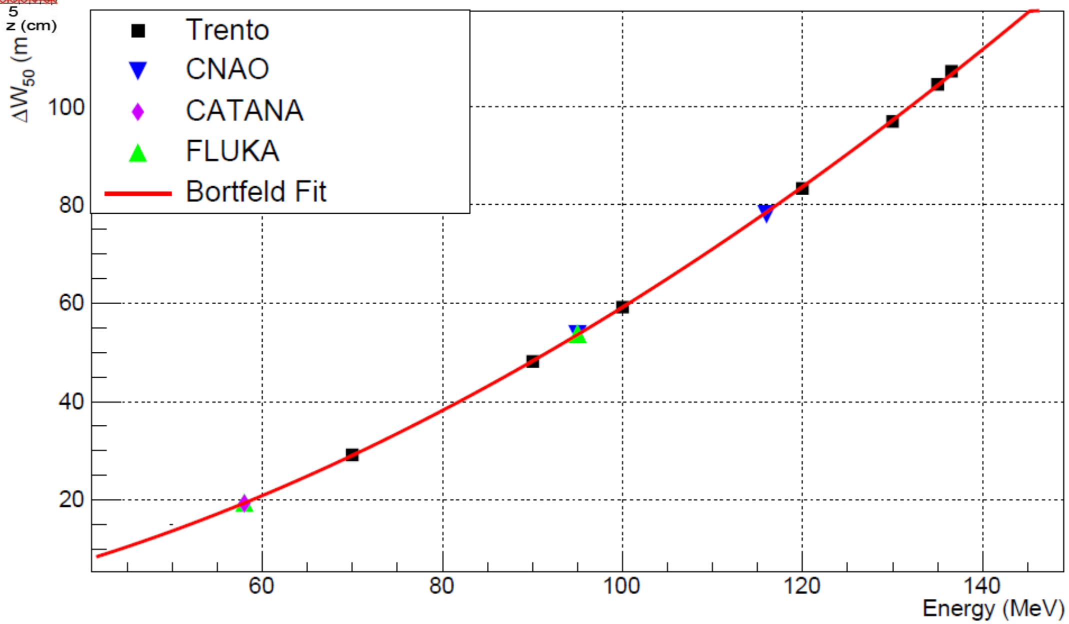


Center	Particle	Energy	Accelerator type	Collima-tion
CATANA	Protons	62 MeV	Cyclotron	passive
CNAO (Pavia)	Protons /C-ions	Up to 230MeV	Synchrotron	active
Trento	Protons	Up to 230Mev	Cyclotron	active

Comparison between measurements taken in the 3 Italian centers

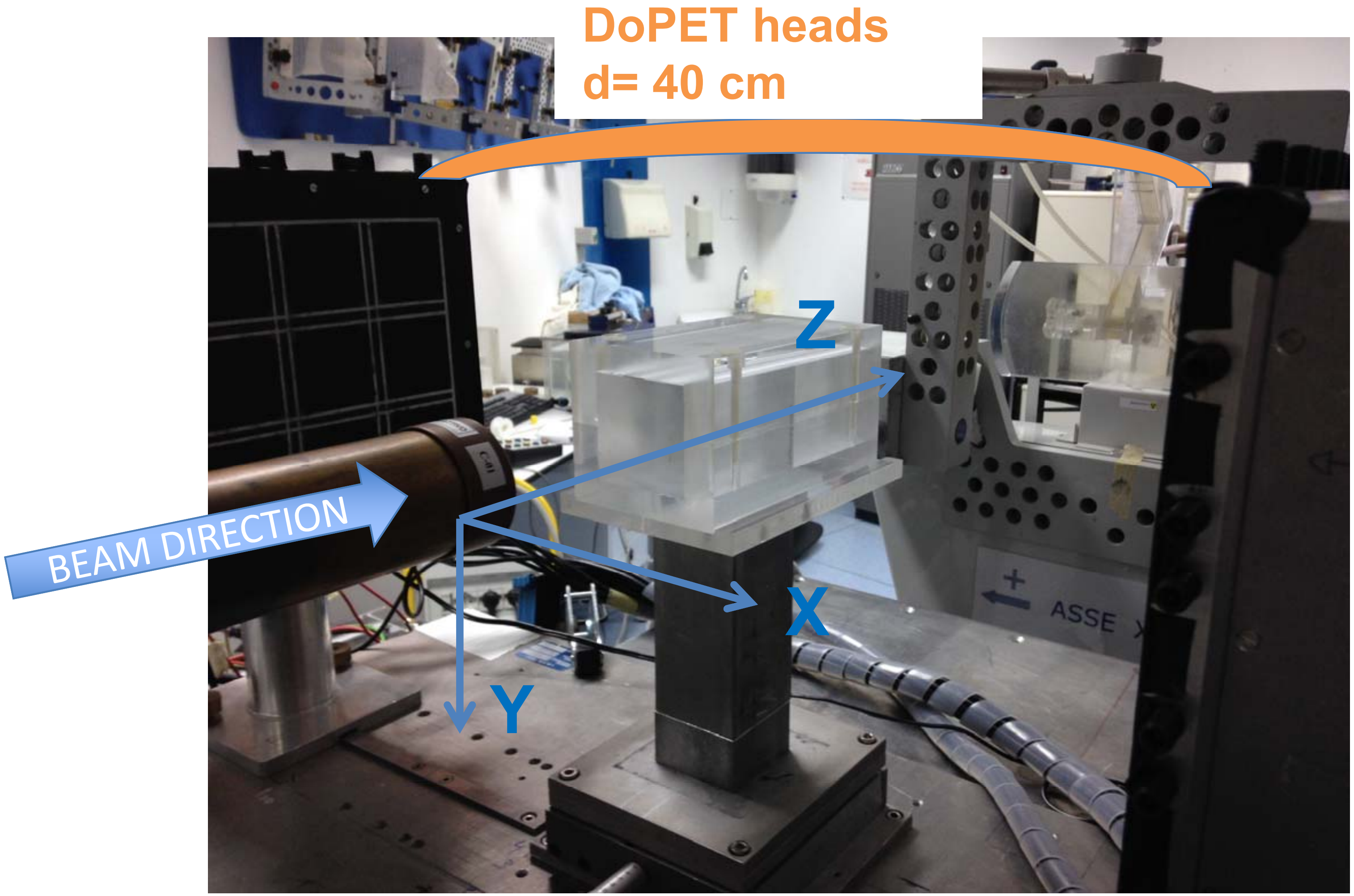


$$\Delta w_{50} = -5{,}15 + 0.02 E_0^{1.77}$$



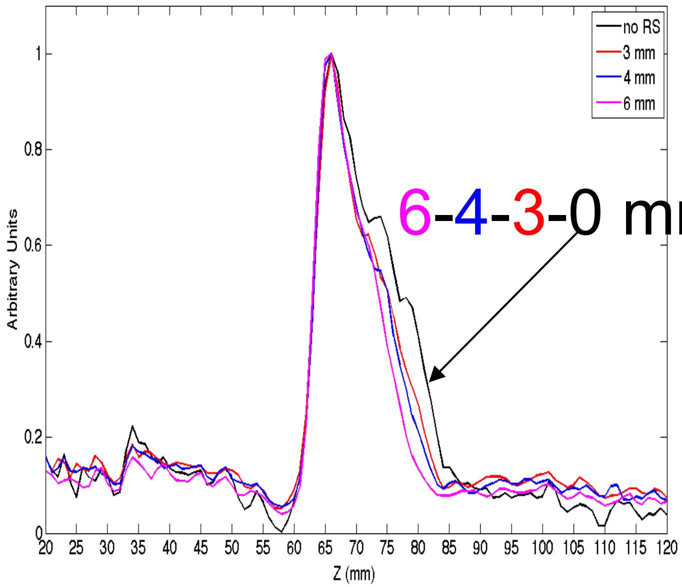
The data acquired in the 3 Italian proton therapy centers fit well together

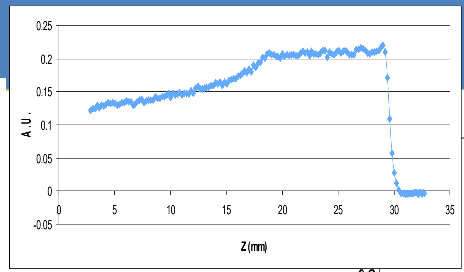
The DoPET system @CATANA

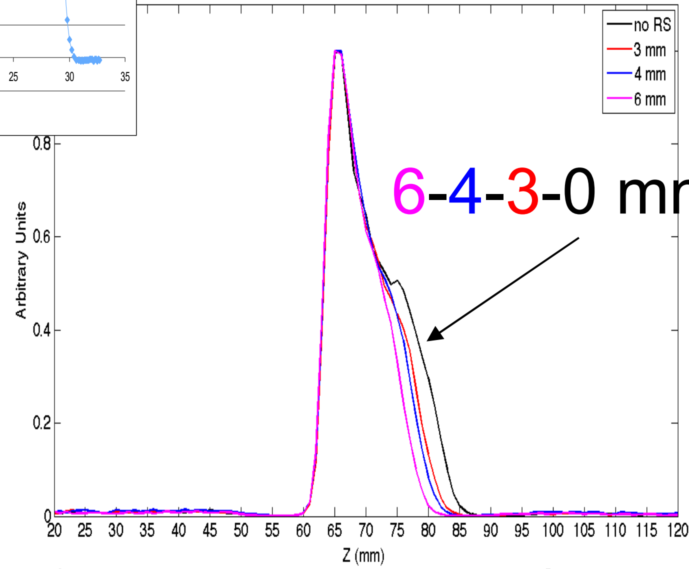


Capability to detect variation in delivered energy

SOBP 2cm, ∅ 30mm, 15 Gy

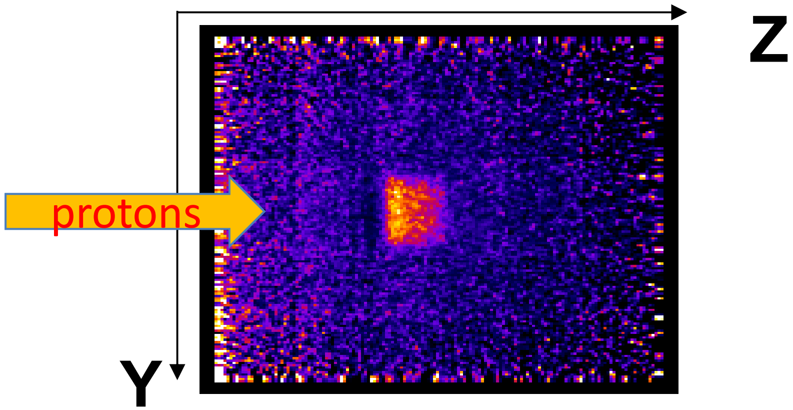


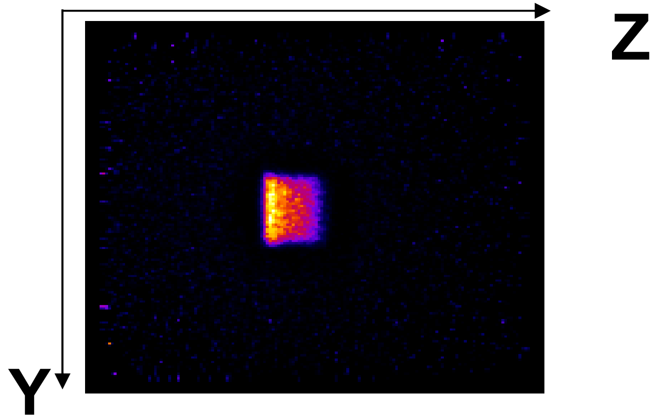




in-treatment [0-73 *s]

after-treatment [73*-600s]





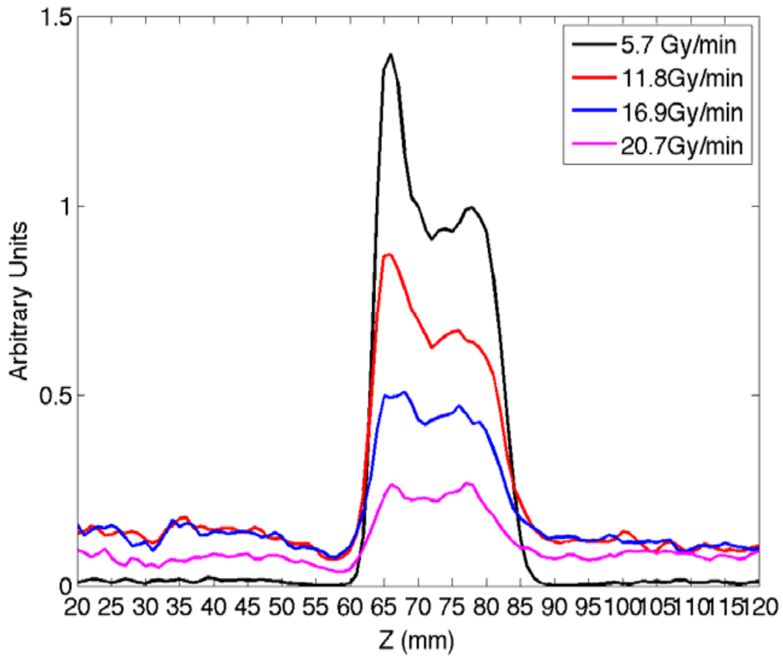
IN-TREATMENT = 73 s no range shifter

AFTER-TREATMENT = 73-600 s no range shifter

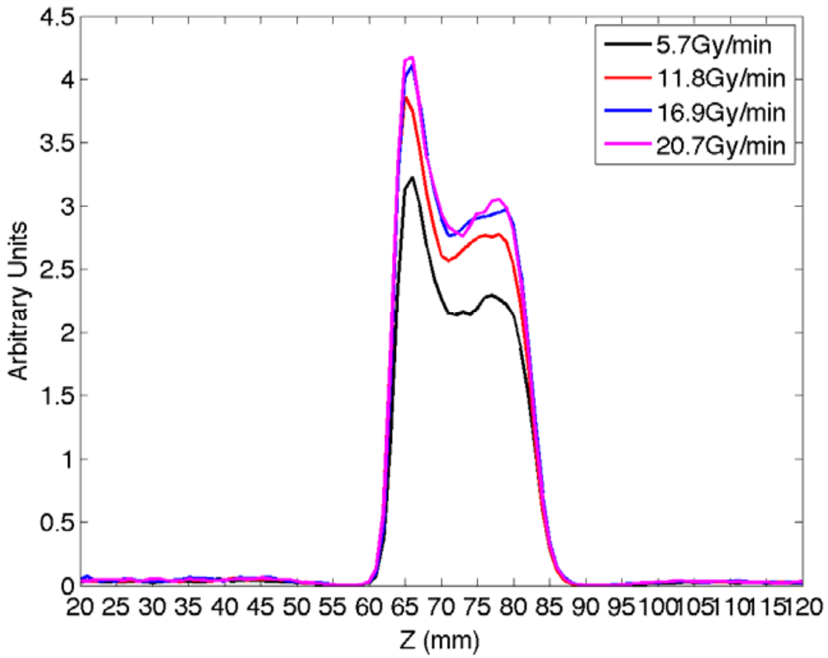
CATANA: response to different dose rates

58MeV protons, Ø 30mm, D=15Gy, PMMA

in-treatment activity profiles
Δt-acq: see table below



after-treatment activity profiles
Δt-acq: 300 s – 600 s

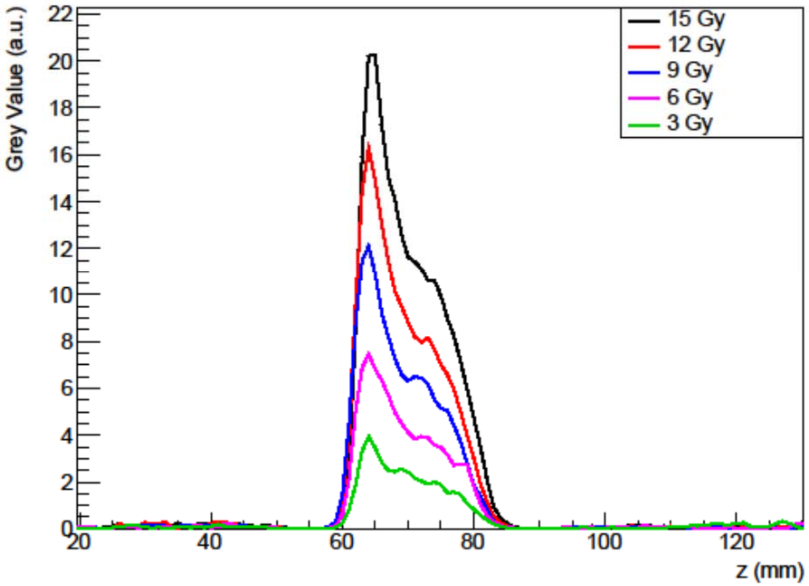


Dose rate [Gy/min]	5.7	11.8	16.9	20.7
Δt-in treatment [s]	157.9	76.5	53.1	43.4

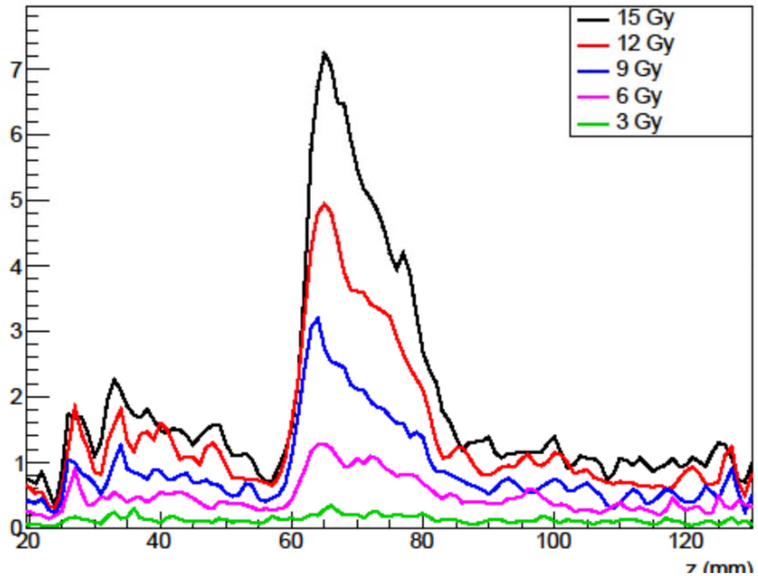
Response to different doses

SOBP 2cm, ∅ 30mm, ~12Gy/min

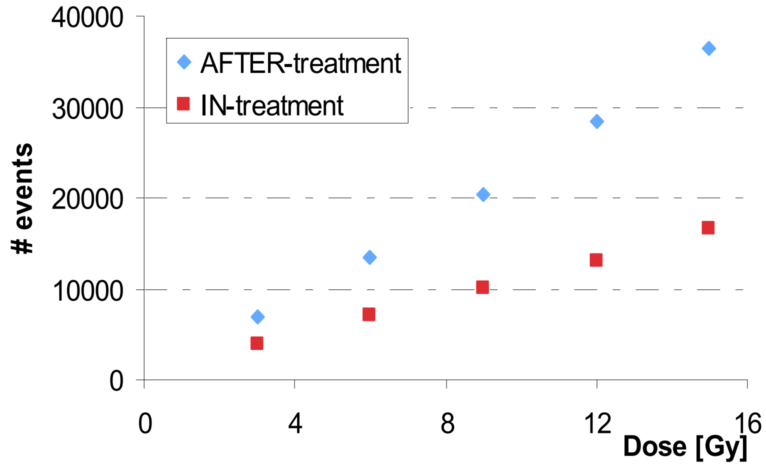
after-treatment [300s-600s]



In-treatment: different Δt see table below

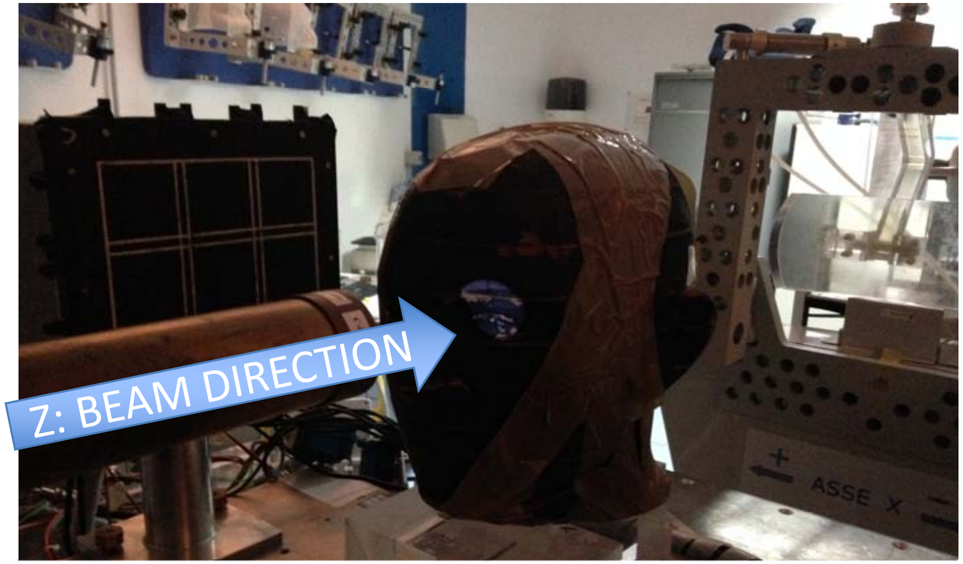


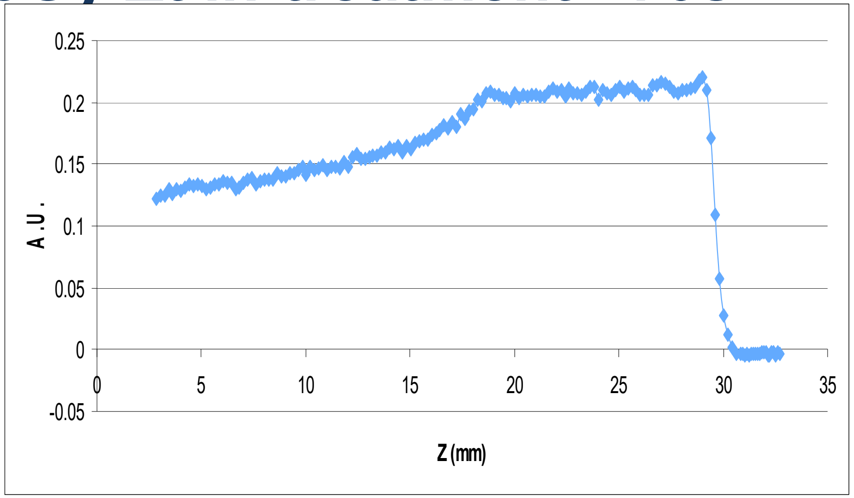
DOSE	Dose-deliver time [s]	Dose/rate [Gy/min]
3 Gy	16.3	11.04
6 Gy	30	12
9 Gy	48	11.25
12 Gy	56.4	12.77
15 Gy	72.9	12.35

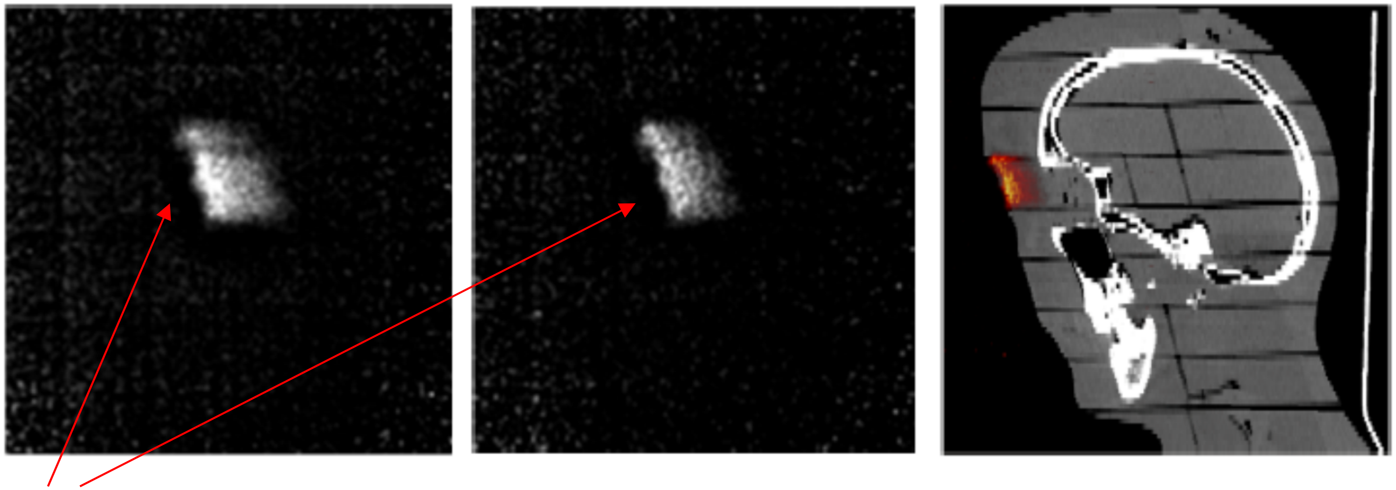


Imaging capabilities using range shither and an antropomorphic phantom

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



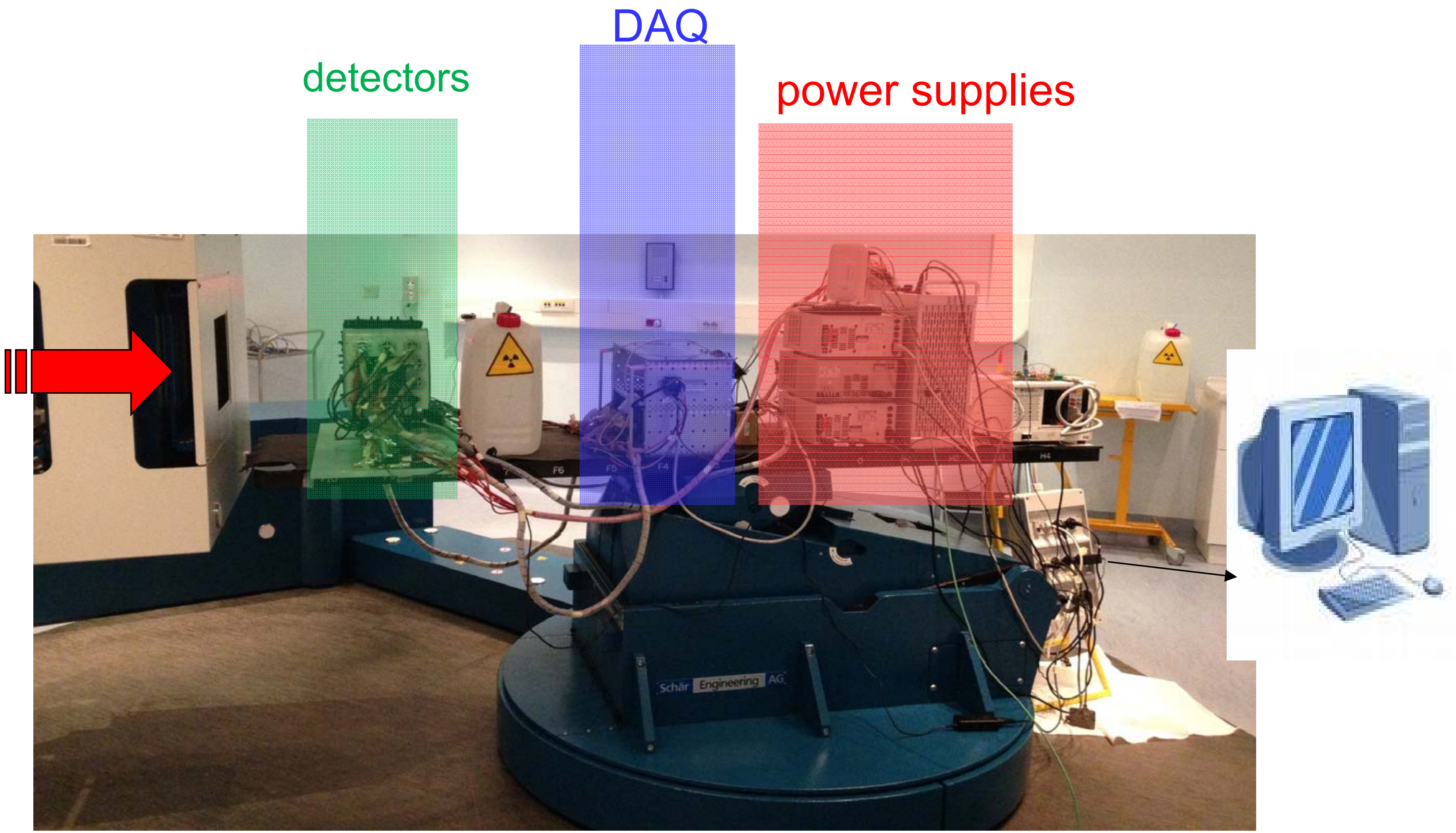




In-and-after
Treatment data:
Δt-acq= 0-190 s

Phantom eyelid 3 mm range shifter

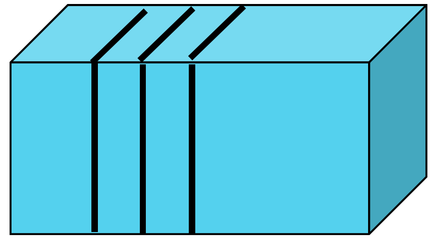
the DoPET system @ CNAO

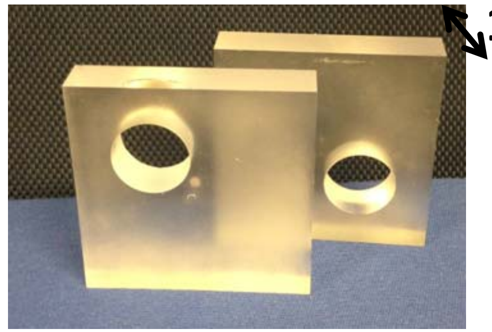


CNAO:PMMA phantom with 2 air cavities

TPS: Syngo PT Planning VC12, Siemens

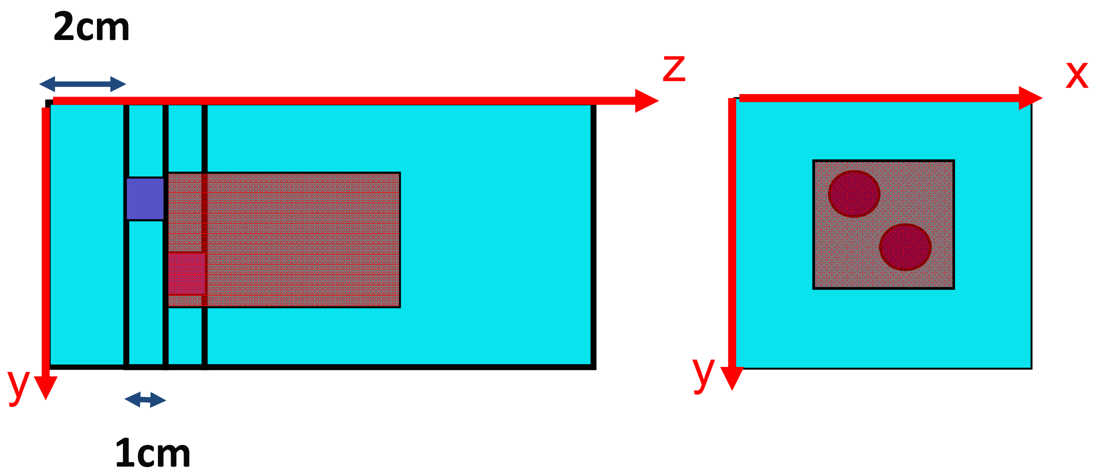
- protons
- **2Gy** on PTV: 4x4x6 cm^3 (z: 3-9 cm)
- 62.3 MeV - 116 MeV (35 EL)





Ø 1.6 cm

- PMMA phantom: 8x8x14 cm3
- 2 cavities: z=1cm Ø=1.6cm



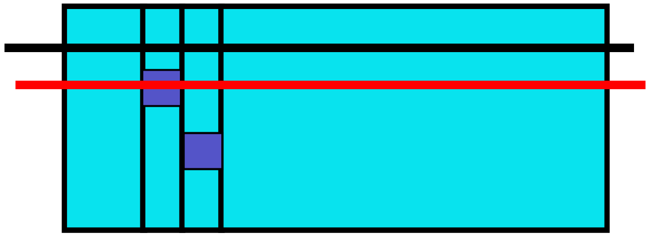
CNAO: 2 cavities profiles

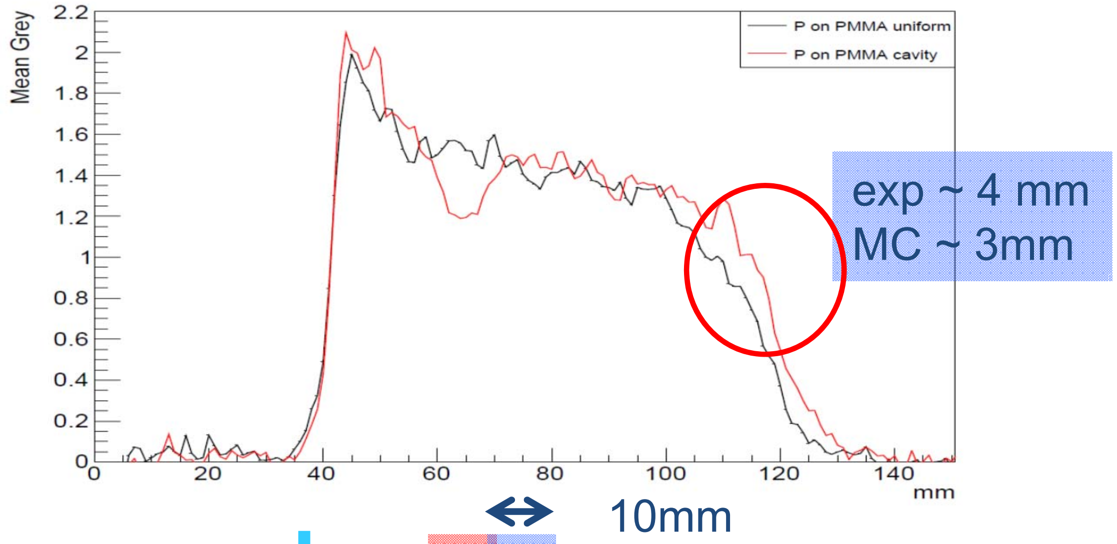
D= 2Gy

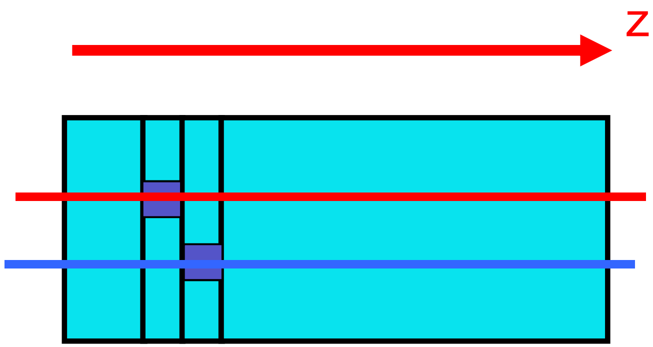
Acquisition time [0, 600 s]

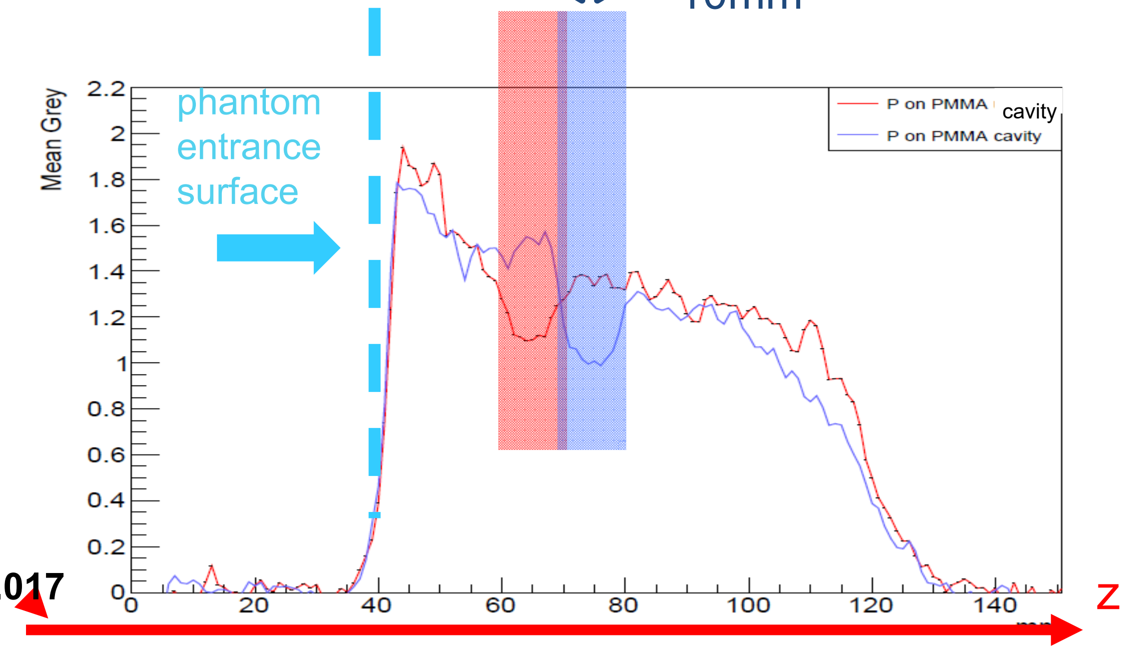
TP delivered in 230 s

Activity: z profile



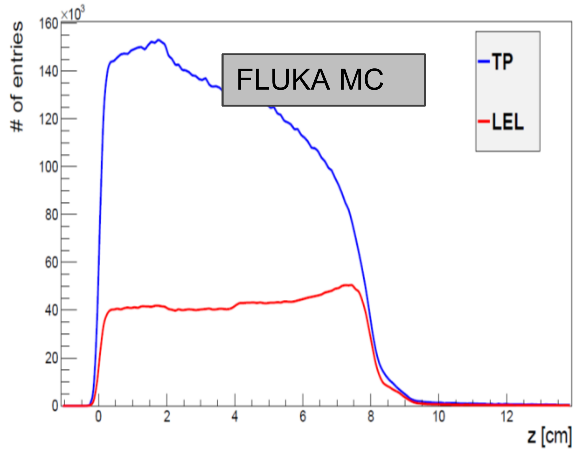






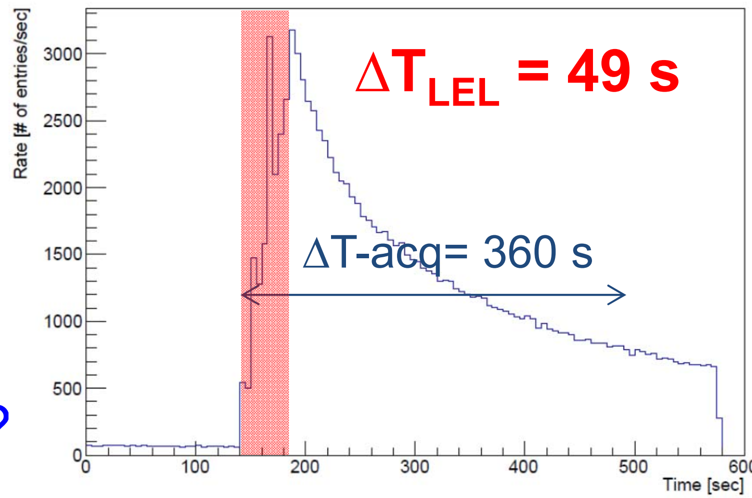
V. Rosso et al., http://dx.doi.org/10.1016/j.nima.2015.11.017

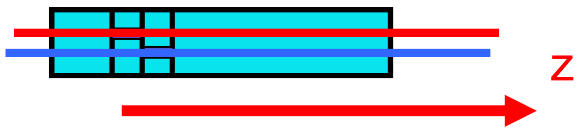
CNAO: Last Energy Layer



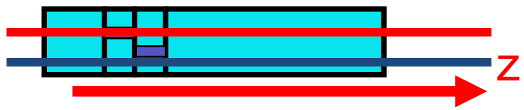
only LEL protons

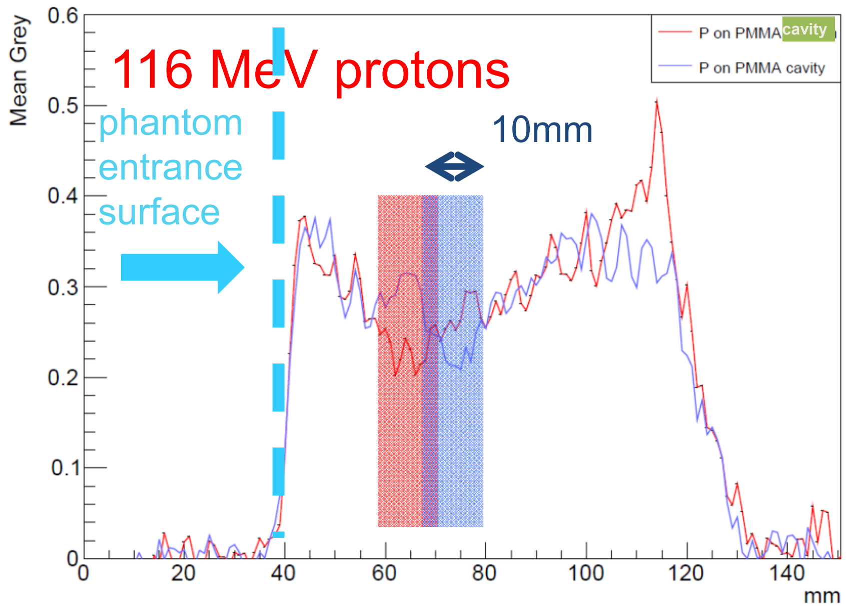
The same information with a smaller dose: helpful for hypofractionation?

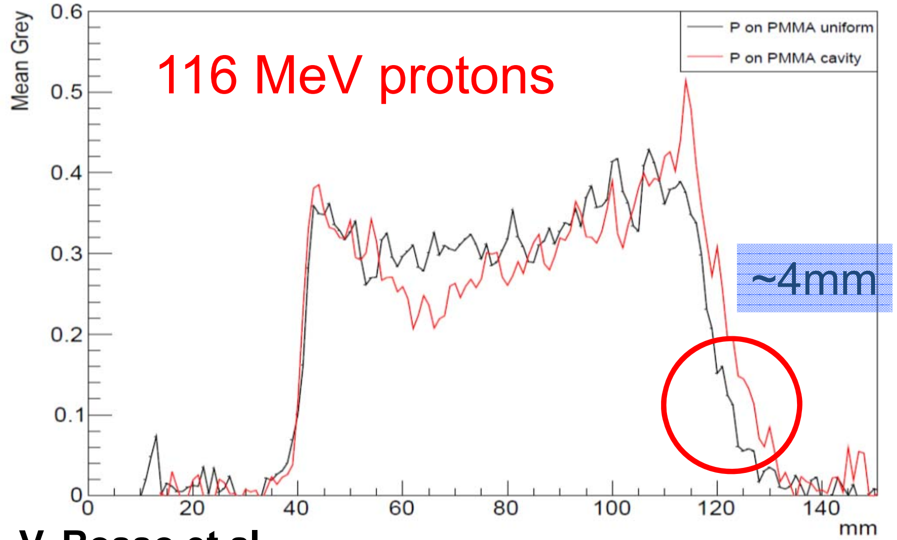




ΔT-acq= 360 s





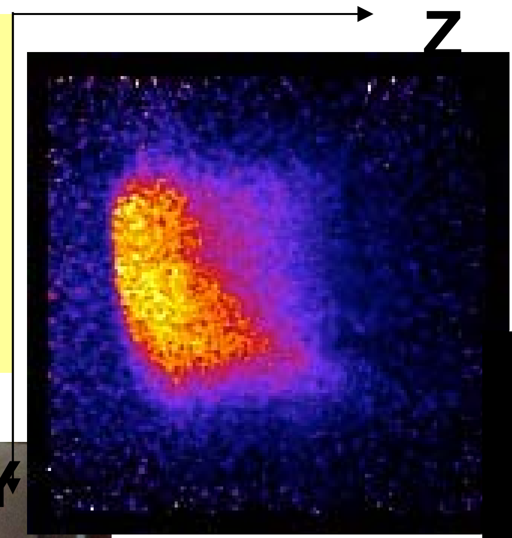


V. Rosso et al., http://dx.doi.org/10.1016/j.nima.2015.11.017

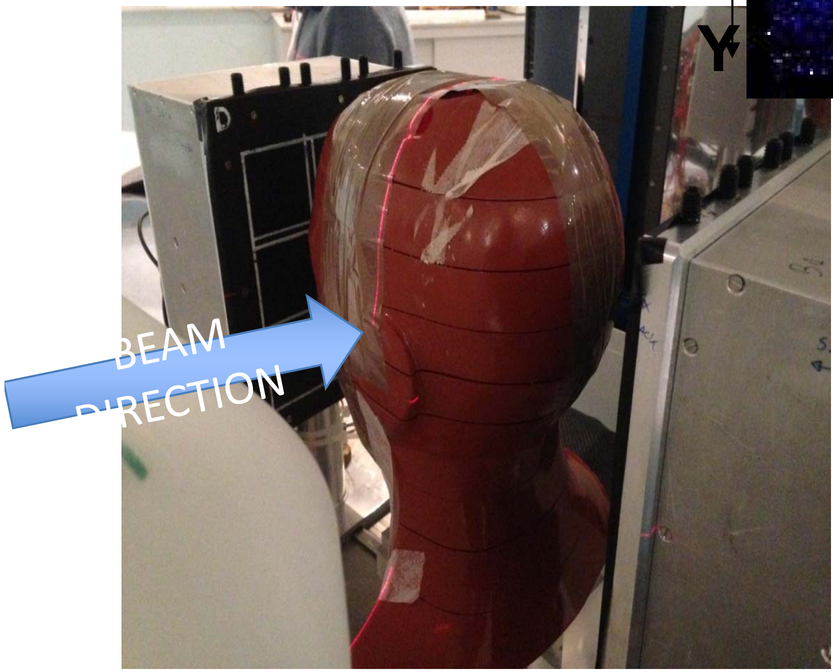
CNAO: an example of an antropomorphic phantom irradiation

2 Gy on PTV: 5x5x6 cm^3 (z: 1-7 cm)

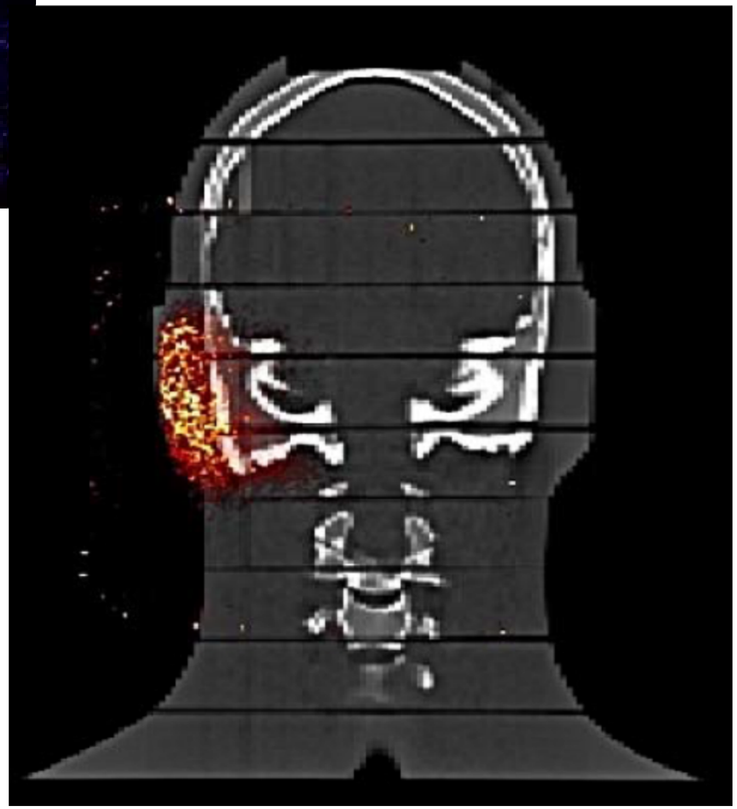
Δt in-treatment= 287s



Acquisition time [0, 600 s]



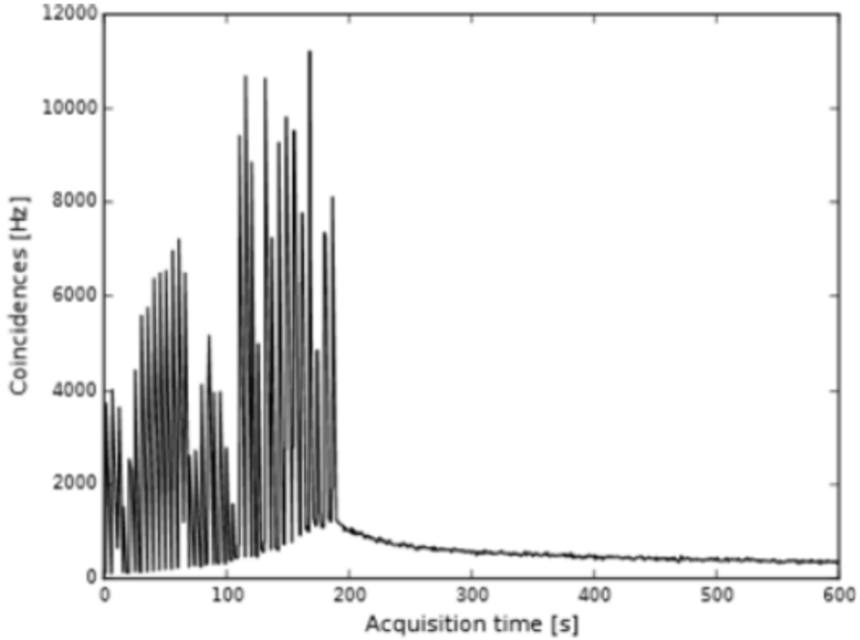
coronal view



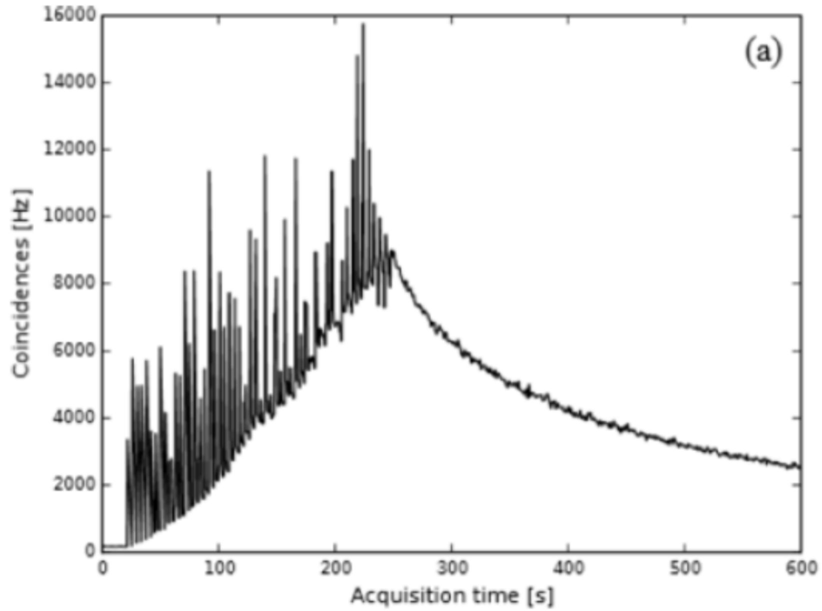
CNAO: proton and carbon irradiations

2 Gy on PTV: 4x4x6 cm^3 (z: 3-6 cm)

Carbon TP

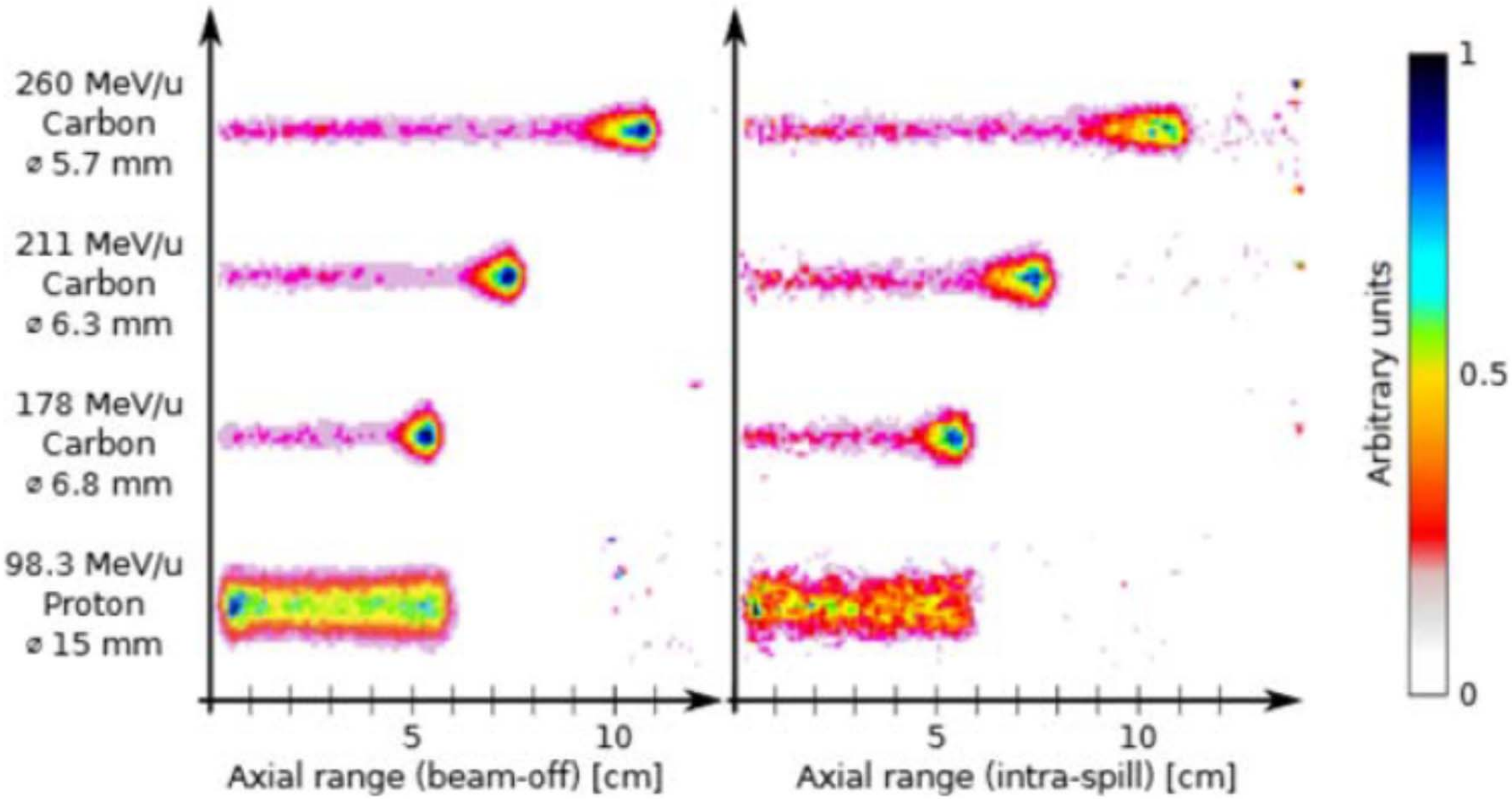


Proton TP



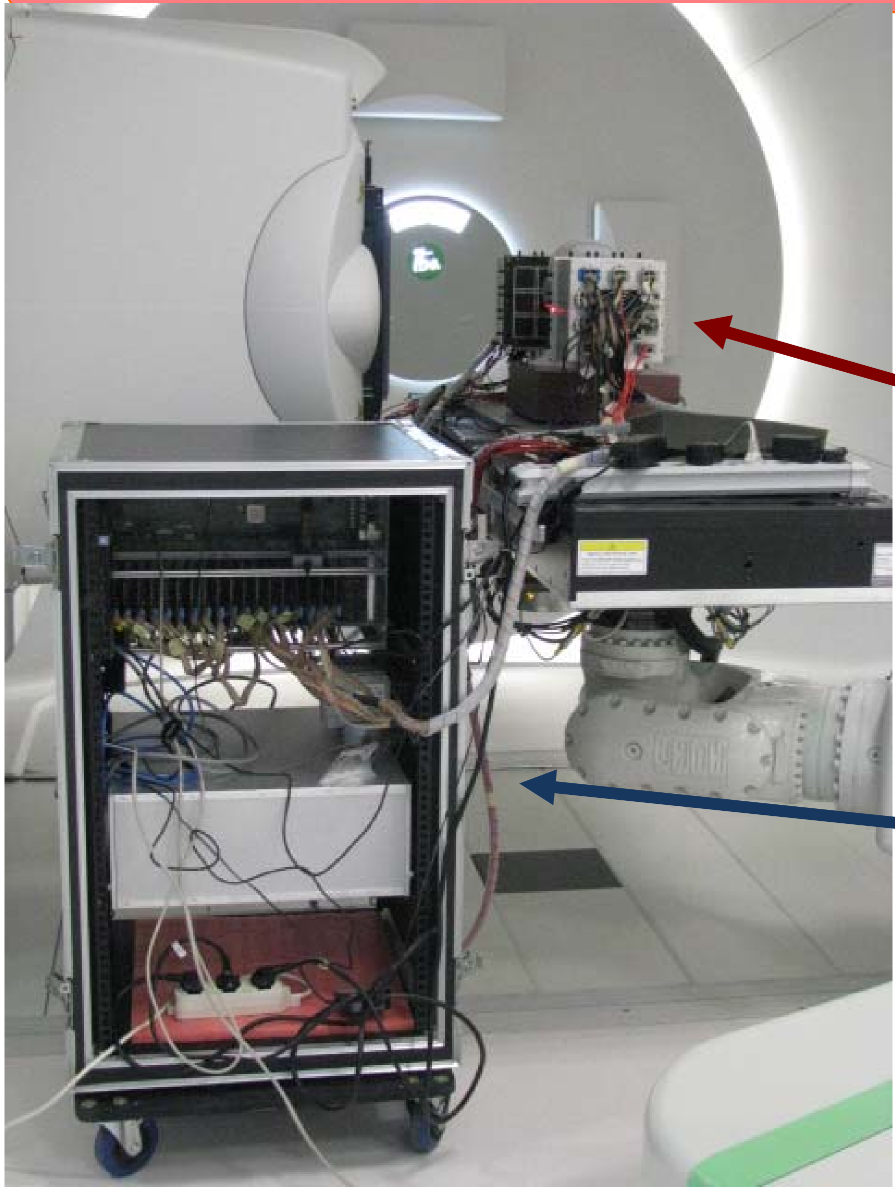
Different statistic…

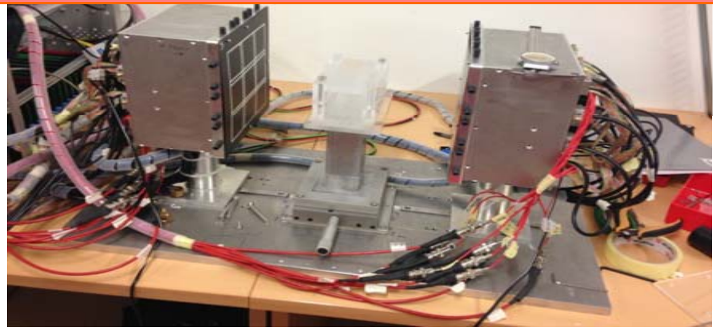
CNAO: carbon and proton monoenergetic irradiations



G. Sportelli et al., JINST, 10, C12029 (2015) 1-11

the DoPET system @ Trento

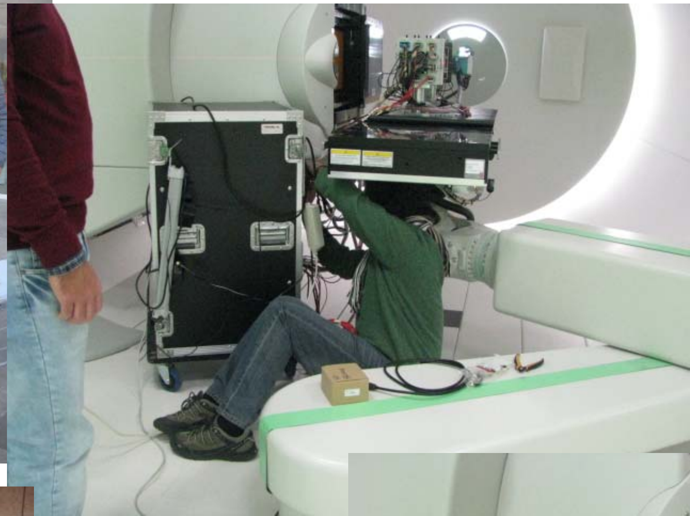


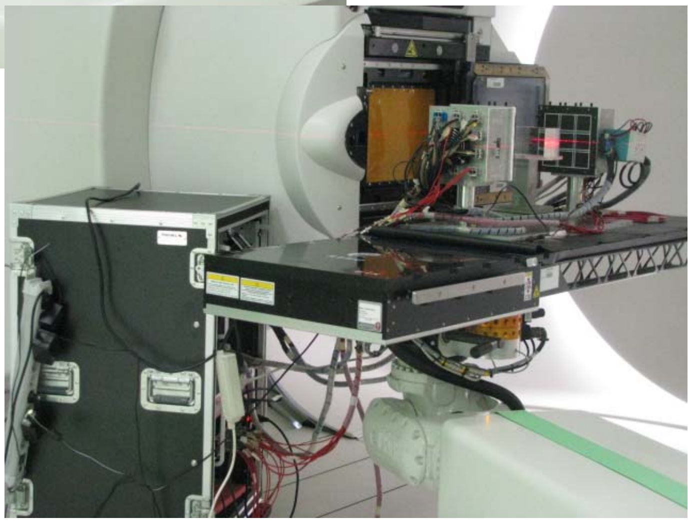


The 2 detecting heads

The fly-rack: a compact housing for the DAQ and the power supplies

the DoPET system @ Trento



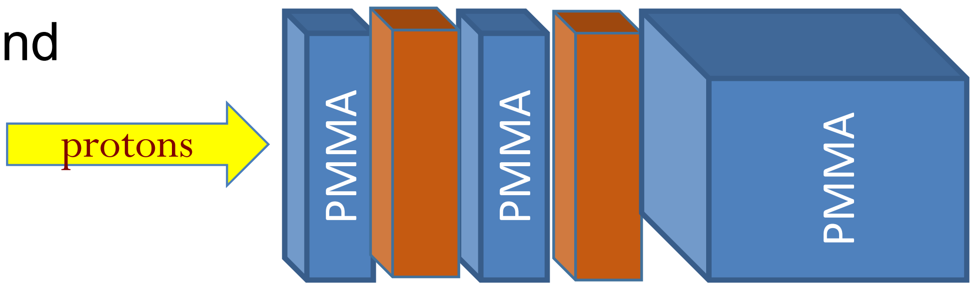


Ready for data taking in 30' !

Capability to detect variations in composition

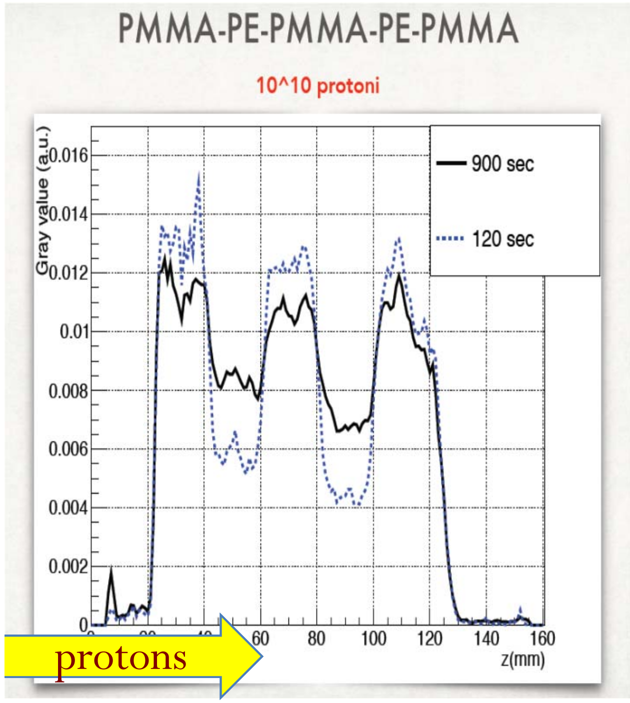
	Densita'	H (%)	C (%)	0 (%)	N (%)	Ca (%)
PMMA	1.18	8	60	32		
Solid H2O	1.046	8.02	67.23	19.91	2.41	2.31
brain	1.049	10.83	72.54	14.86	1.69	
polyethylene		14	86			

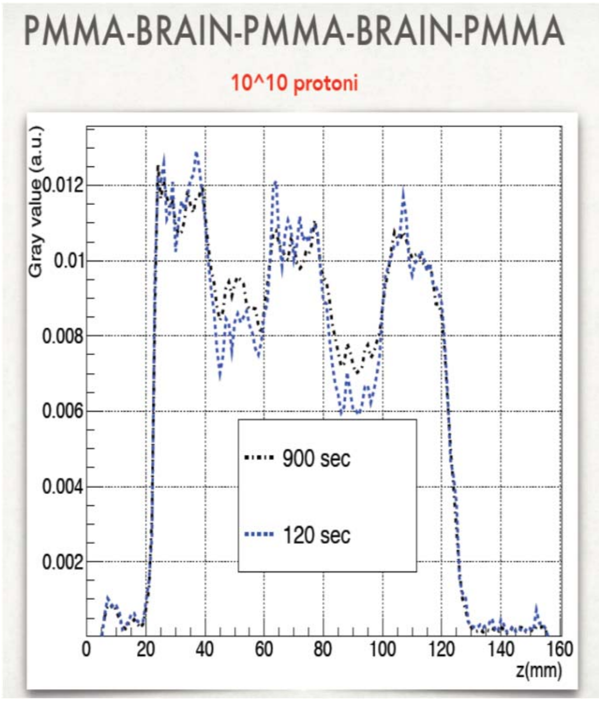
3 "zebra" phantoms were realized:
I) PMMA-PE-PMMA-PE-PMMA –to-end
II) PMMA-BRAIN-PMMA-BRAIN-PMMA —to-end
III) PMMA-H2O-PMMA-PMMA —to-end
Slabs thickness: 2cm
Phantom thickness:14cm

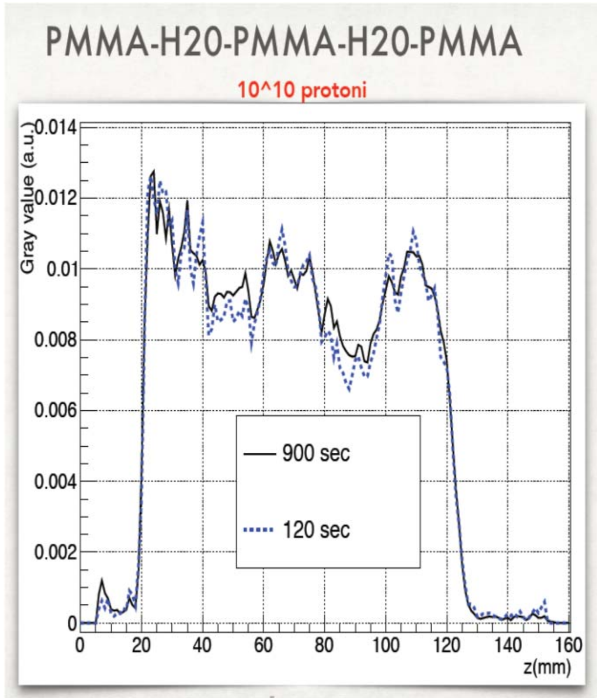


Capability to detect variations in composition
Zebra-phantoms profiles

Pencil beam: energy 130MeV , 10^10 protons
Different acq. time to enhance the contribution of the 15O and 11C isotopes (120 and 900s)

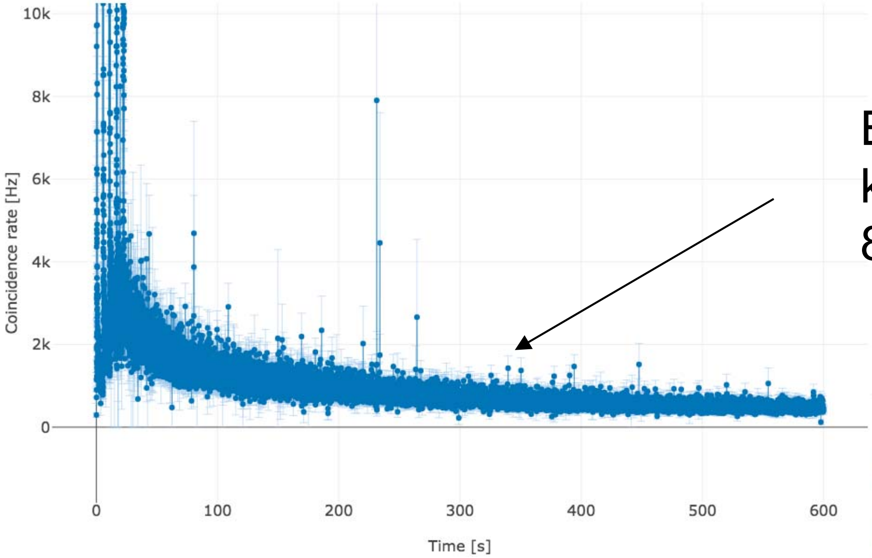




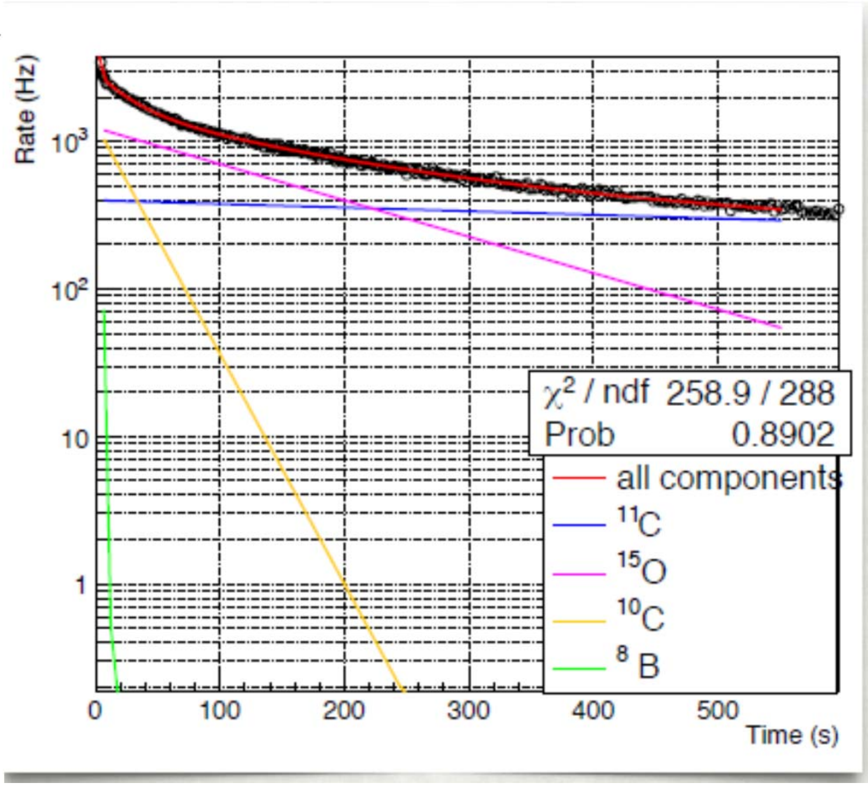


The different slabs are well visible

Capability to detect variations in composition: a time approach



Evaluate the different contributions knowing the isotopes: 11-C, 15-O, 10-C, 8-B and 13-N



The contributions of the different isotopes was calculated, modeling the frequency signal as:

$$f(t) = \sum_{i=1}^{n} a_i e^{-t \ln 2 / T_i}$$

ΔT-acq= 550s

Capability to detect variations in composition: a time approach

isotopes	11-C (%)	15-O (%)	10-C (%)	8-B (%)
PMMA	39.7±0.3	52.2±0.4	7.8±0.1	0.24±0.02
H2O solid	51.4±0.3	37.4±0.4	10.0±0.2	1.15±0.03
BRAIN	58.6±0.4	29.3±0.4	11.8±0.2	0.34±0.03
PE	81.9±0.3	0	17.1±0.1	0.98±0.04
PMMA-H2O	44.8±0.3	46.7±0.4	8.2±0.2	0.28±0.14
PMMA-BRAIN	46.9±0.3	43.6±0.4	8.8±0.2	0.68±0.24
PMMA-PE	52.0±0.3	37.1±0.4	10.5±0.1	0.38±0.03

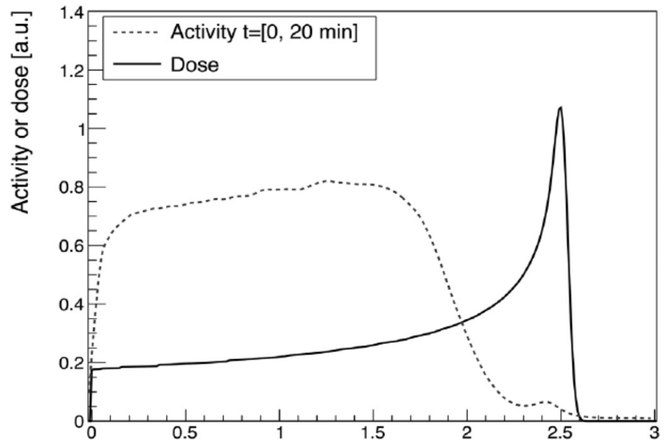
The percentage of the different contributions highlights the different composition

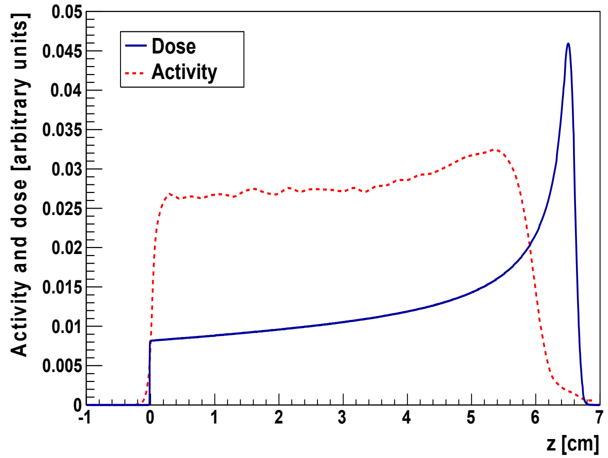
Only 4 cm in thickness are different from one phantom to the other

Expected profiles: FLUKA and comparison with experimental data

As the relation between activity and dose is indirect

58 MeV protons on PMMA





95 MeV protons on PMMA

…by comparing predicted with planned activity, the treatment quality can be monitored

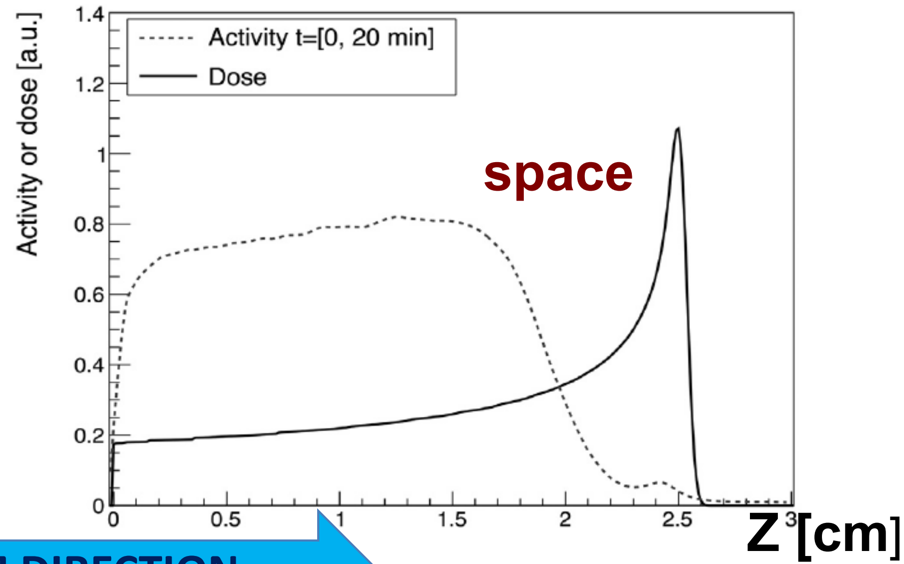
Monte Carlo:

FLUKA (development), new user interface developed to record the β^+-activity and annihilation products in space and time

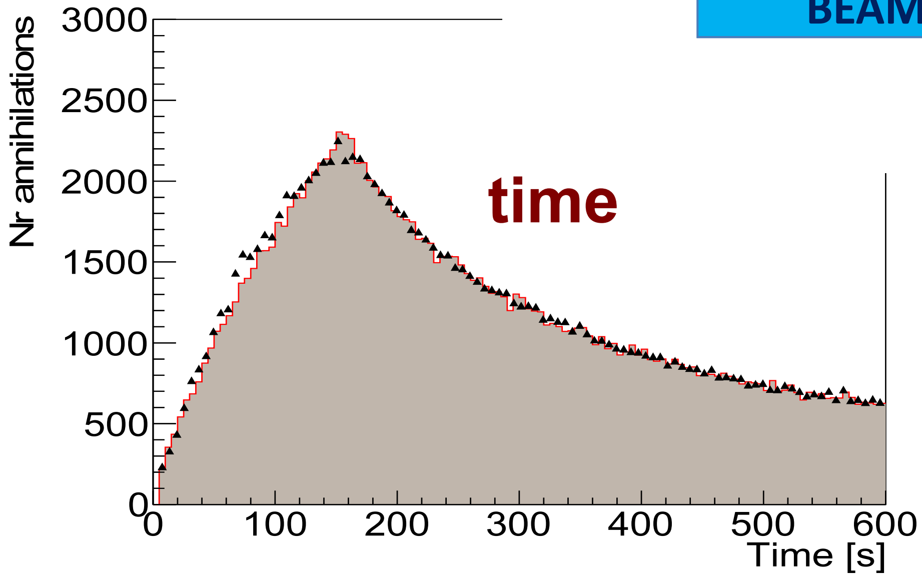
CATANA: expected activity profiles (FLUKA MC)

- **58 MeV protons on PMMA (ocular melanoma)**
- **collimator: ∅ 30mm**
- **D= 15 Gy**
- in-treatment: 0-158s (5.7 Gy/min)
- after-treatment: 158s-300s

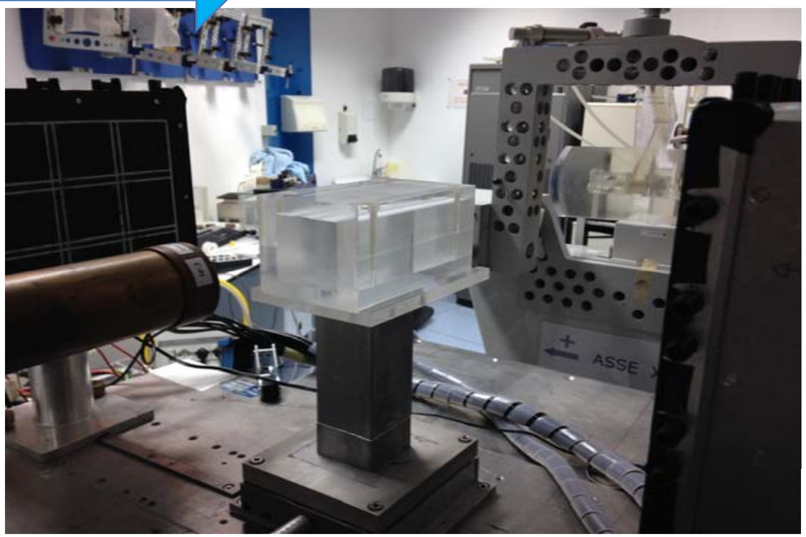
❖ Simulations with FLUKA
http://www.fluka.org



BEAM DIRECTION



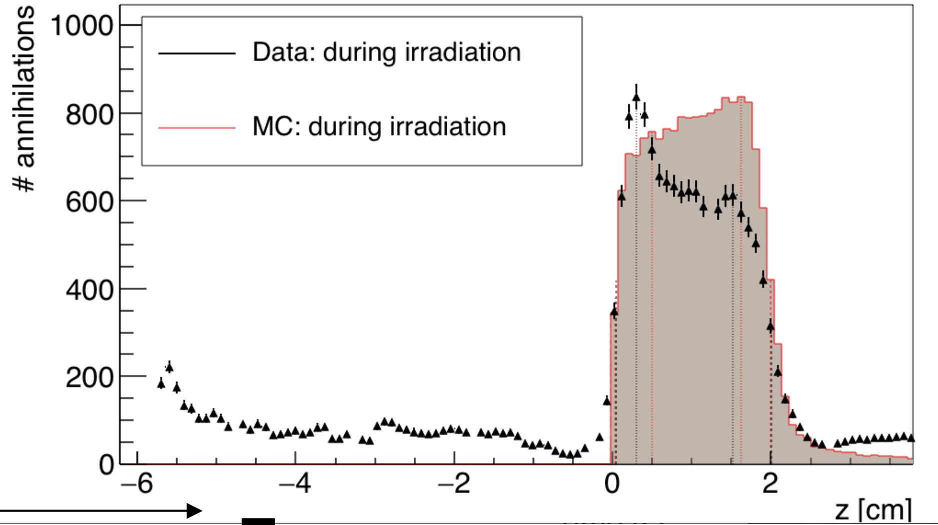
Annihilation Time profile



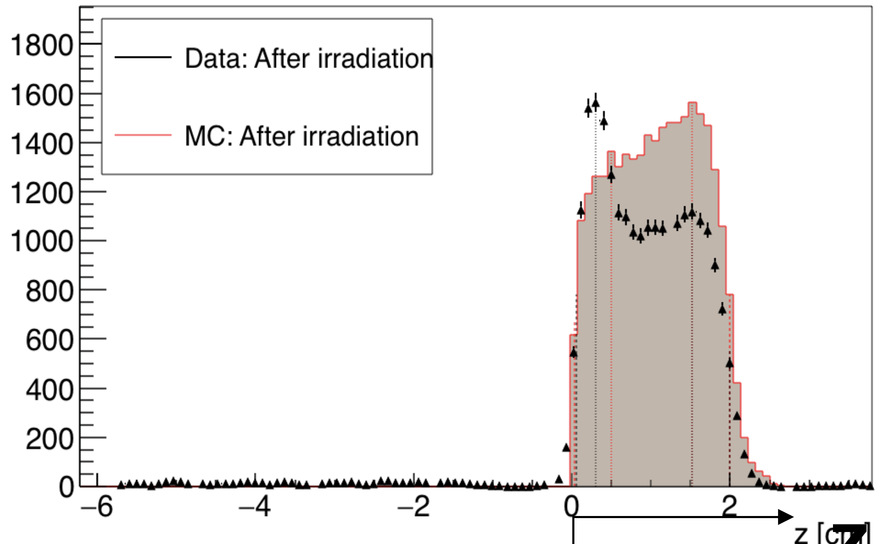
CATANA: comparison between simulated and experimental data

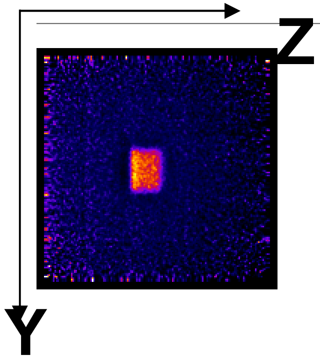
- 58 MeV protons on PMMA
- collimator: ∅ 30mm
- D= 15 Gy (5.7 Gy/min)

z-profile
In-treatment: t< 158 s

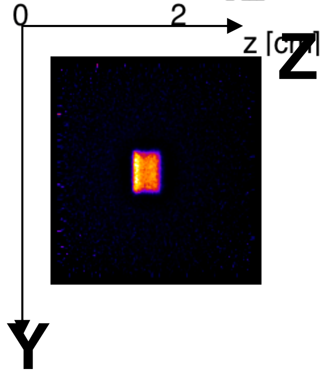


z-profile
After treatment: 158s-280 s





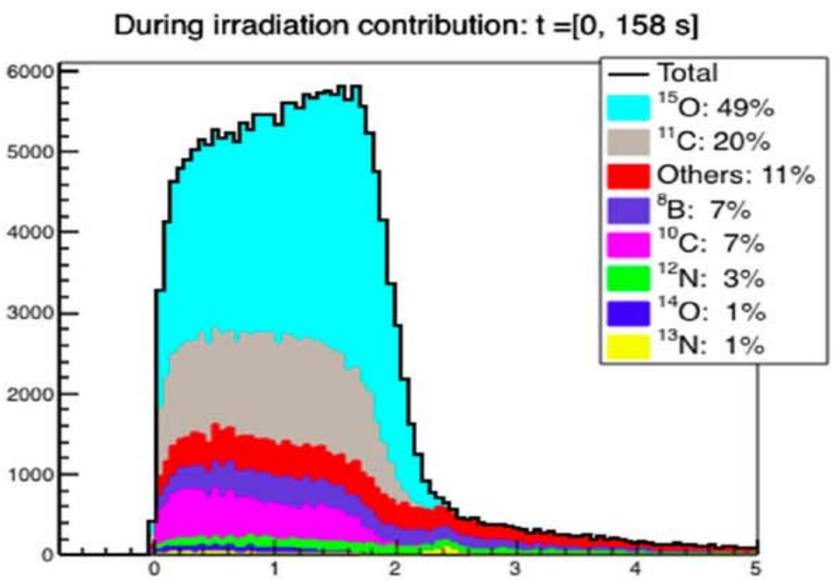
Δw50%	in-treatment [cm]	after-treatment [cm]
MC	1.96	1.96
data	1.95 ± 0.03	1.93 ± 0.03

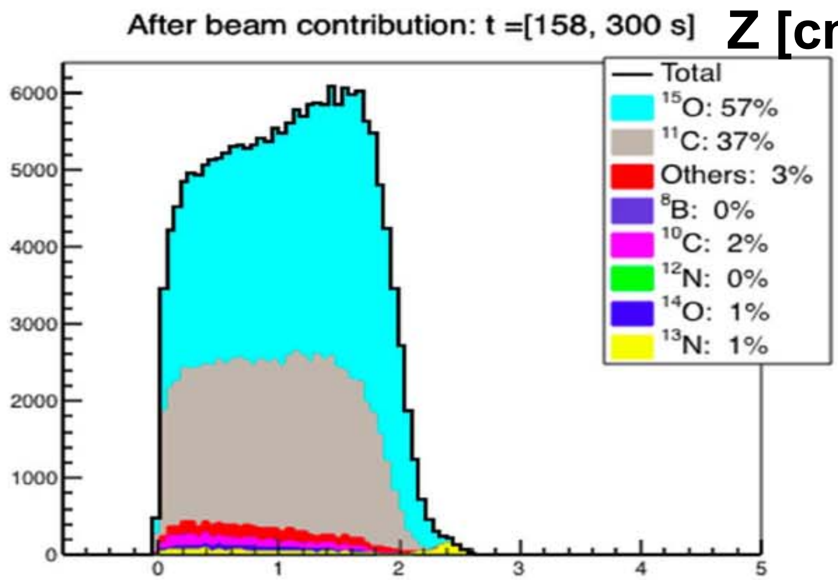


CATANA: expected activity profile (FLUKA MC)

- 58 MeV protons on PMMA
- collimator: ∅ 30mm
- D= 15 Gy (5.7 Gy/min)
- in-treatment: 0-158s
- after-treatment: 158-300s

BEAM DIRECTION



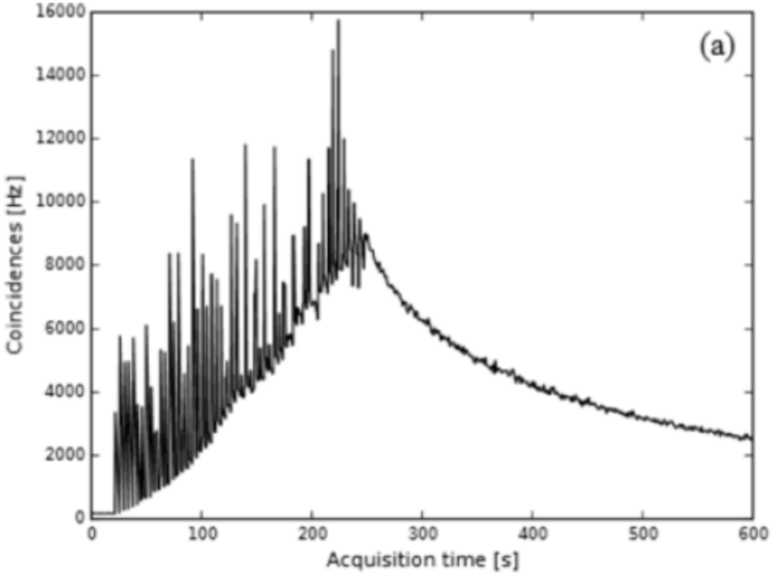


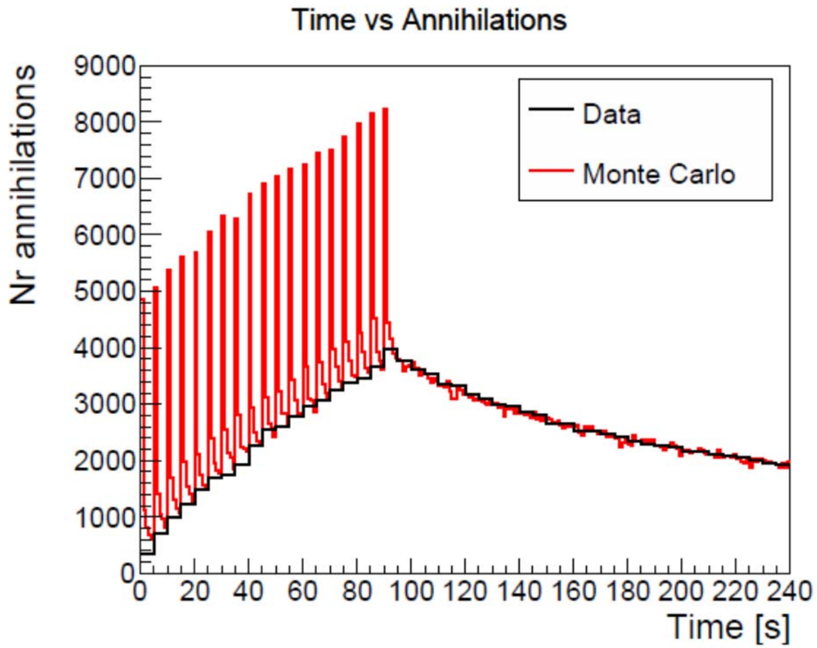
Z [cm]

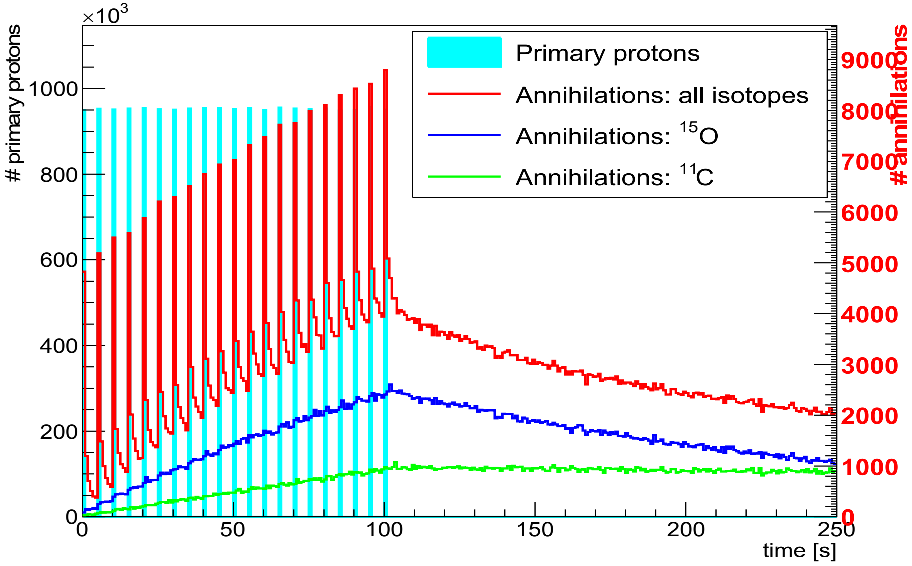
in-treatment activity profile Z [cm]

after-treatment activity profile Z [cm]

FLUKA for CNAO data







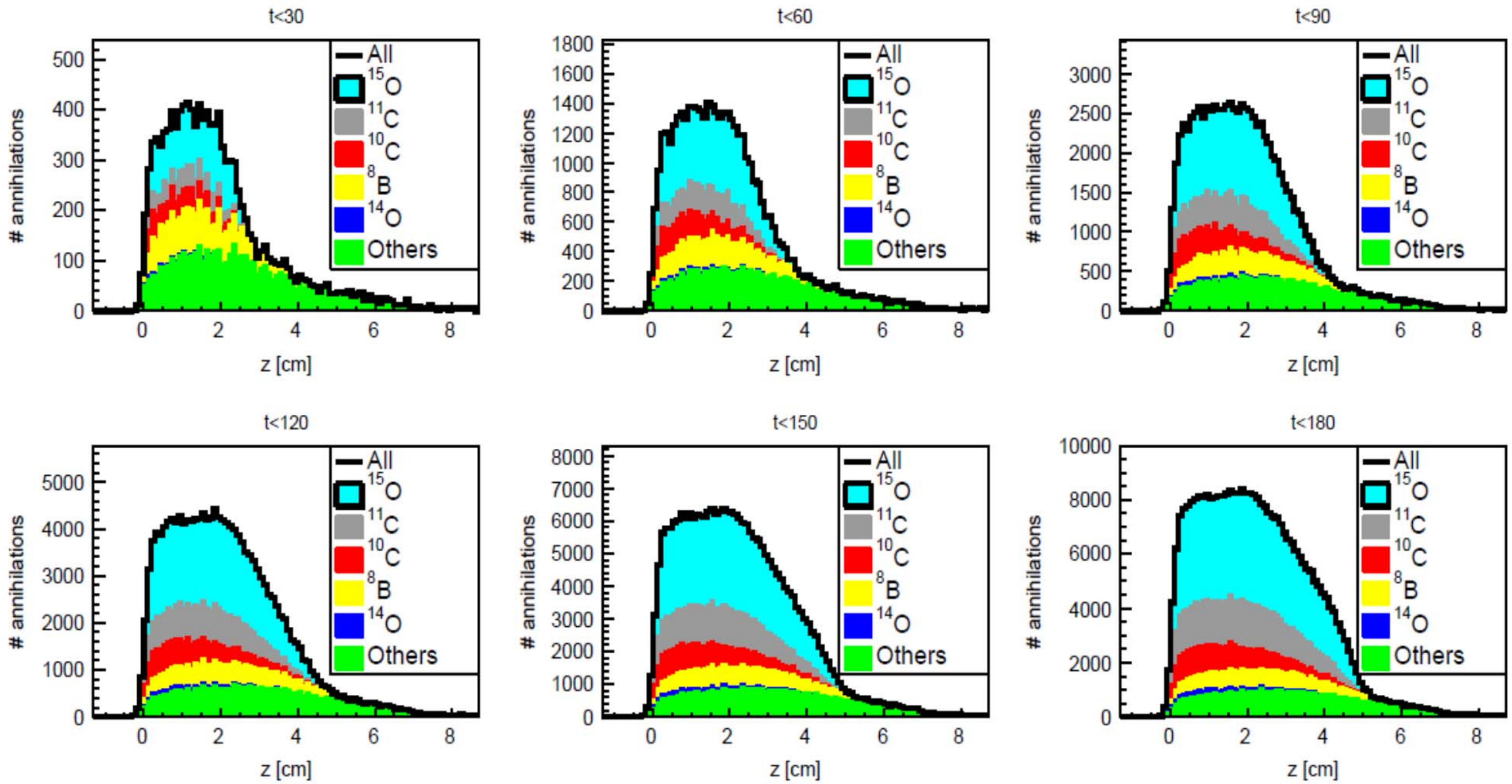
several information are available

CNAO: an example of expected profiles and isotopes contribution

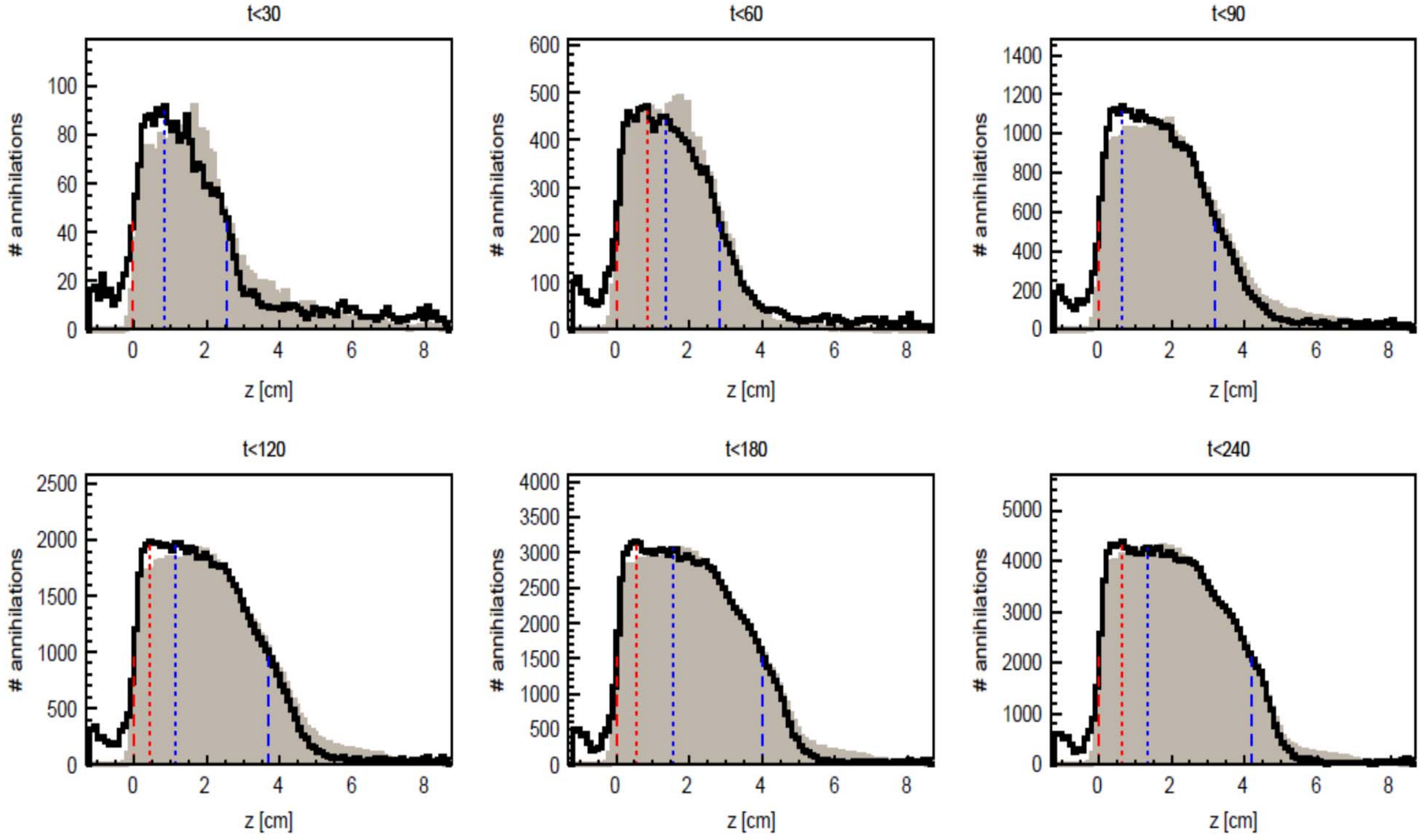
Protons on PMMA

2 Gy on PTV: 3x3x3 cm^3 (z: 3-6 cm)

T-irradiation: 146 s



CNAO: an example of camparison between expected and experimental profiles



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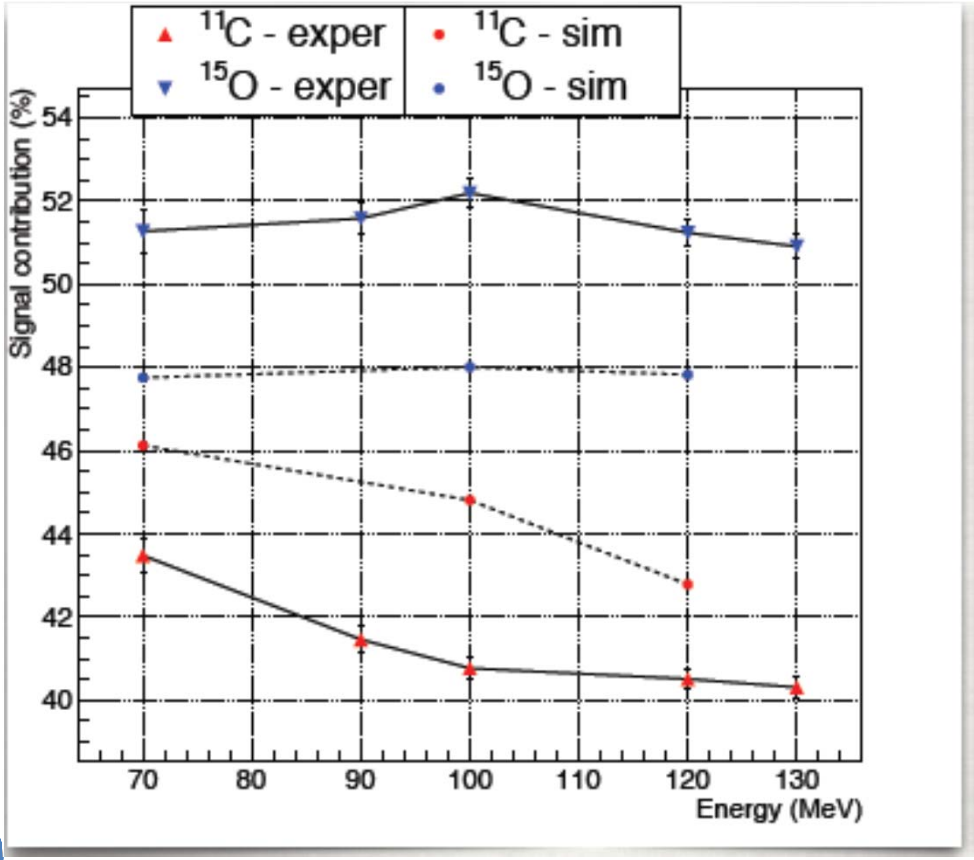
FLUKA for Trento data

Comparison for proton irradiation
Data: 70 MeV, 90 MeV, 100 MeV, 120 MeV and 130 MeV
FLUKA: 70 MeV, 100 MeV and 120 MeV



Work in progress!

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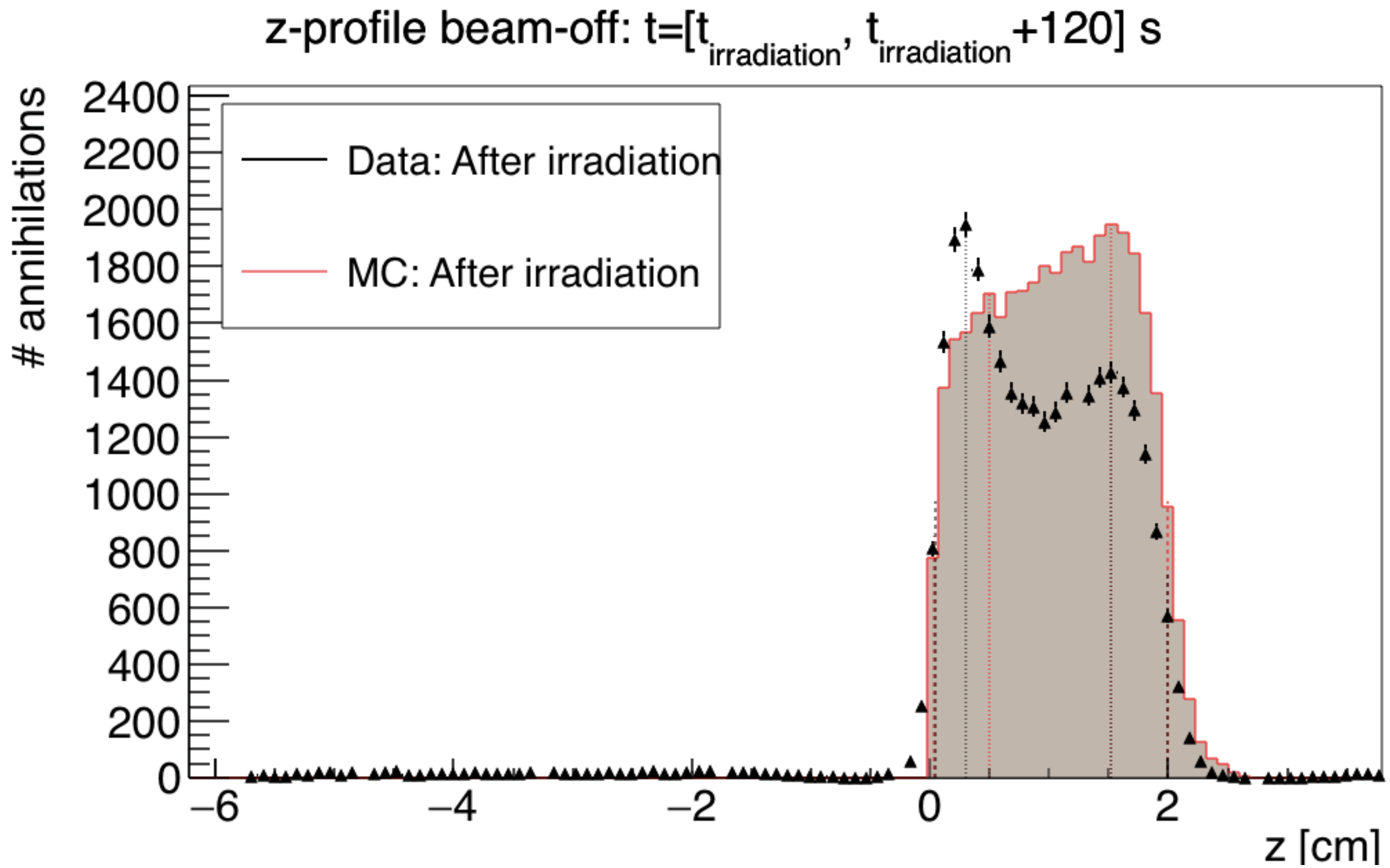
Prime valutazioni delle capacità di risposta del sistema DoPET nel monitoraggio dei trattamenti presso il centro di protonterapia di Trento
XVII Convegno Nazionale SIRR, Trento, 25-27 September 2016

Con 10^9 protoni:

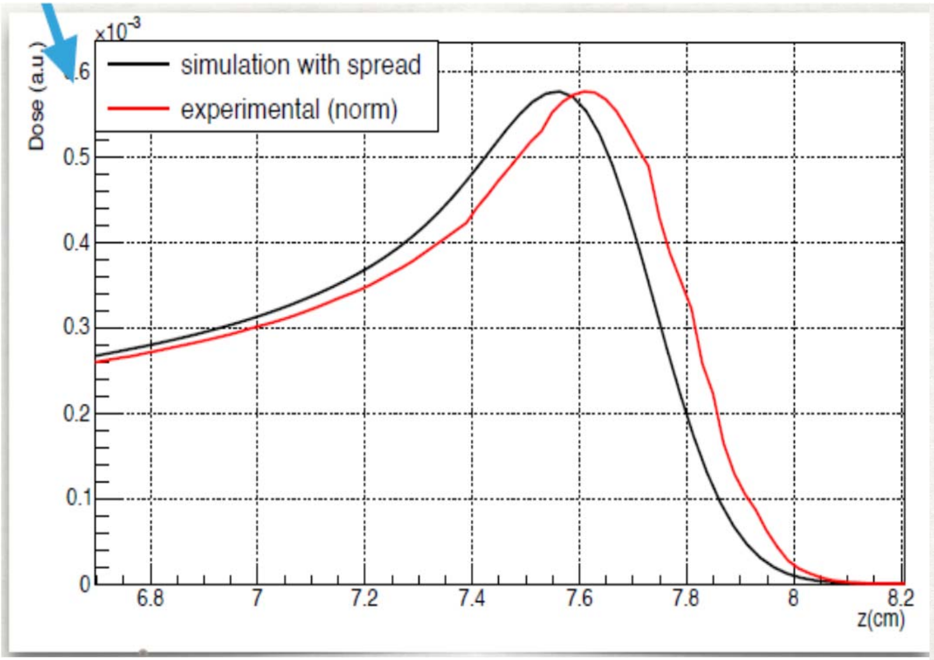
- -Non tutti i file con 10^9 sono stati ancora analizzati.
- Passando a 10^9 protoni l'errore aumenta

contributi	11-C (%)	15-O (%)	10-C (%)	8-B (%)
PMMA-BRAIN 10^10	46.9±0.3	43.6±0.4	8.8±0.2	0.68±0.24
PMMA-BRAIN 10^9	47.5±1.6	42.1±1.8	9.6±0.6	0.74±0.10

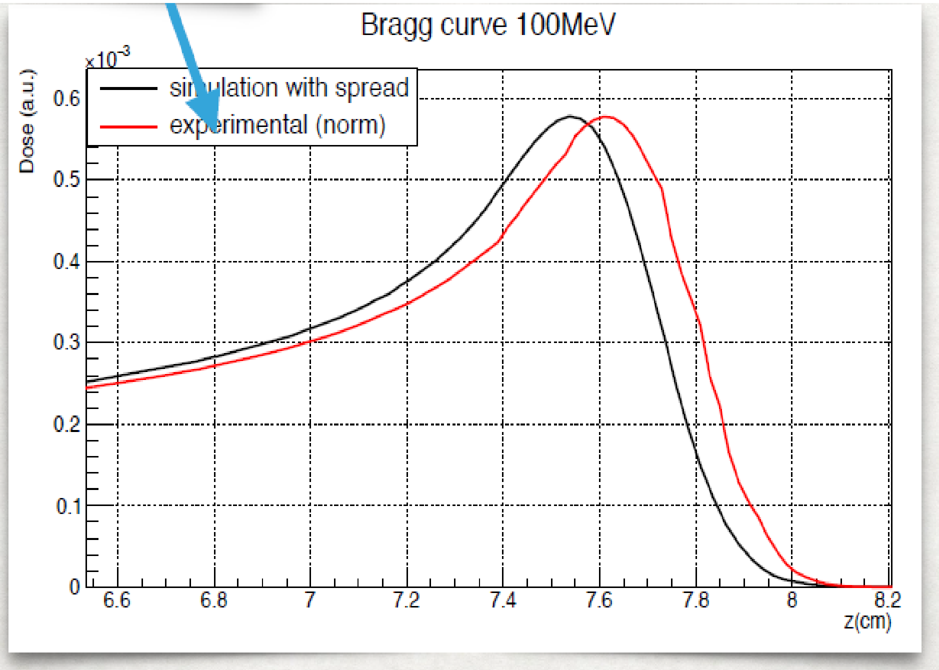
PROBLEMATICHE



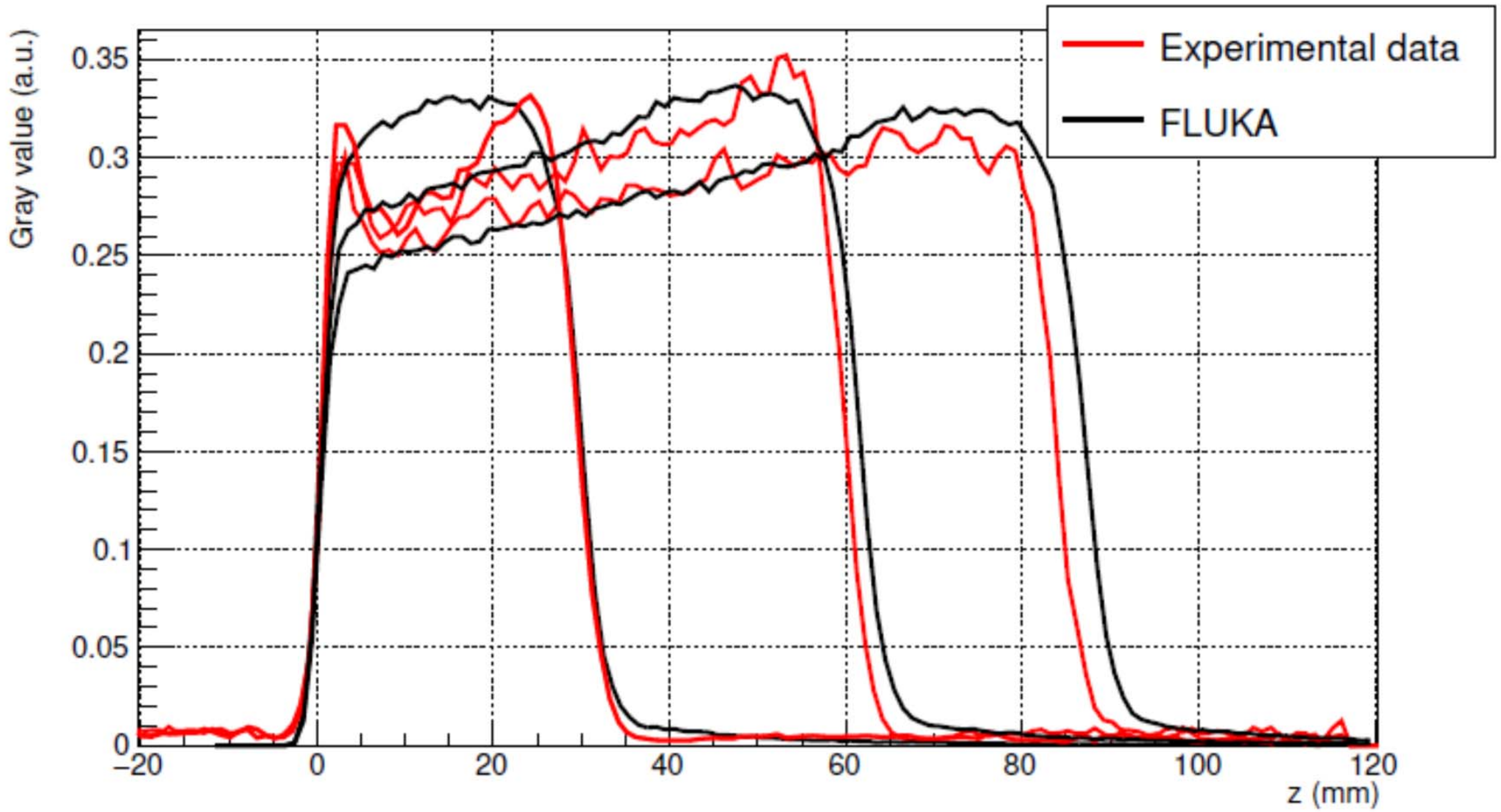
I=78 eV



I=76.9 eV



100MeV	sperimentale	sim. I=78eV	sim. I=76.9eV
peak (mm)	76.09	75.63	75.38
R50 (mm)	78.29	77.63	77.38



Experimental data
FLUKA
Gray value (a.u.)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−20
0
20
40
60
80
100
120
z (mm)