Activities of GFN-UCM and associates pertaining to task 1

José Manuel Udías Moinelo, GFN* chair

http://nuclear.fis.ucm.es (select english language)

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[a] Grupo de Fíısica Nuclear & IPARCOS, Universidad Complutense, CEI Moncloa, Madrid,Spain

[b] Instituto de Investigación Sanitaria del Hospital Clínico San Carlos (IdISSC), Madrid, Spain

-Experimental Nuclear Physics

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-Experimental Nuclear Physics

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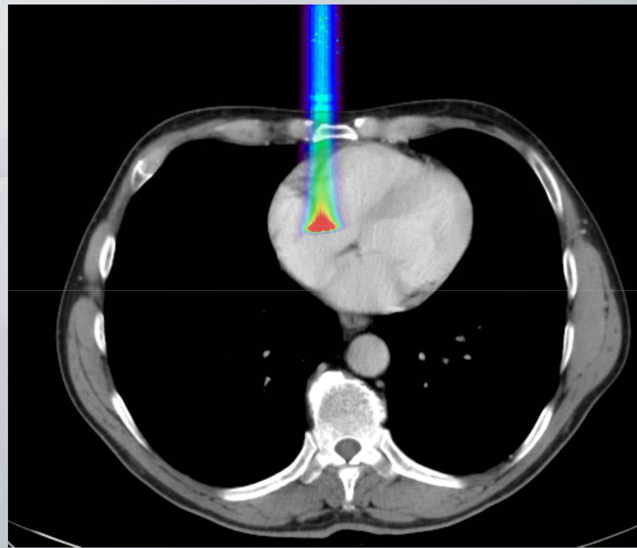
-Experimental Nuclear Physics

-MC Simulations

-

-Experimental Nuclear Physics

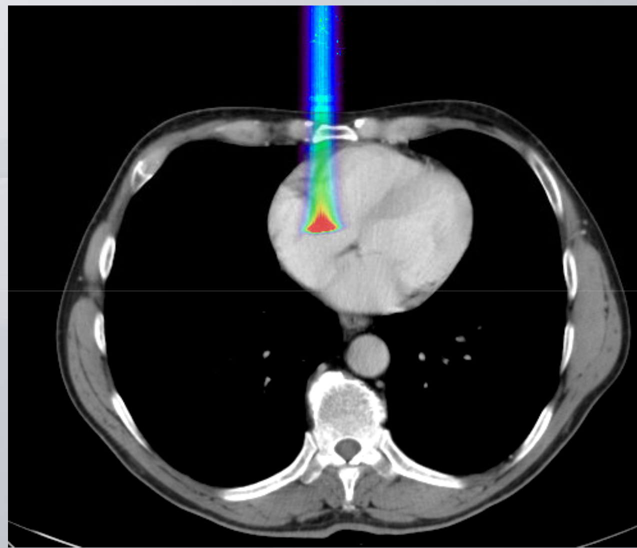


-MC Simulations

-

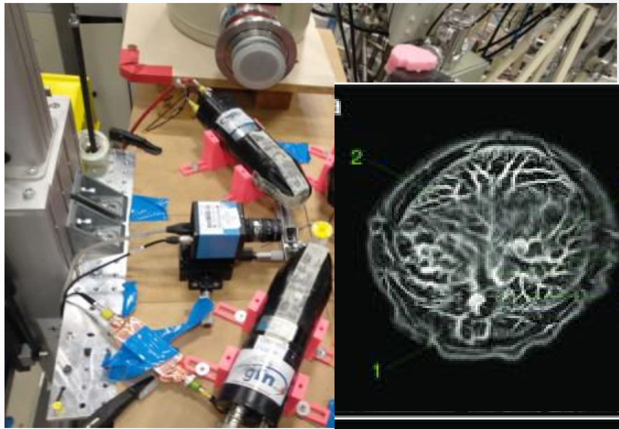
-Experimental Nuclear Physics

-MC Simulations



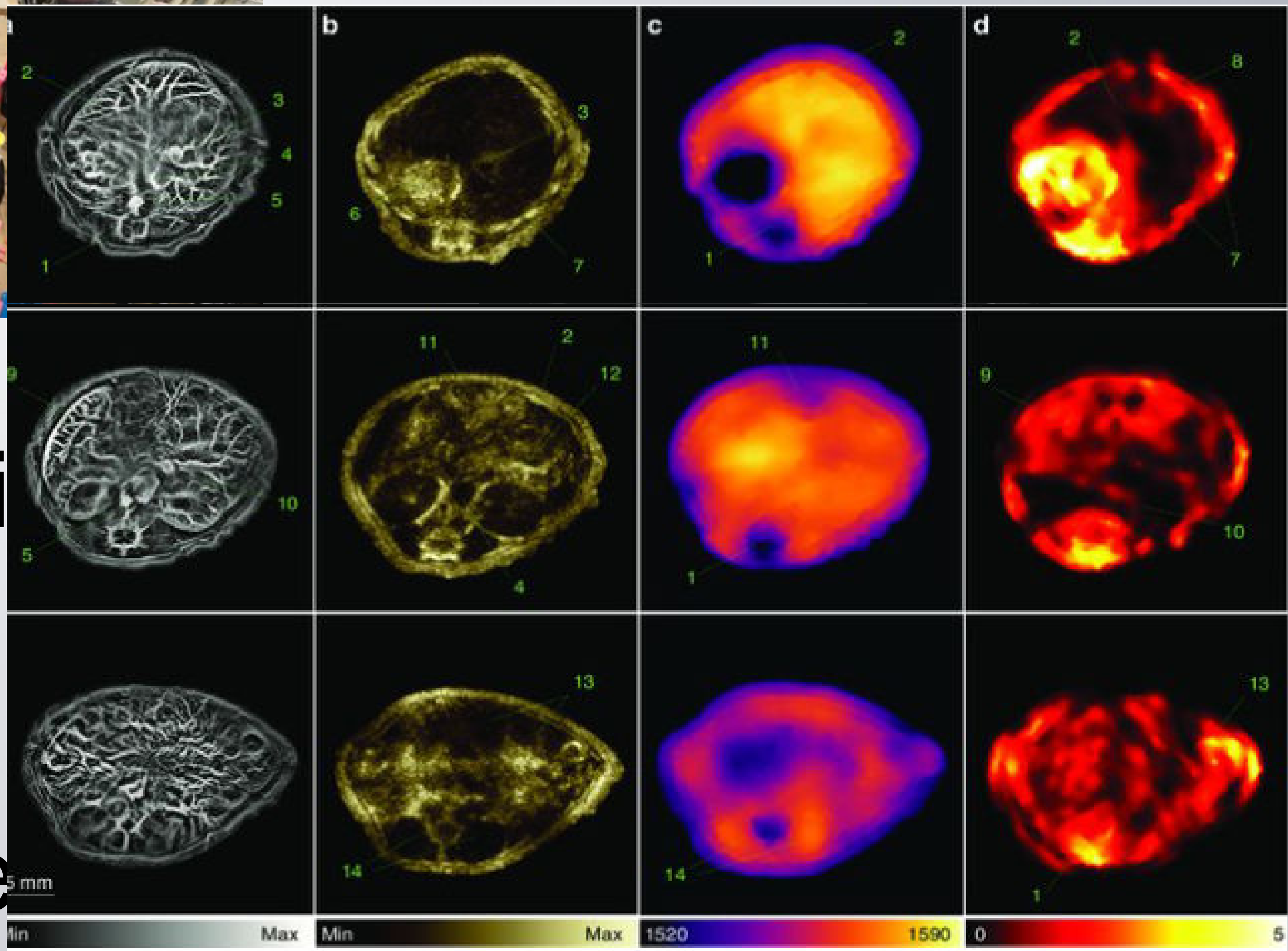
-Image Reconstruction

-Experimental Nuclear Physics



-MC Si

-Image



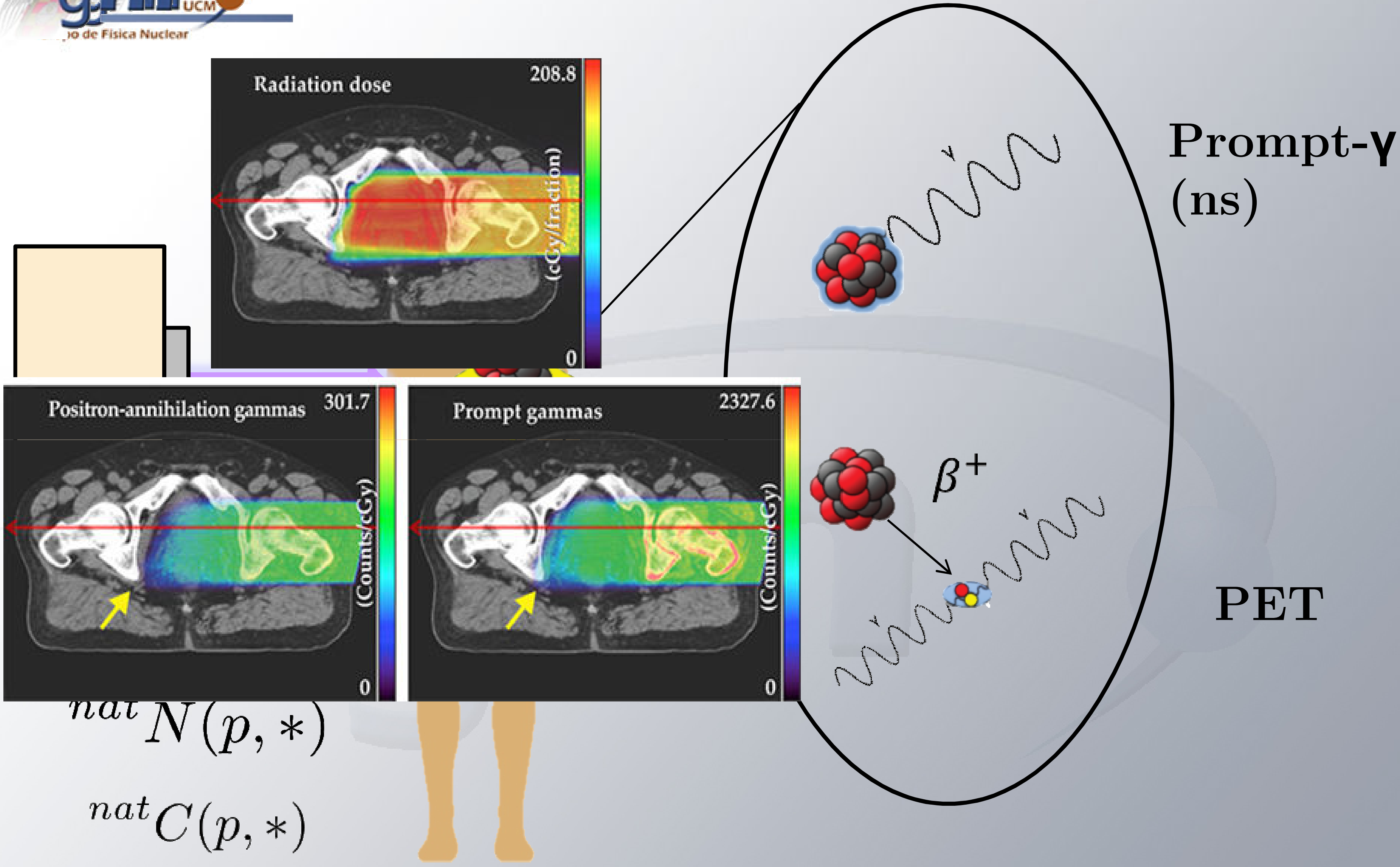
PRONTO

- Partners
  - GFN-UCM (coordinator): Luis Mario Fraile, S. España, D Sánchez-Parcerisa, JM Udías, J.L. Herraiz (…)
  - BIOMED-CIEMAT: M.A. Morcillo, E. Romero, N. Magro **(RBE)**
  - FNEXP-IEM-CSIC: E. Nácher (IFIC Valencia), M.J.G. Borge, O. Tengblad **(proton radiography, proton CT)**
- Associates
  - Sedecal Molecular Imaging
  - CUN: clinical beam (+patients), Quirón interested in joining
  - Justesa Imagen: radiopharmaceuticals
  - CMAM: low energy beams
- Funded for 4 years, we are now mid-project

Comunidad de Madrid

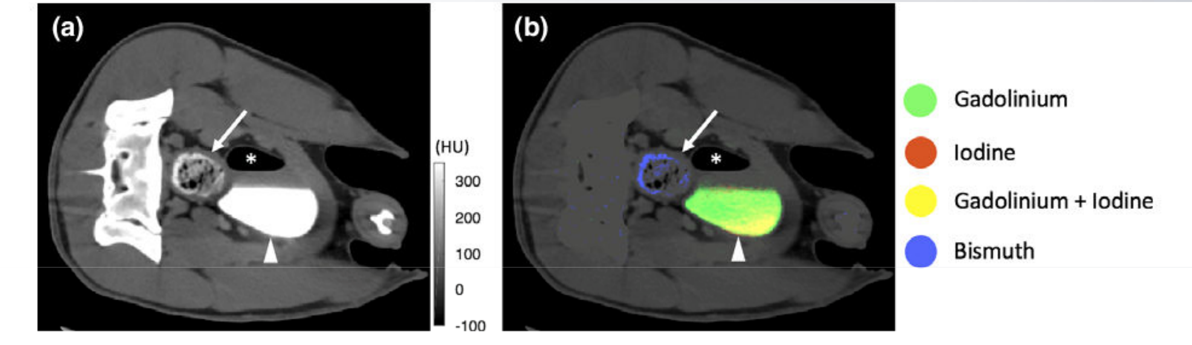
- Biophysics simulation package including PET and prompt-gamma activation
- Exploration of contrast agents for PET and PG
- Development of new detectors for these imaging modalities
- Collaboration with clinical partners to eventually include results in clinical protocols

Range verification



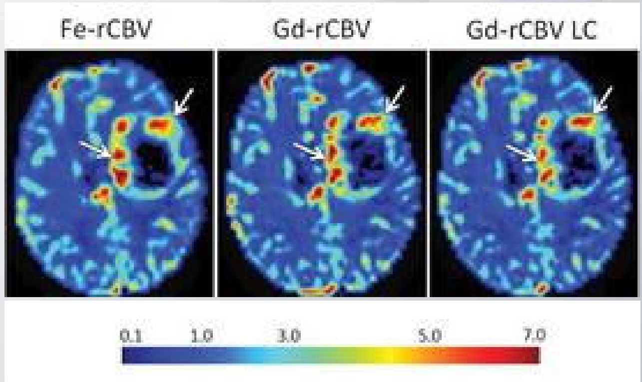
M. Moteabbed, S España, H. Paganetti (2011), *Phys. Med. Biol.*56, 1063

Enhanced image in the medical field → **CONTRAST AGENTS**



CT

Symons, R. et al., *Med.Phys.*, *44*(10), 5120-5127.



MRI

Gahramanov, S. et. al,. *Radiology*, *266*(3), 842-852.

Simulation Diagram

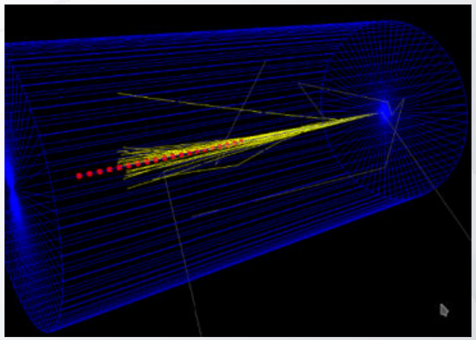
TOPAS

10^{10} H^+ (150 MeV)

↓

5 Gy

TOPAS ACTIVATION IMAGE



PeneloPET

Activation images

18F 15O

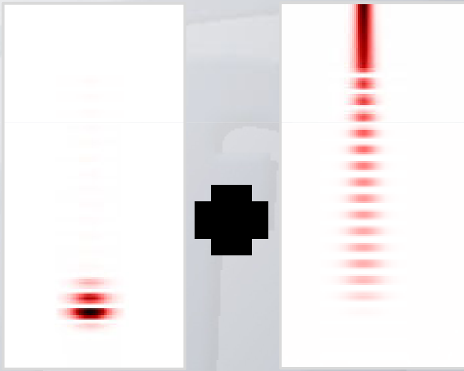
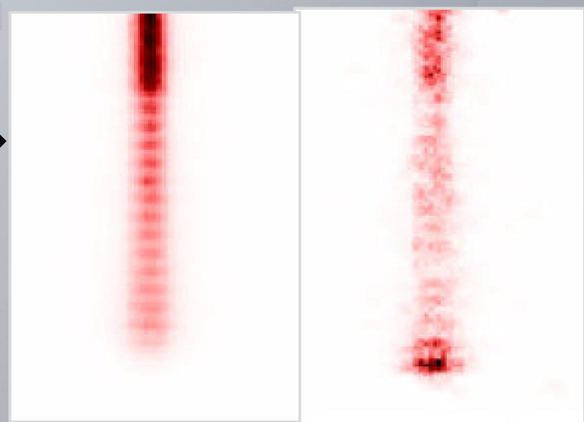


Image reconstruction software

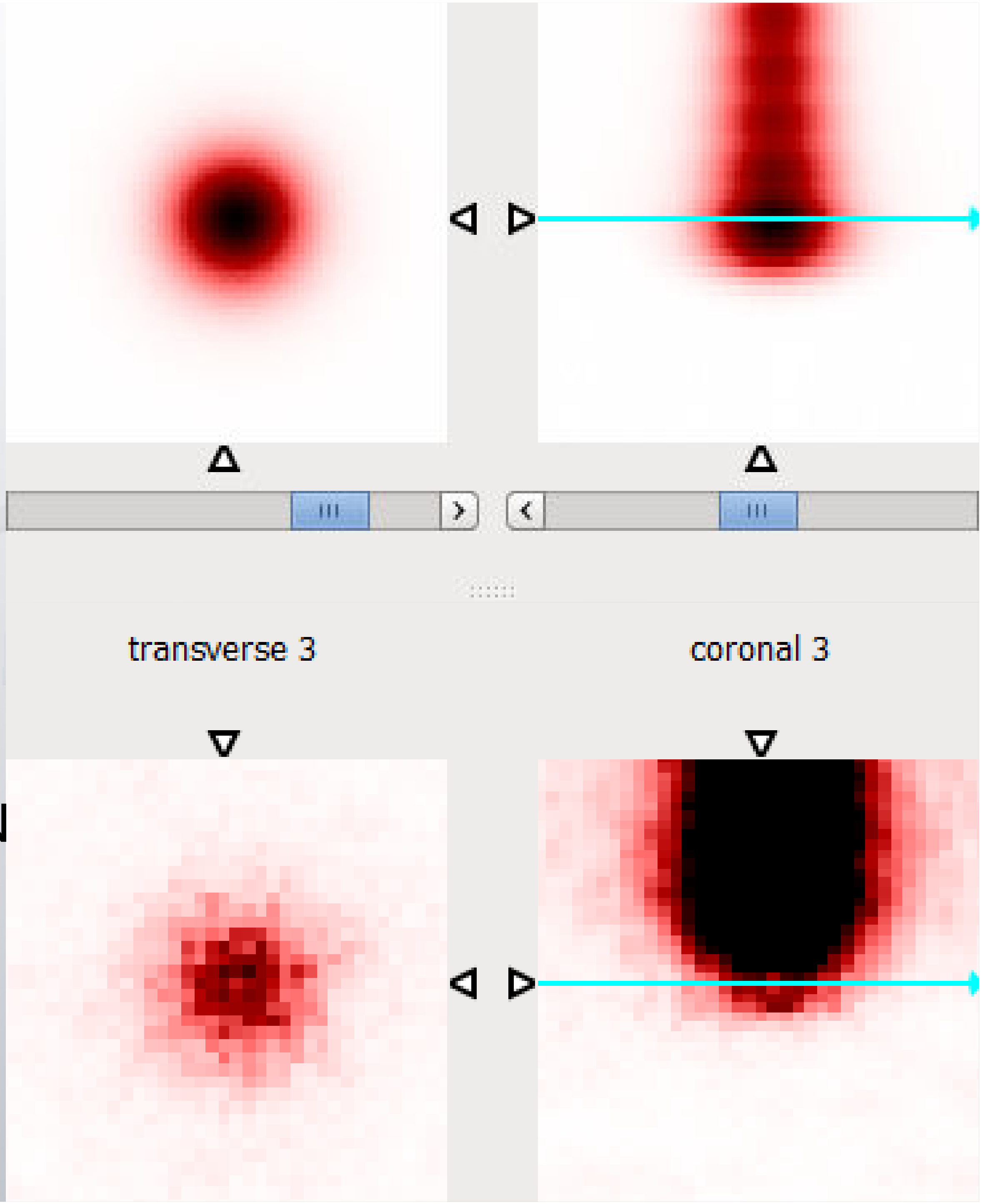
0-5 min 15-20 min



DOSE

3D-reconstructions allow to isolate the **distal end of the instantanoeus activation**. This is the farther away in the dose that we could disentangle **instantanoeus activation** if just **plain water** is irradiated

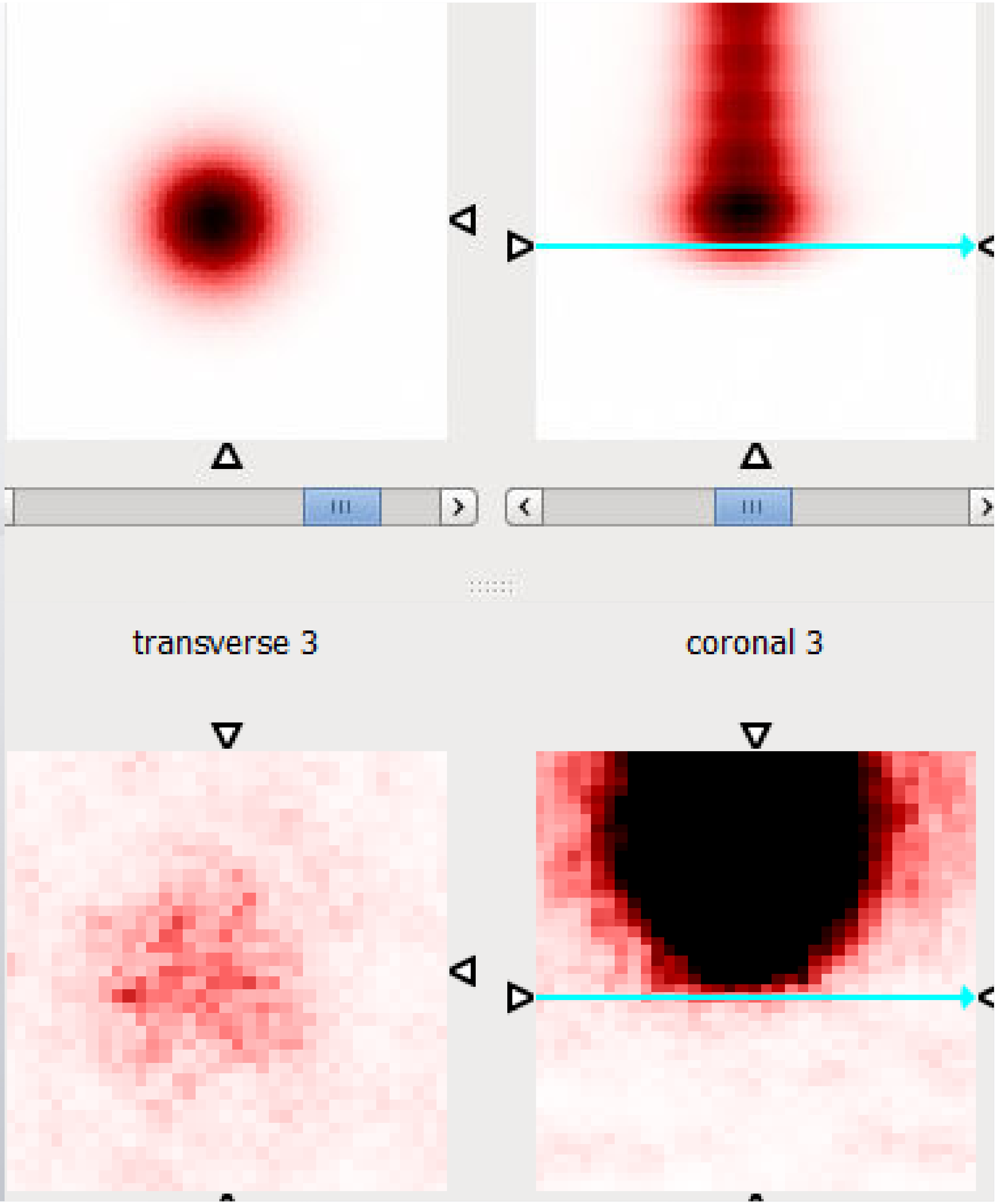
ACTIVATION



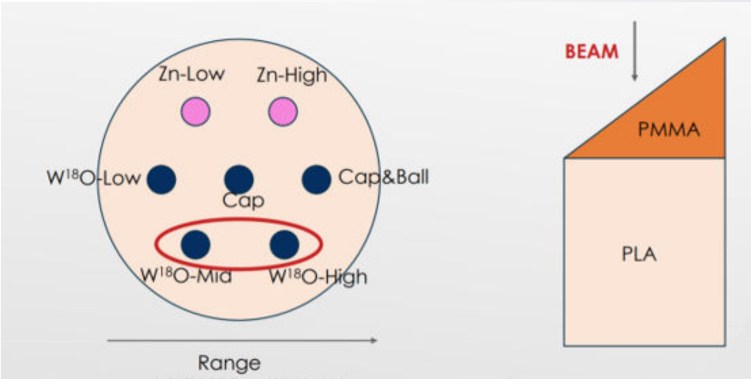
DOSE

3D-reconstructions allow to isolate the **distal end of the instantaneous activation**. This is the farther away in the dose that we could disentangle **instantaneous activation** if **^{18}O-water** is irradiated

ACTIVATION



Use of contrast agents in protontherapy



Range 80 MeV

Range 40 MeV

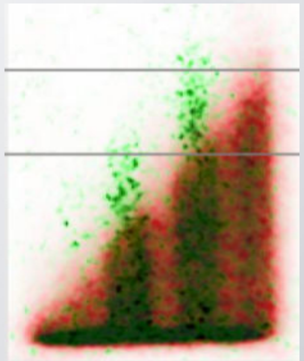


Fig. 1. Activation of an experimental phantom with **Water-18 3 hours** after irradiation

See poster by V. Valladolid-Onecha et al.

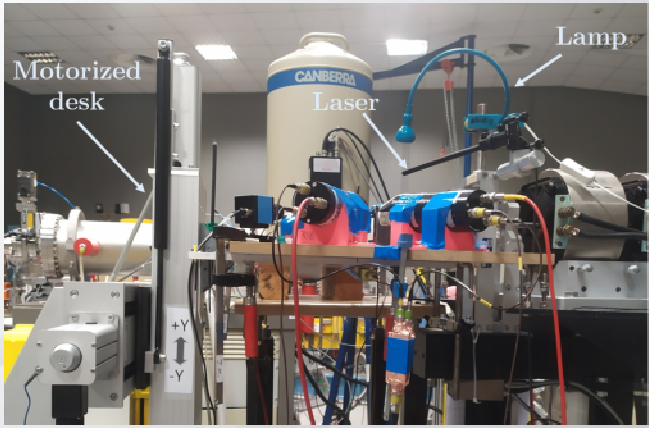
Protontherapy and nuclear techniques for oncology

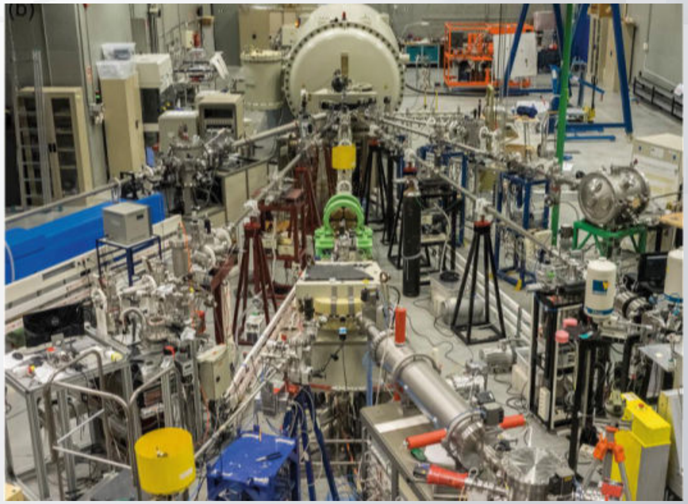
Proton activation analysis of potential contrast agents:

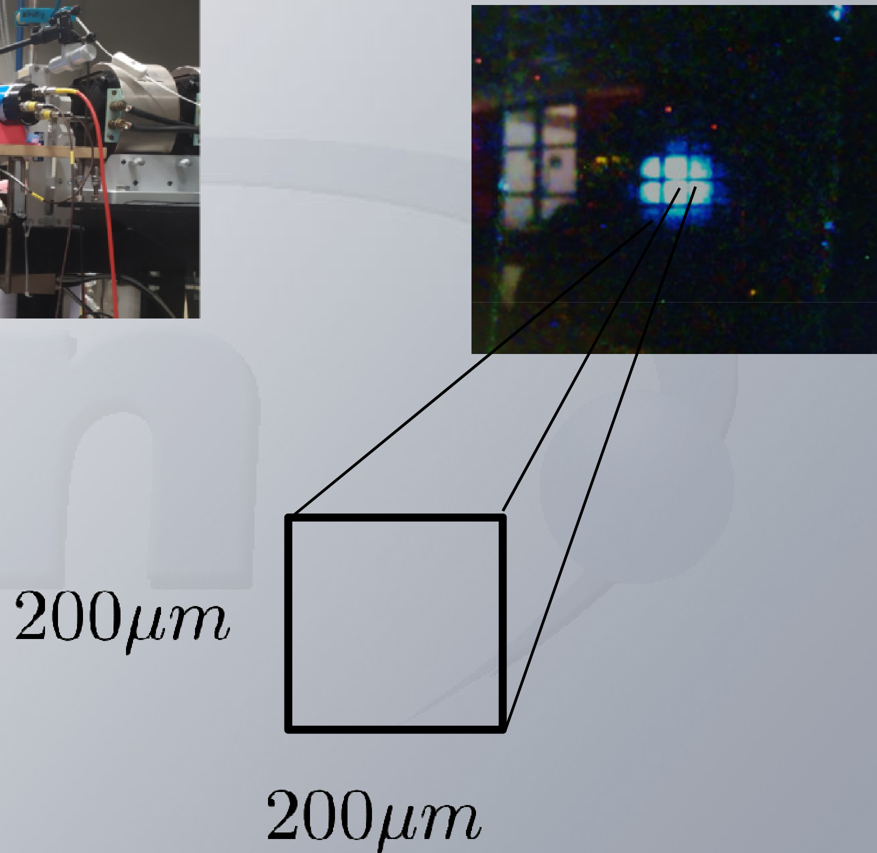
Zinc, Iodine, Water-18O…

2-10 MeV proton beam

5 MV tandetron accelerator

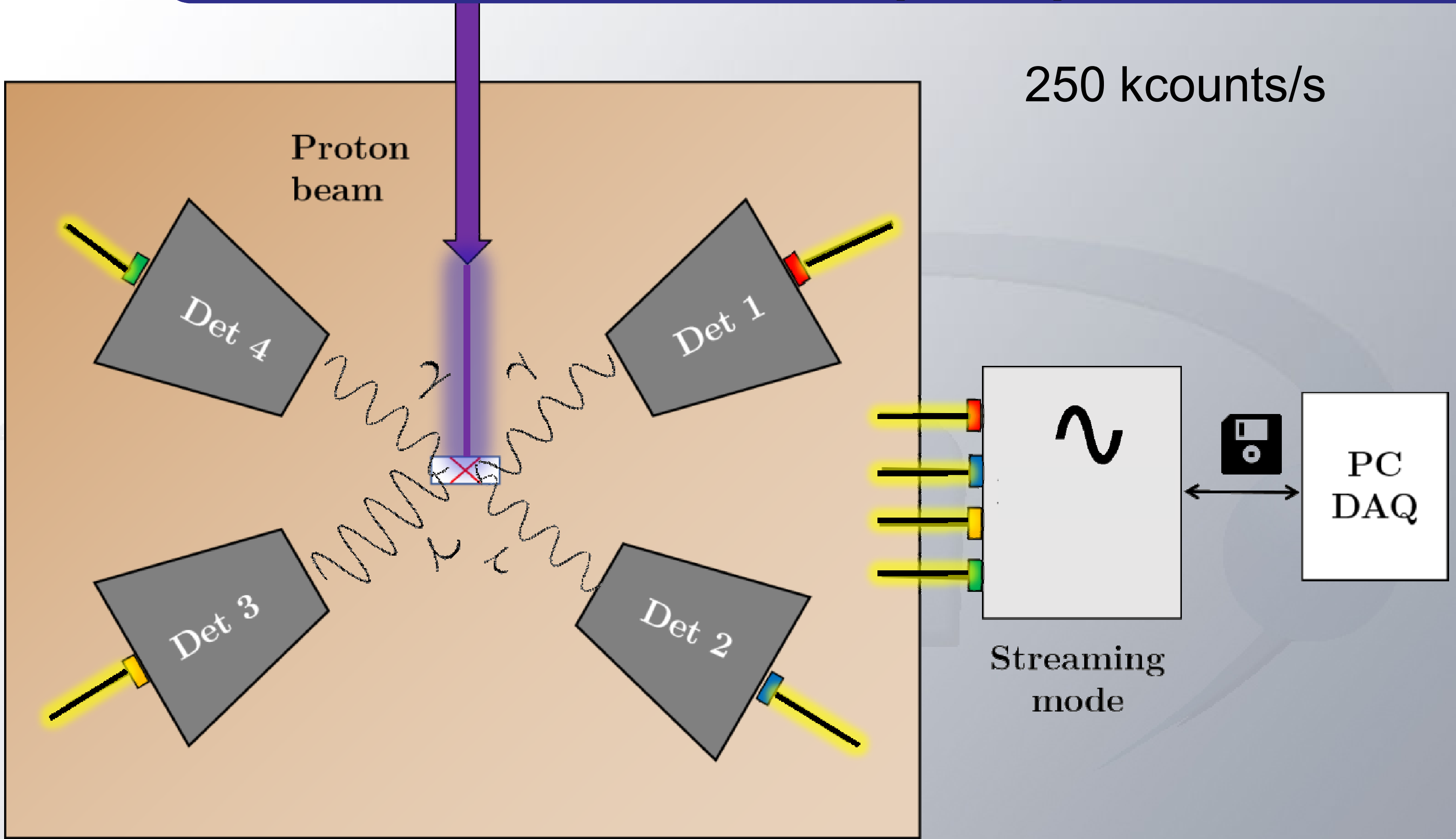




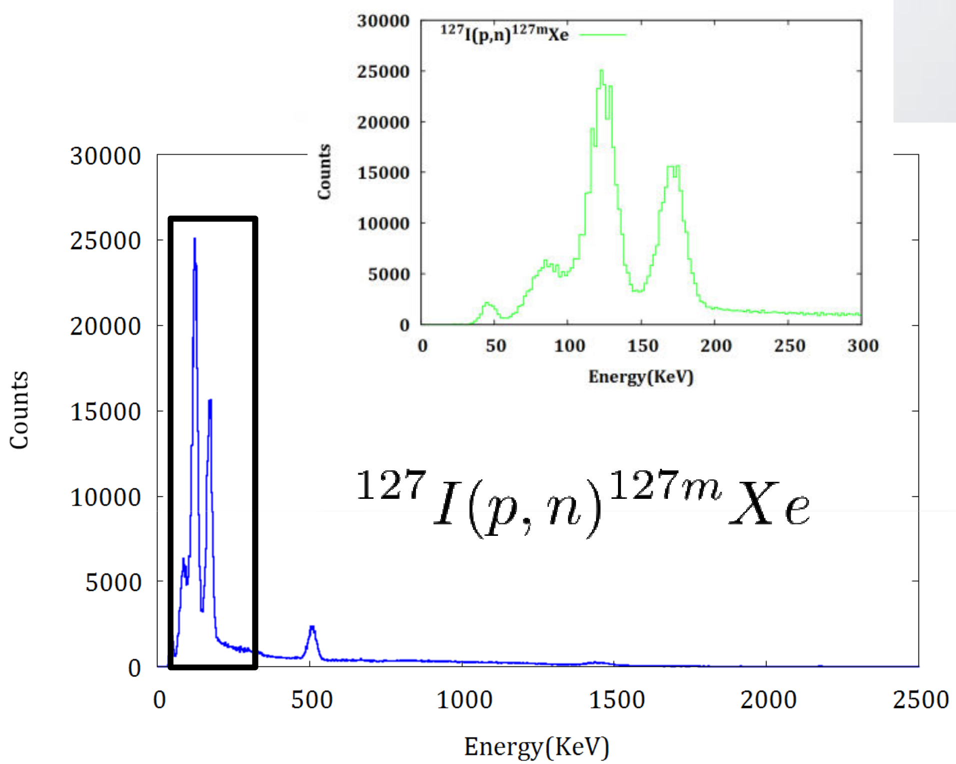


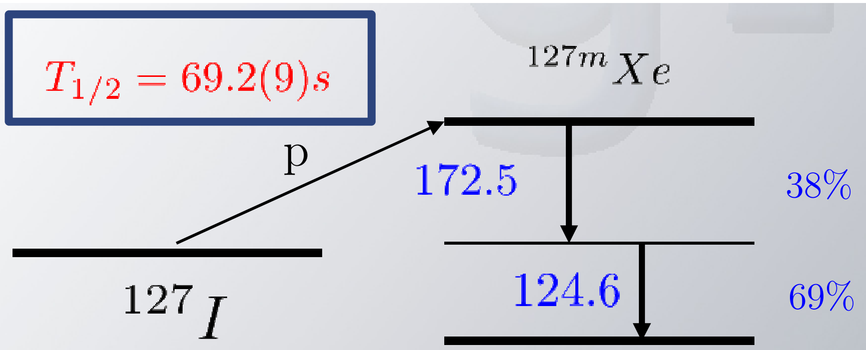
On line, fully digital 4 channel DAQ, on the fly list mode time-stamped data, limited only by detector pile-up

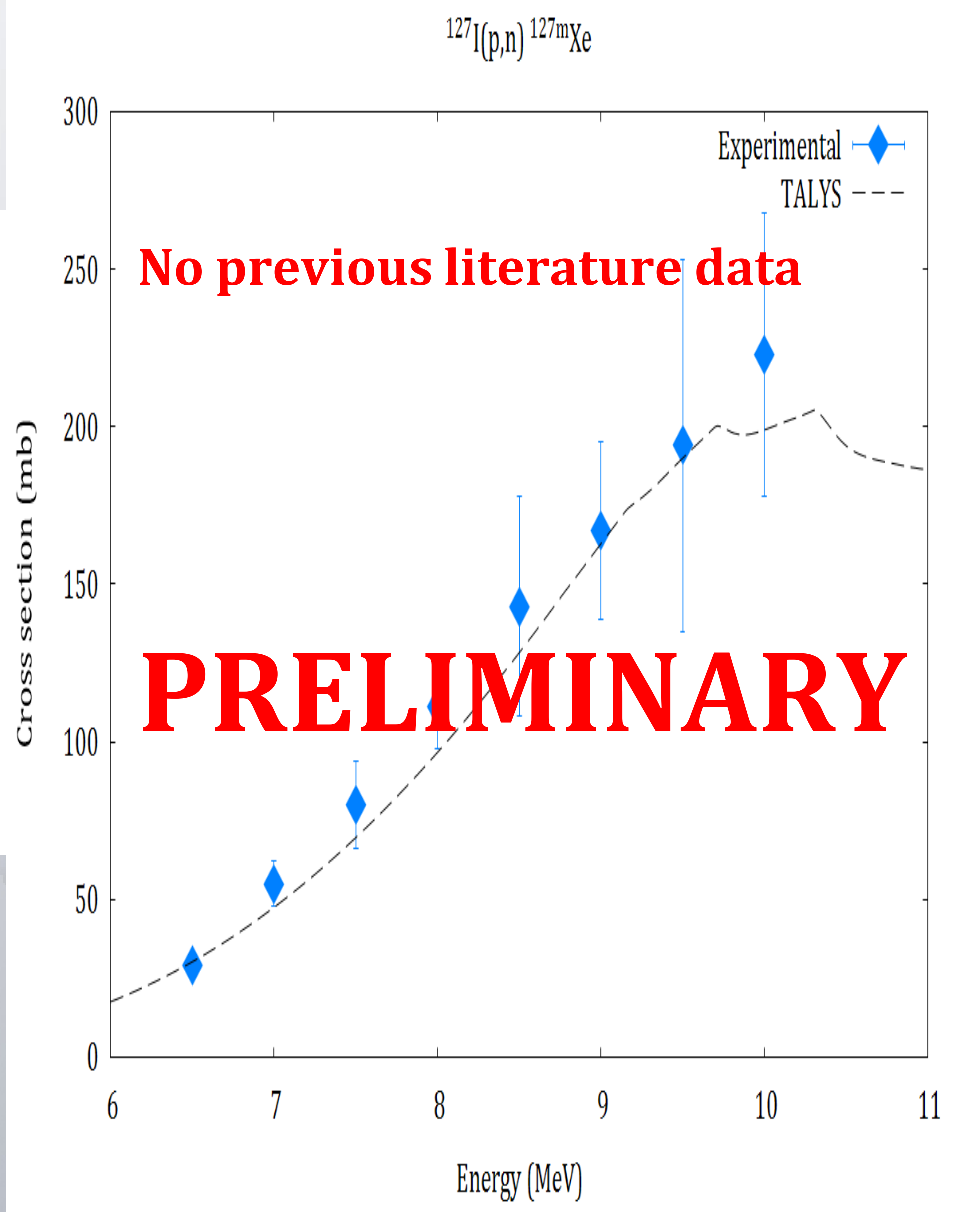
250 kcounts/s



Sanchez-Tembleque, V., et. al (2019). Nucl. Instrum. Methods Phys. Res. A, 927, 54-62.


30000
25000
20000
15000
10000
5000
0
Counts
0
500
1000
1500
2000
2500
Energy(KeV)
$^{127}I(p,n)^{127m}Xe$
^{127}I(p,n)^{127m}Xe
Counts
Energy(KeV)
0
50
100
150
200
250
300


$T_{1/2} = 69.2(9)s$
^{127m}Xe
p
172.5
38%
124.6
69%
^{127}I


^{127}I(p,n) ^{127m}Xe
Experimental
TALYS
No previous literature data
PRELIMINARY
Cross section (mb)
Energy (MeV)
0
50
100
150
200
250
300
6
7
8
9
10
11

Next PRONTO proposal at CMAM

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E. Nácher[e]

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M.A. Morcillo[f]

[f]Unidad de aplicaciones biomédicas y farmacocinética, CIEMAT, Madrid, Spain

Further experiments performed at KVI-CART in collaboration with C. Guerrero *et al.* (CNA) and P. Dendooven *et al* (KVI) and at UK-Essen in collaboration with Christian Baeumer *et al.*

Ionoacoustics at GFN

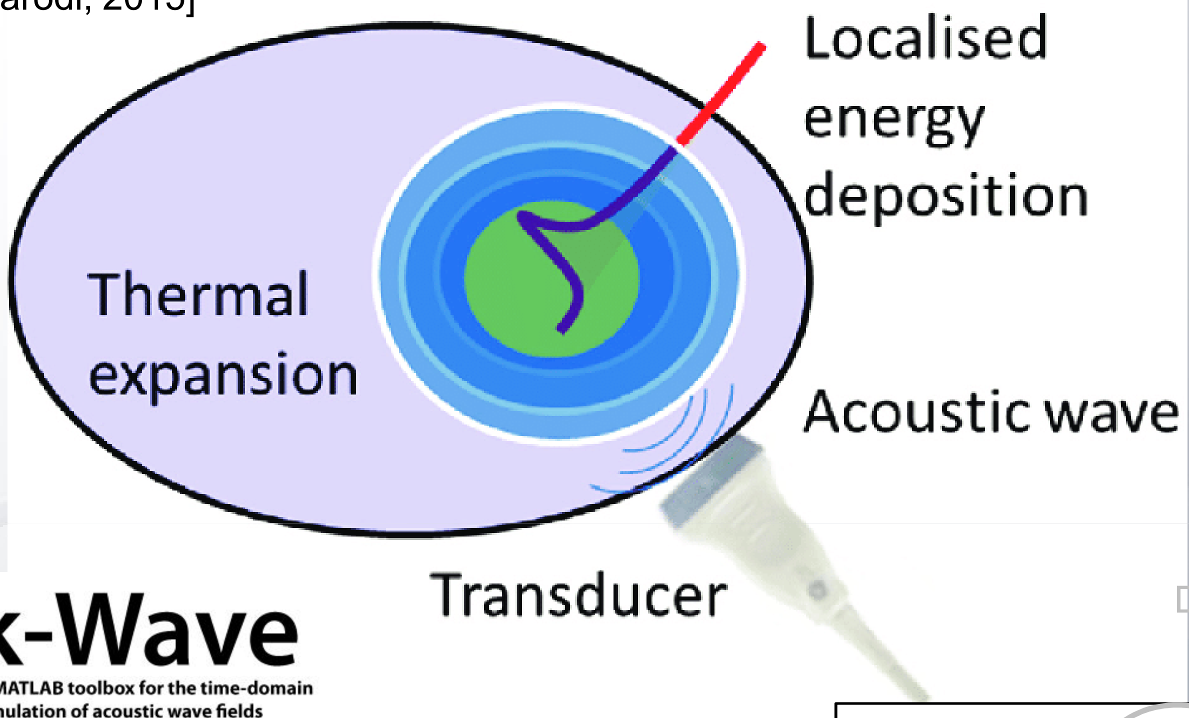
J.L. Herraiz, D. Sánchez Parcerisa, C. Freijo, V. Sánchez-Tembleque, V. Valladolid, M. García, M. Pérez-Lyva, J.M. Udías, …

Builds on our experience in US imaging
Collaboration with k-wave developers to use it as a FWI image reconstructor

k-Wave
A MATLAB toolbox for the time-domain simulation of acoustic wave fields

Protoacoustic. Thermoacoustic effect

[Parodi, 2015]



k-Wave
A MATLAB toolbox for the time-domain
simulation of acoustic wave fields

Dose

$$H(\mathbf{r}) = D(\mathbf{r})\rho(\mathbf{r})$$

- Wave propagation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) p(\mathbf{r},t) = -\Gamma \frac{\partial}{\partial t}\mathcal{H}(\mathbf{r},t)$$

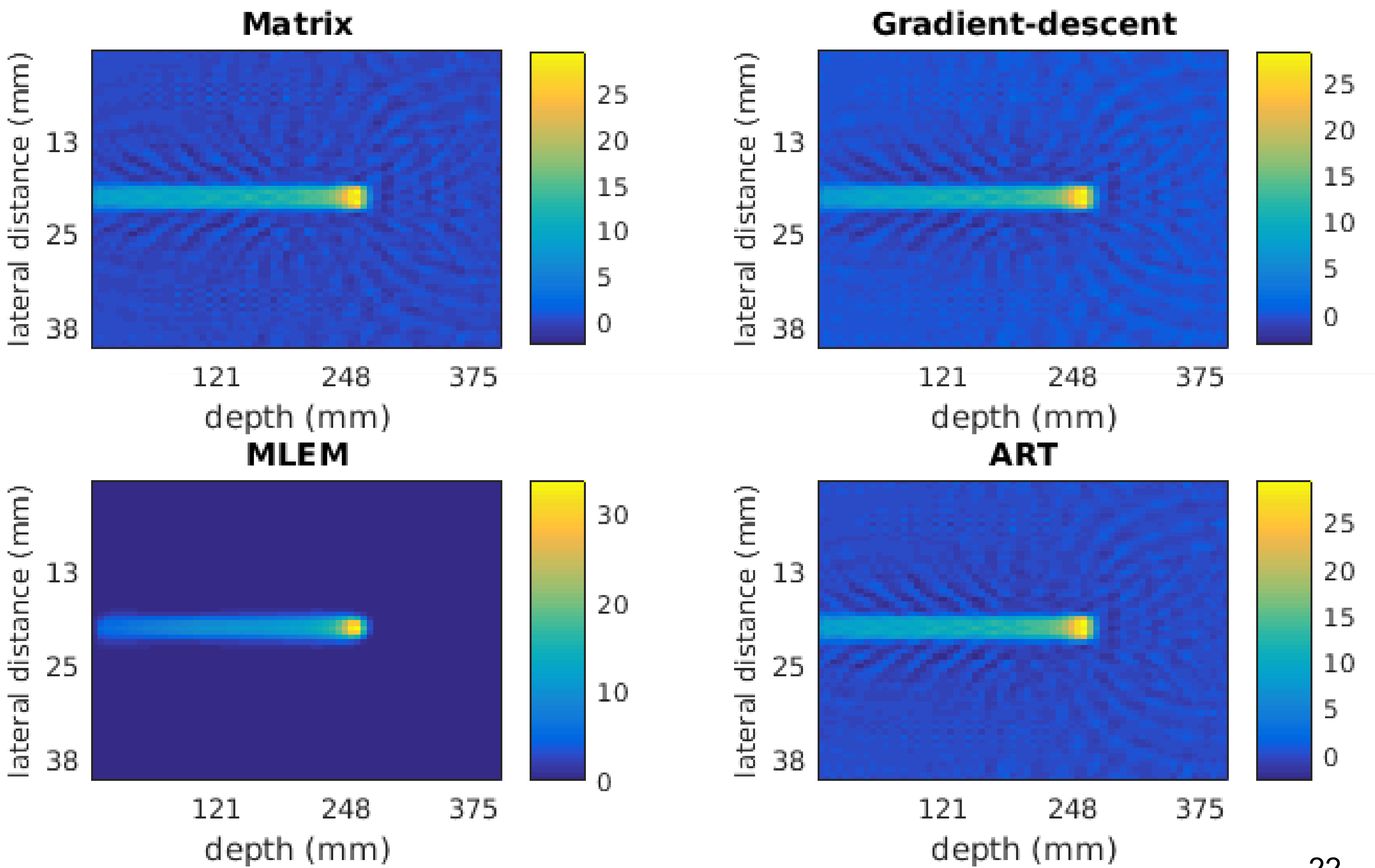
Wave equation

Source term: deposited energy

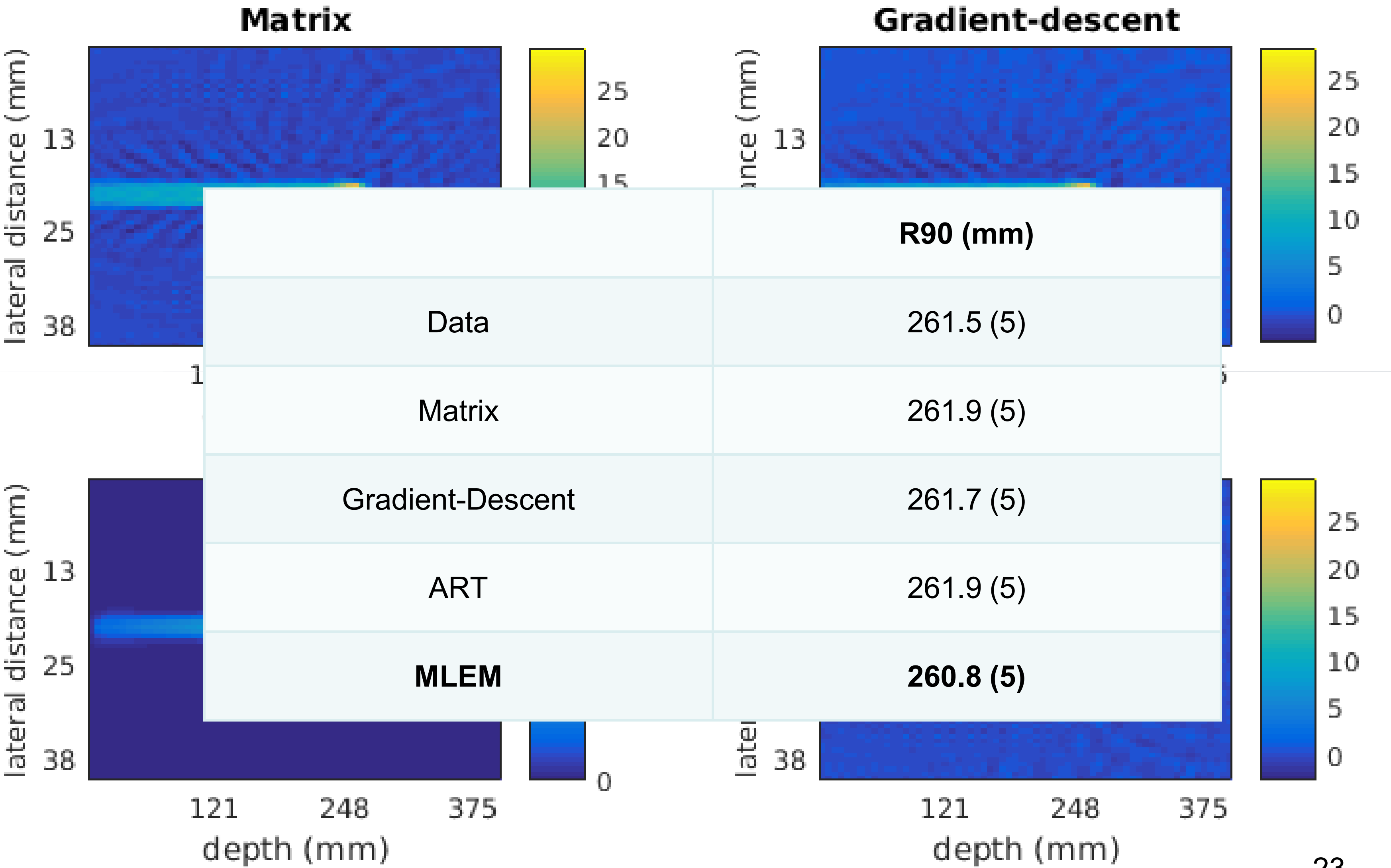
$$\Gamma = \frac{\beta c^2}{C_p}$$

Grüneisen coefficient

2D Proton Dose Distribution Reconstruction



Results. 2D Proton Dose Distribution Reconstruction



	R90 (mm)
Data	261.5 (5)
Matrix	261.9 (5)
Gradient-Descent	261.7 (5)
ART	261.9 (5)
MLEM	**260.8 (5)**

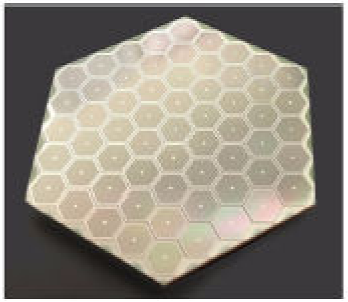
Activation monitorization during in beam PET we expect challenging geometries

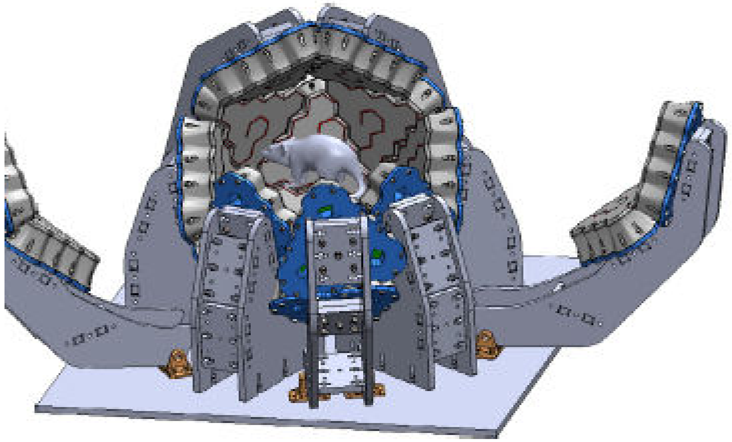
And we need very fast reconstructions

Developed a very fast (1 billion decays per minute in GPU) PET realistic simulation tool allowing very flexible geometries

Developed a very fast (1 billion decays per minute in GPU) PET realistic simulation tool allowing very flexible geometries

And the associated MLEM GPU reco code: what we can simulate, we can reconstruct also very fast

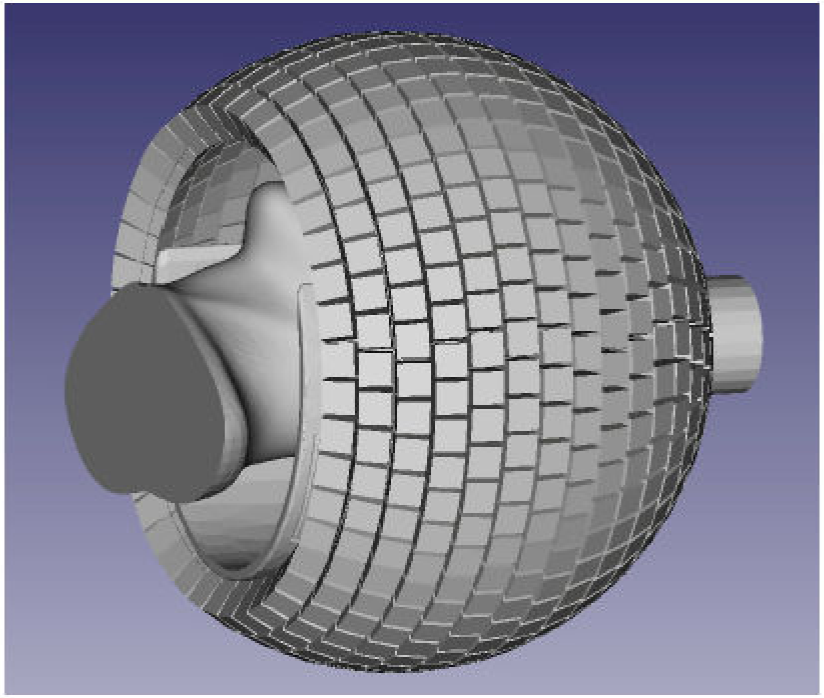




Developed a very fast (1 billion decays per minute in GPU) PET realistic simulation tool allowing very flexible geometries

ICOPET, D Pérez et al (UC3M) j.nima.2018.10.179

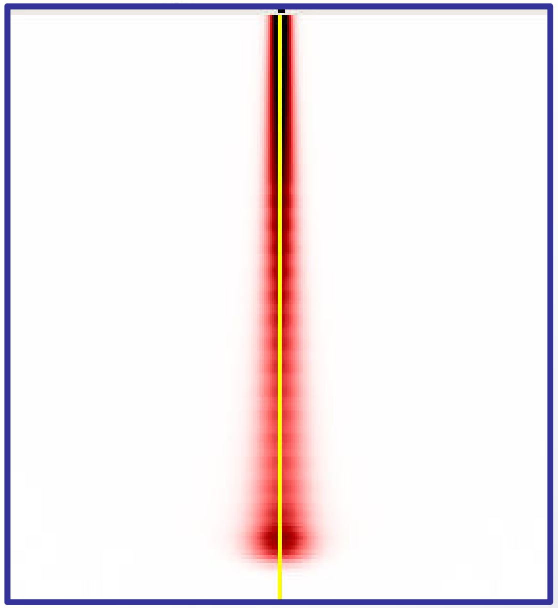
And the associated MLEM GPU reco code: what we can simulate, we can reconstruct also very fast



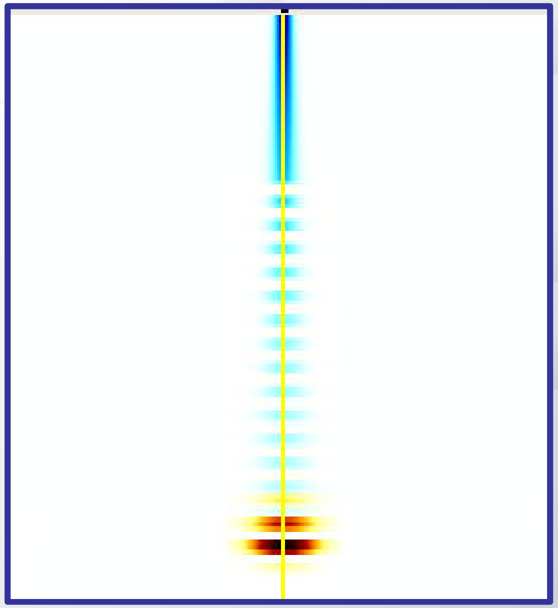
BRAINPET-2 (Martinos Center)

Ciprian Catana *et al*, jnumed118.2179

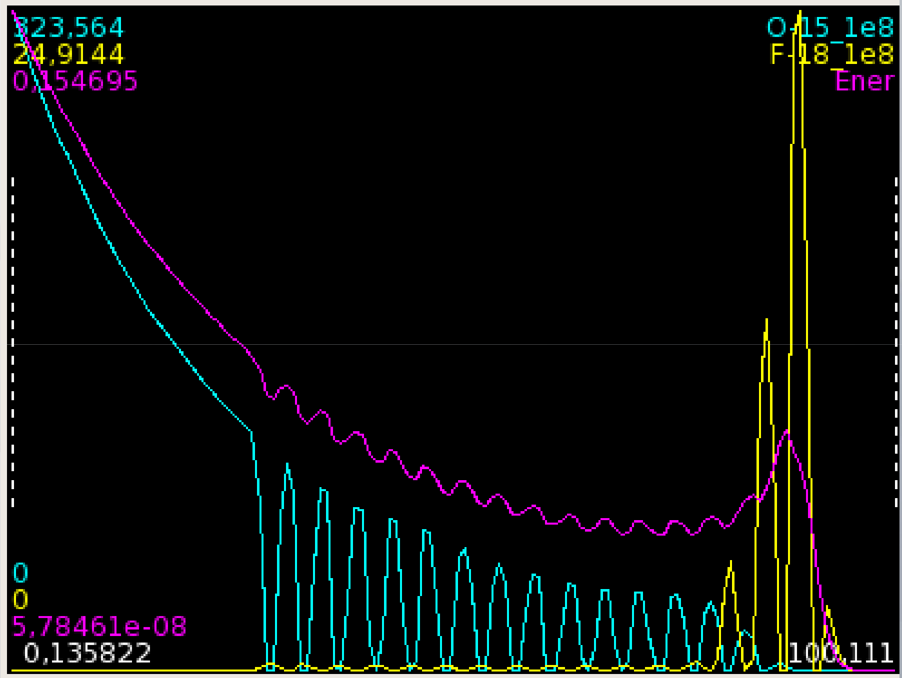
USEFUL INFORMATION FOR PROTONS



Dose distribution

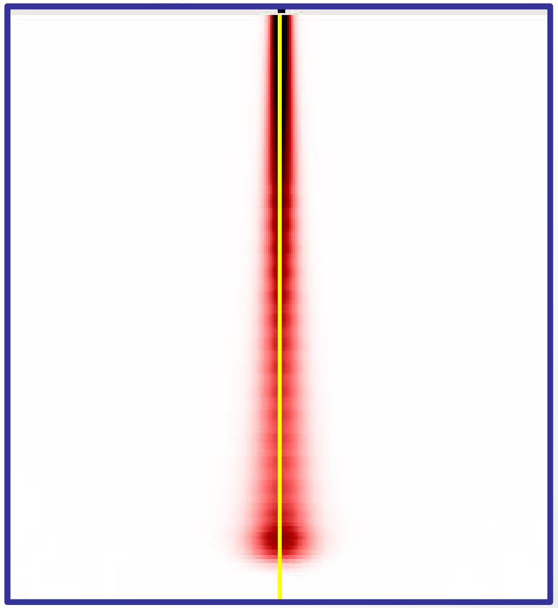


Activation maps

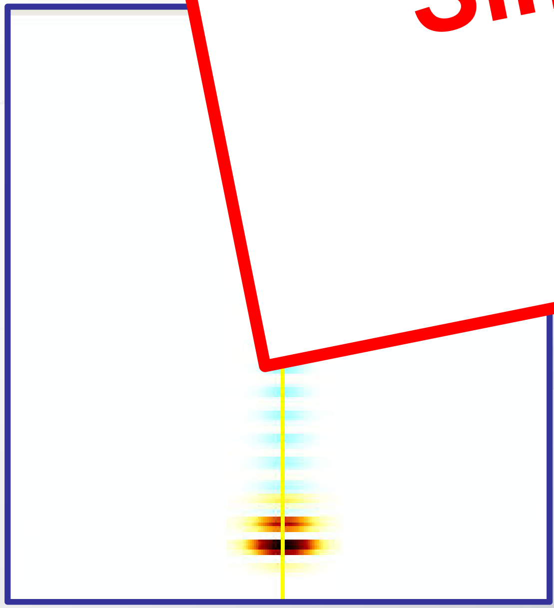


Blue: **O-15**
Orange: **F-18**
Purple: **Deposited energy**

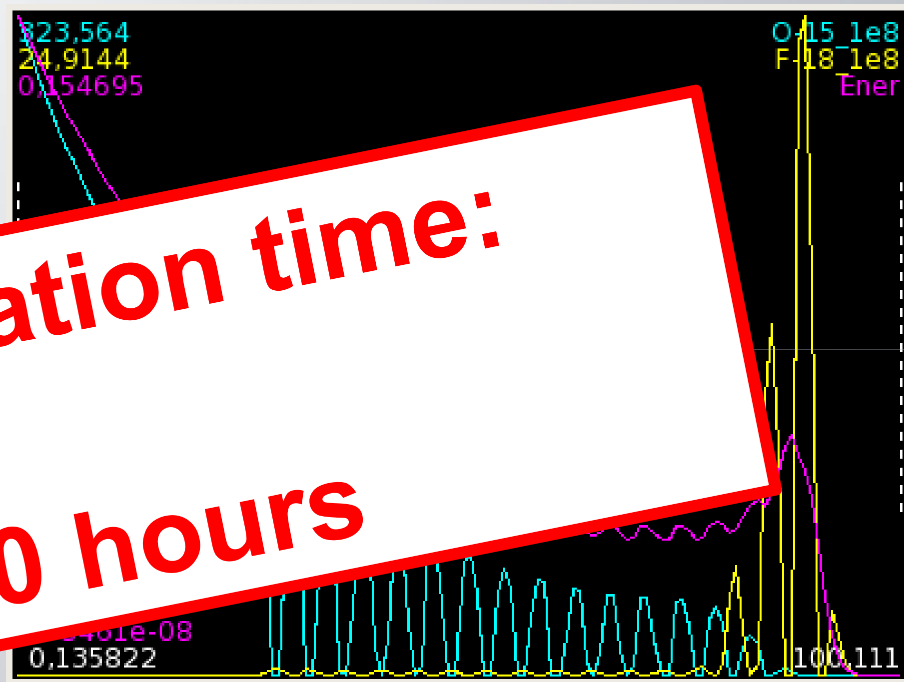
USEFUL INFORMATION FOR PROTONS



Dose distribution



Activation maps



Simulation time:

20 hours

Blue: O-15
Orange: F-18
Purple: Deposited energy

GHMCp: GPU-HYBRID MONTE CARLO FOR PROTONS

- **<u>Precalculated database</u>** of monoenergetic protons in different materials extracted from (any) MC code
  - Includes all the physics of the protons → **NOT a pencil beam approximation**
  - Possibility of changing from one physics model to another with the same code, in a snap
  - Tracking of secondary particles (electrons, photons…)
  - Allows the calculation of activation, neutron production…
  - Other reactions can be easily introduced

- **<u>Dose normalization</u>**
  - Simulations with a low number of initial protons and low noise
  - Noiseless energy/angle distributions

- **<u>GPU implementation</u>**
  - Possibility of real time dose and activation calculations

GHMCp: GPU-HYBRID MONTE CARLO FOR PROTONS

Proton beam

E, direction

Proton nuclear absorption?
Electron emission?
Secondary proton emission?
Nuclear interaction (activation)?

- Generate tables after analyzing ***thousands*** of TOPAS / PenH-NUC or any other MC (FLUKA and SRIM are on the work) simulation runs for different energies and materials, with fixed thickness (about 0.1 mm)
- **Tables take <8GB**: fit in modern GPUs
- Need from 1 Mhistories to 1000 Mhistories or more per tissue / energy and proccess. Run on a supercomputer for weeks

PERFORMANCE STUDY: EM case

Particles and simulation time needed to reach the same noise level in water (less than 5% at D50, 3 cm spherical applicator)

CPU		
Code	**Particles**	**CPU time (1 core)**
MC	10^{10}	55:30:00
Hybrid	$5 \cdot 10^{6}$	00:22:00

GPU		
Code	**Particles**	**GPU time**
Hybrid	$5 \cdot 10^{6}$	00:00:25

GPU: NVIDIA 1080 Ti (3584 cores, 1.58 MHz, 11 GB, approx 700 euros)
CPU: (1 core): Intel Xeon E5-2650 (2 GHz) (8 cores per cpu)

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Cod		**GPU time**
Hybri	$5 \cdot 10^{6}$	00:00:25

Speed-up X7000

GPU: NVIDIA 1080 Ti (3584 cores, 1.58 MHz, 11 GB, approx 700 euros)
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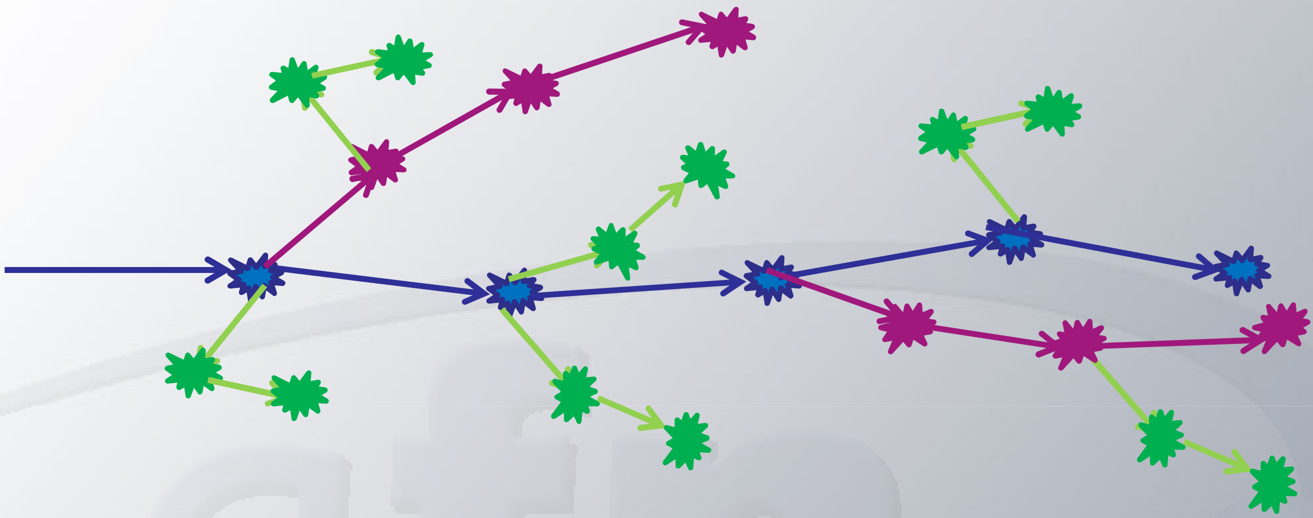
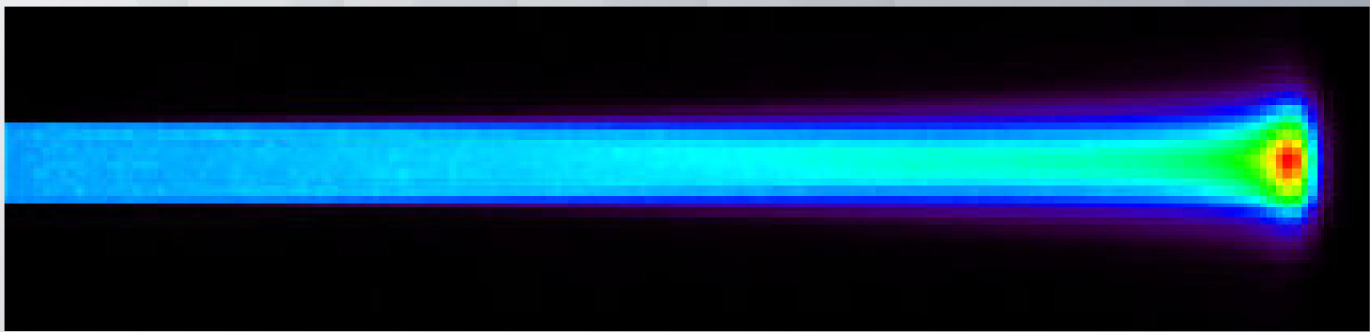
GHMCp: GPU-HYBRID MONTE CARLO FOR PROTONS

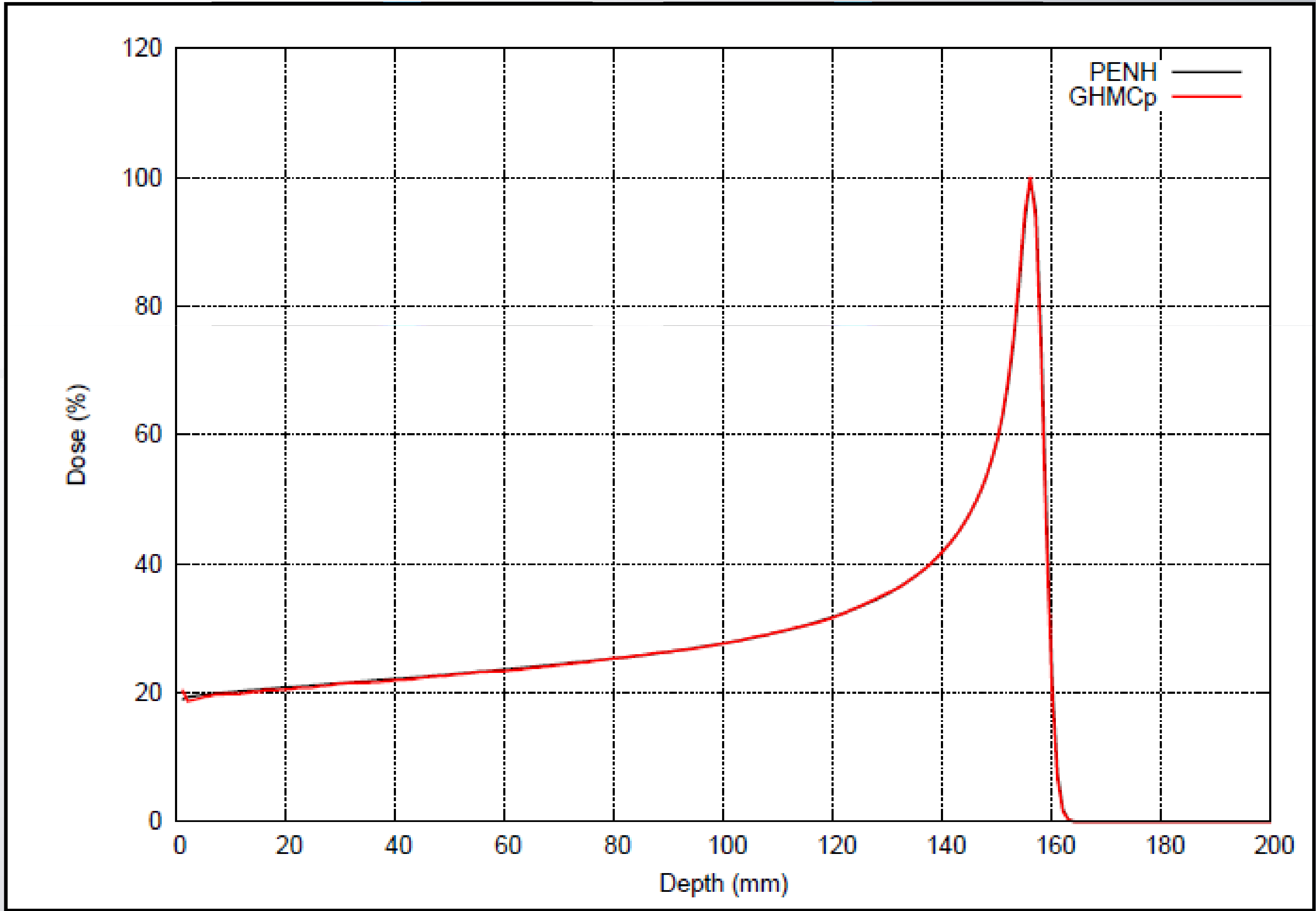
Proton beam





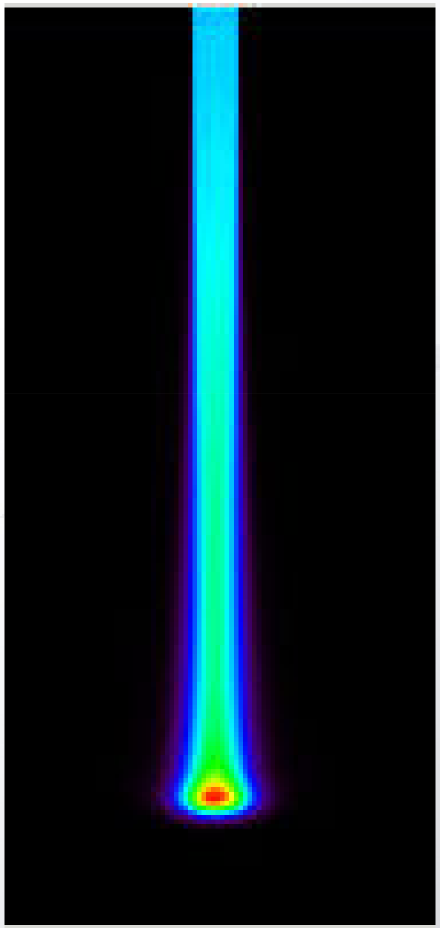
GHMCp. COMPARISON WITH PENH-no NUC

150 MeV protons in water. 10^6 histories

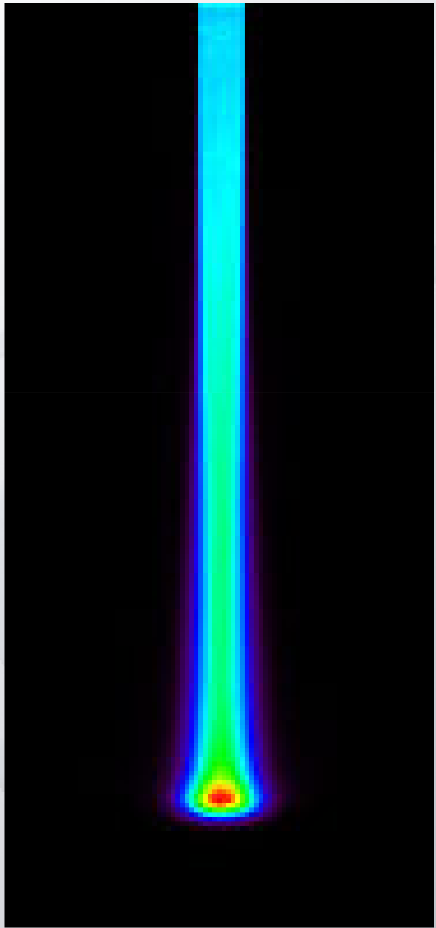


GHMCp. COMPARISON WITH PENH-NUC

80 MeV protons in lung

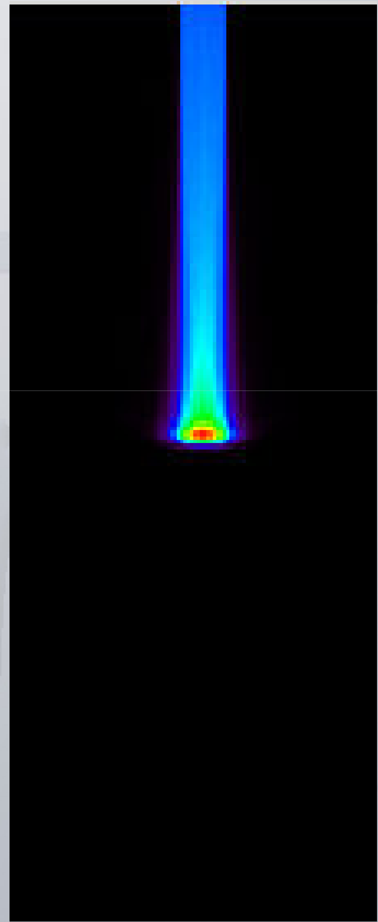


PENH

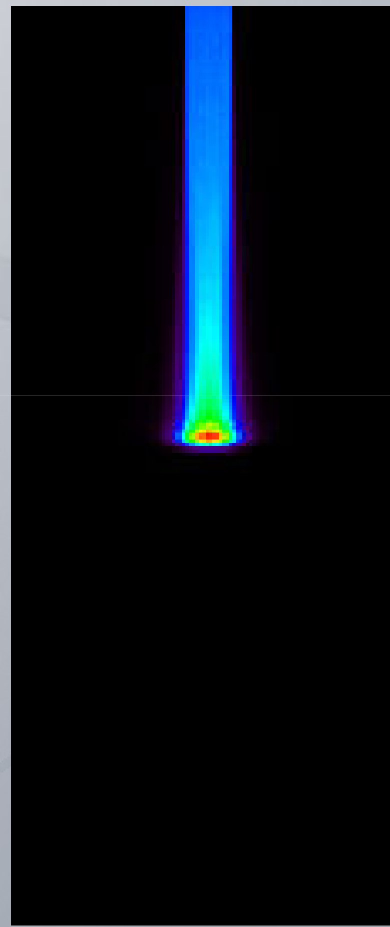


GHMCp

150 MeV protons in bone



PENH



GHMCp

PERFORMANCE STUDY

Number of histories per second in water calculated with TOPAS, PENH and with the Hybrid Monte Carlo, for 100 MeV protons, a pencil beam of 1x1 cm^2 cross-section.

	Histories/s
TOPAS (16 cores)	$5 \cdot 10^3$
PENH (1 core)	400
HMCp (CPU, 1 core)	$9 \cdot 10^4$
GHMCp (GPU)	$2.5 \cdot 10^7$

GPU: NVIDIA 1080 Ti (3584 cores, 1.58 MHz, 11 GB, approx 700 euros)
CPU: (1 core): Intel Xeon E5-2640 (2.4 GHz) (10 cores per cpu)

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PERFORMANCE STUDY

Number of histories per
PENH and

Speed-up X5000

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CPU: (1 core): Intel Xeon E5-2640 (2.4 GHz) (10 cores per cpu)

CONCLUSIONS

- Developed of a fast and versatile computational tool that allows:
  - Changing from one MC physics model to another with a snap
  - Full consideration of secondary particles or nuclear reactions of interest
  - Real time calculations of dose and activation maps

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- SEDECAL
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Pronto
Protontherapy and nuclear techniques for oncology

UNION EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
"Una manera de hacer Europa"

Comunidad de Madrid

topus
Tomografía por emisión de positrones y ultrasonidos

MINISTERIO DE CIENCIA E INNOVACIÓN

CDTI
Centro para el Desarrollo Tecnológico Industrial

gmv
INNOVATING SOLUTIONS

CPAN
ingenio 2010

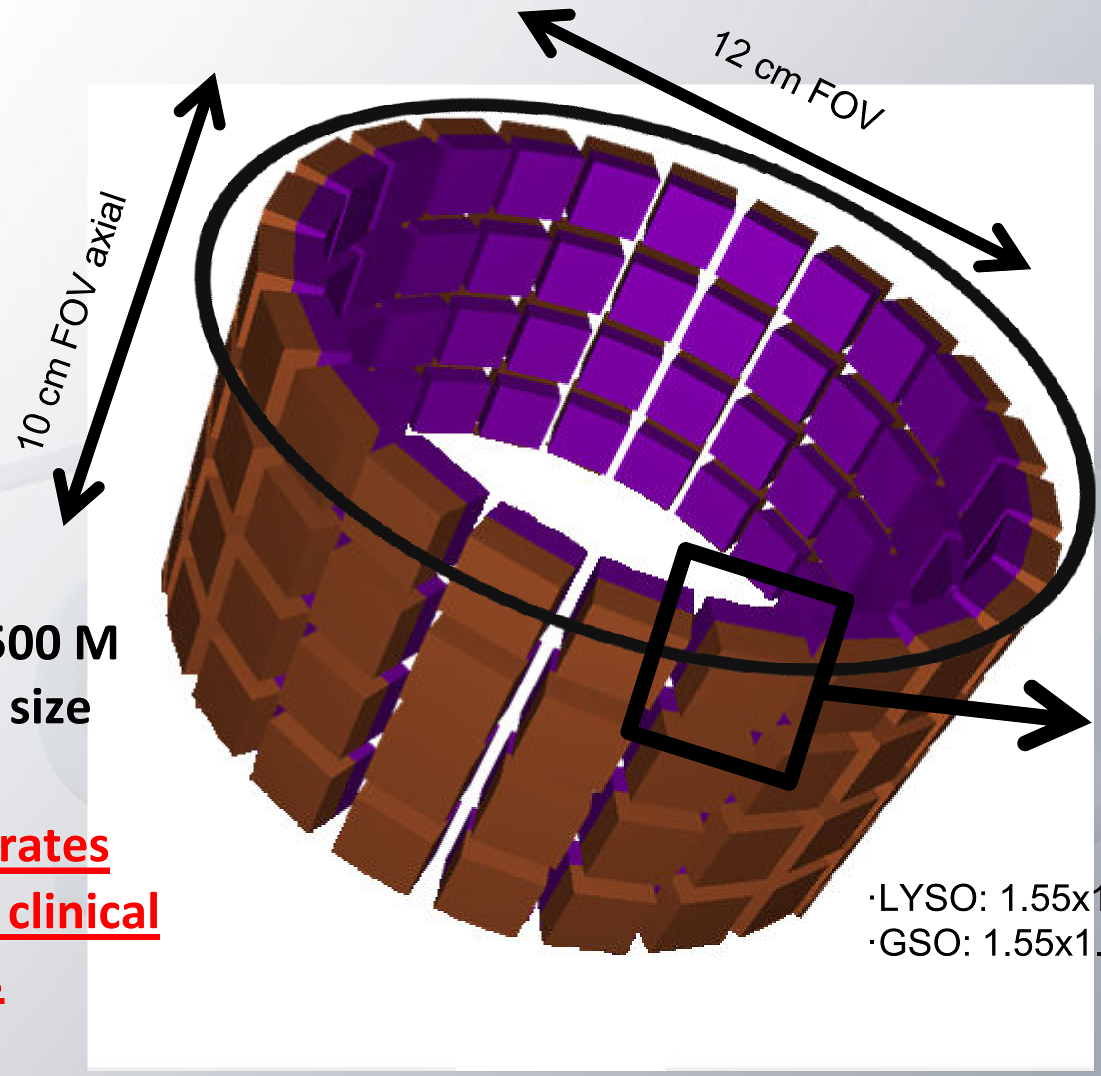
IPARCOS

campus
MONCLOA

SEDECAL

The SuperArgus PET/CT (4R, 6R)

<1 mm spatial resolution!!!



24 LYSO-GSO detector blocks per ring (24x4)

13x13 (x2 layers) crystals per detector block

·LYSO: 1.55x1.55x0.7 mm^3
·GSO: 1.55x1.55x0.8 mm^3

>42000 crystals, >500 M LORs, 17 cm bore size
Size apart, complexity and rates similar to total body clinical PET scanners.

Time resolution typically 1.5 ns, coincidence windows of <5 ns. Events can be gated and time stamped from external trigger inputs with 20 ns accuracy

Validation of physics Models in different MC also requires many hours of simulations