GATE simulations for the J-PET scanner

GATE Workshop @ IEEE NSS/MIC 2019

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On behalf of the J-PET collaboration

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PRESENTATION PLAN

1. J-PET technology

2. Physics studies and diagnostic applications
   - Physics studies (positronium imaging, quantum entanglement, discrete symmetries studies)
   - Global actor concept
   - Scanner performance studies according to NEMA norms

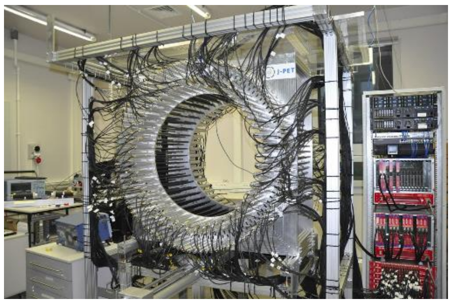
3. Proton therapy application
   - Proton beam range monitoring
   - Treatment plan verification

J-PET TECHNOLOGY

- **Cost-effective, plastic based technology**
- **Towards total-body PET imaging**

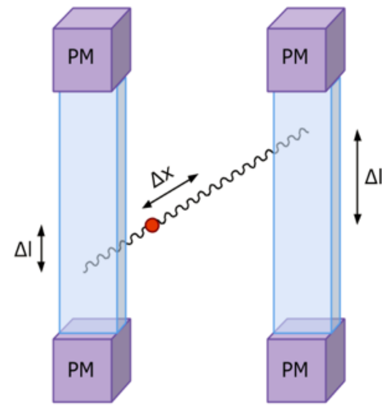
Photos by courtesy of Sz. Niedźwiecki and J-PET team

J-PET tomograph prototype (2016)



3-layer scanner consists of 192 EJ-230 plastic scintillators (7x19x500mm^3)

J-PET tomograph principle

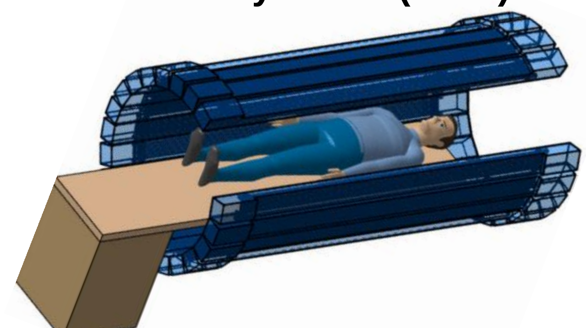


- **Compton scattering instead of fotoelectric absorbtion**
- **Two TOFs: in plastic and at the LOR level**
- **CRT = 400 ps**

Modular J-PET (2019)

2nd generation, light, portable and easy reconfigurable JPET tomograph consists of 24 modules (13 single 5x24x500mm^3 plastic strips in each module).

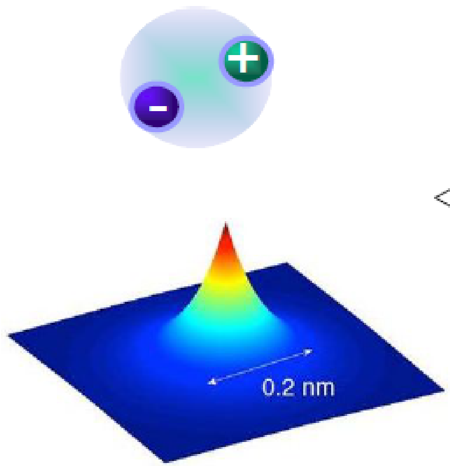
Total-body J-PET (202X)



2-layer total-body scanner with WLS and 2 m long axial FOV

PHYSICS STUDIES

Courtesy of W. Krzemień



Para-positronium:
- **lifetime ~125 ps**
- **two-photon decay**

Ortho-positronium:
- **lifetime ~142 ns**
- **three-photon decay**

Positronium tomography

Fundamental physics studies (symmetries)

Quantum entanglement tomography

1) P. Moskal et al., Phys. Med. Biol. 64 (2019) 055017
2) P. Moskal et al. Eur. Phys. J. C 78 (2018) 970
3) D. Kaminska et al., Eur. Phys. J. C (2016) 76:445

PHYSICS STUDIES

Nature Reviews Physics **vol 1**, 527–529 (2019)

Courtesy of W. Krzemień

COMMENT

Positronium in medicine and biology

Paweł Moskal[1], Bożena Jasińska[2]*, Ewa Ł. Stępień[1]* and Steven D. Bass[1,3]**

In positron emission tomography, as much as 40% of positron annihilation occurs through the production of positronium atoms inside the patient's body. The decay of these positronium atoms is sensitive to metabolism and could provide information about disease progression. New researcl is needed to take full advantage of what positronium decays reveal.

Positronium Physics

Positronium atoms are bound states of an electron and its antiparticle, the positron. Positronium has two ground states, which are distinguished by their decay processes and their lifetimes, which differ by a factor of more than 1,000. Spin-zero para-positronium is even under charge conjugation symmetry — that is, exchanging all particles with their anti-particles results in the same atom — and in vacuum has a lifetime of 125 ps, decaying to two photons. Spin-one ortho-positronium is odd under charge conjugation and in vacuum has a lifetime of 142 ns, decaying to three photons. More details of the fundamental physics of positronium are given in BOX 1.

typically of similar strength, with the details dependen on the size of intermolecular voids and the concentratio of bio-active molecules. Key observables are the positro nium lifetime in the medium, the ratio of two-photo to three-photon decay rates and the probability o positronium production in the biomaterial.

Measuring positronium lifetimes

The fate of the positronium atom is investigated by posi tron annihilation lifetime spectroscopy (PALS). Th advantage of using PALS to investigate the structura transformations and micro-environmental changes o a biological sample is that PALS is nondestructive an

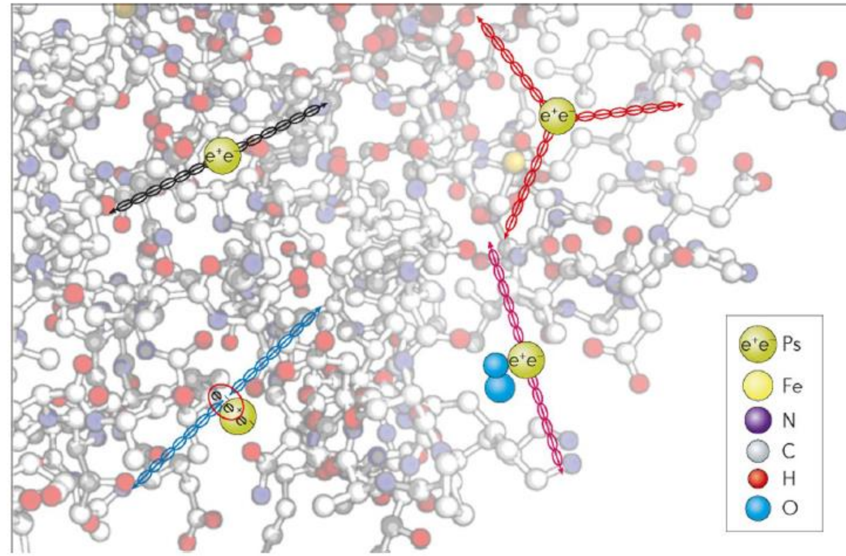
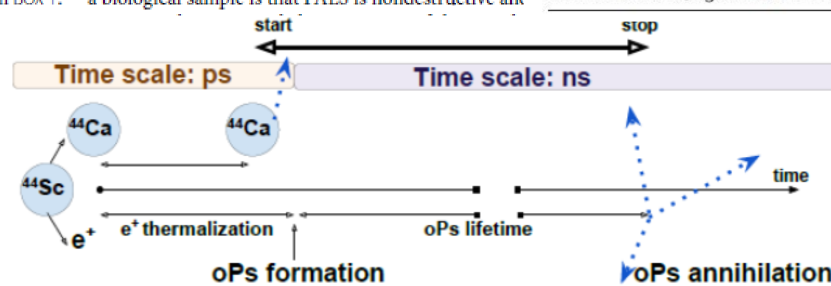


Fig. 1 | **Possible decays of positronium atoms trapped in the intramolecular voids in haemoglobin.** In the free space between atoms, para-positronium decays to two photons (black arrows) and ortho-positronium decays to three photons (red arrows). Positronium (Ps) can annihilate through the interaction with an electron from the surrounding molecule (blue arrows indicate the resulting photons). Ortho-positronium can interact with an oxygen molecule and convert into para-positronium, which subsequently decays into two photons (magenta arrows). Image courtesy of A. Kamińska and E. Kubicz, Jagiellonian University, Poland.

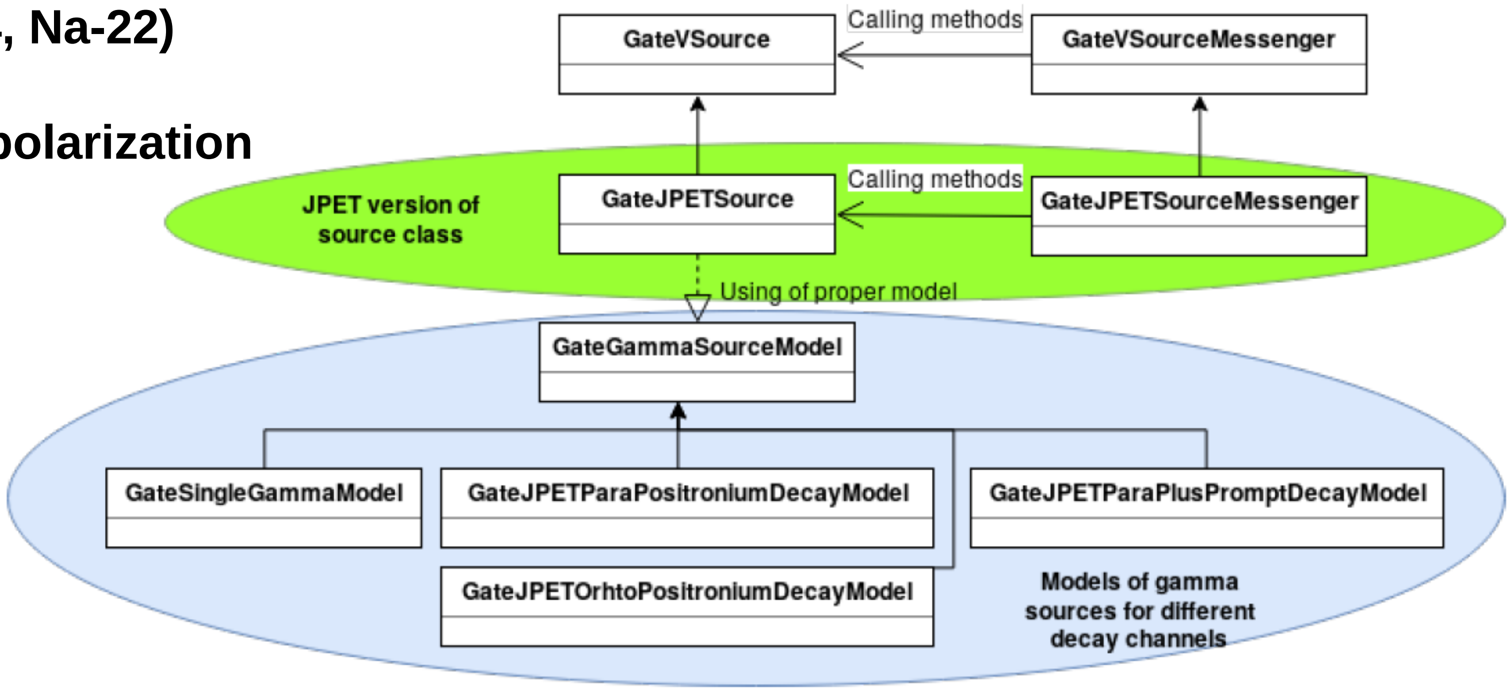


Ortho-positronium decay scheme. (Courtesy of W. Krzemień)

PHYSICS STUDIES

Courtesy of W. Krzemień and M. Bała

- **Ortho-positronium**
- **Para-positronium**
- **Non-pure positronium emitters (i.e. Sc-44, Na-22)**
- **Photons polarization**



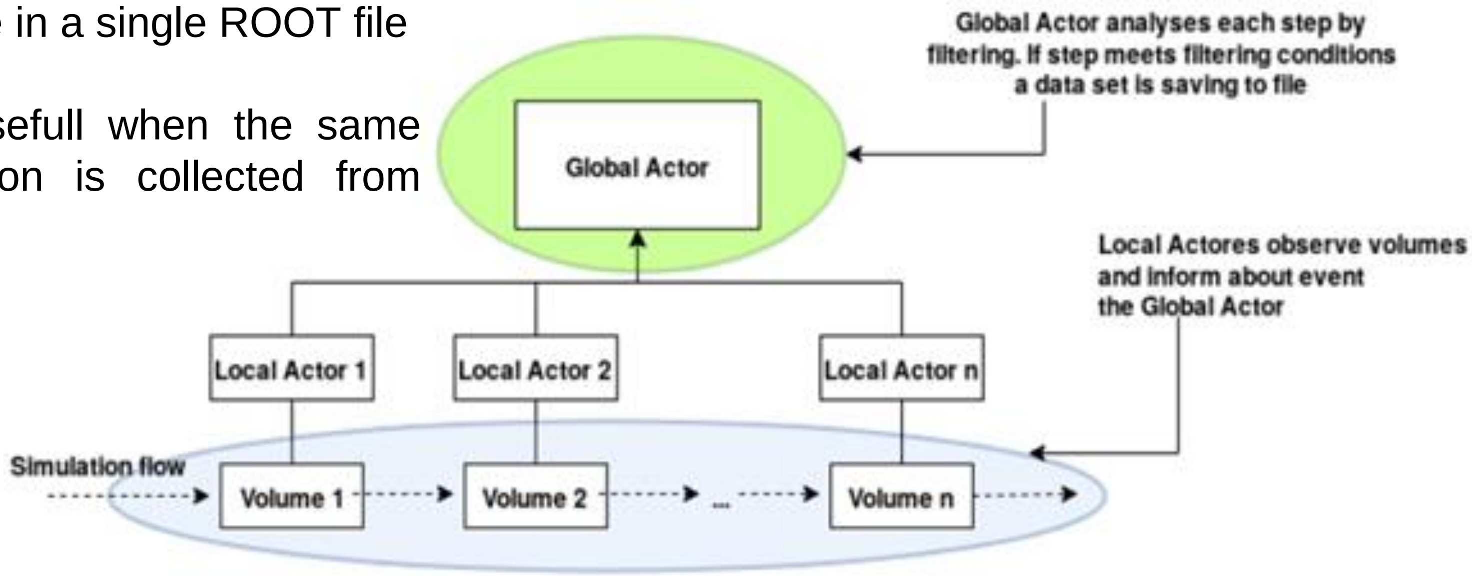
Schematic view of the libraries used to model different positronium decays. PR for the official GATE release is currently under the preparation. (Courtesy of W. Krzemień and M. Bała)

GLOBAL ACTOR CONCEPT

Courtesy of W. Krzemień and M. Bała

- **Local Actor (LA)** – standard actor attached to a volume
- **Global Actor (GA)** – feasible to collect data from multiple volumes
- GA with LA attached could collect chronologically data from any number of volumes and store in a single ROOT file
- GA and LA is usefull when the same type of information is collected from different volumes

Two types of output are possible:
- **Standard ROOT Ttree**
- **Data grouped in events**



Schematic view of the global actor concept. PR for official GATE release is currently under the preparation.

DIAGNOSTIC SCANNER PERFORMANCE

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

OPEN ACCESS

CrossMark

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PAPER

Estimating the NEMA characteristics of the J-PET tomograph using the GATE package

P Kowalski[1], W Wiślicki[1], R Y Shopa[1], L Raczyński[1], K Klimaszewski[1], C Curcenau[3], E Czerwiński[2], K Dulski[2], A Gajos[2], M Gorgol[4], N Gupta-Sharma[2], B Hiesmayr[5], B Jasińska[4], Ł Kapłon[2], D Kisielewska-Kamińska[2], G Korcyl[2], T Kozik[2], W Krzemień[6], E Kubicz[2], M Mohammed[2,7], S Niedźwiecki[2], M Pałka[2], M Pawlik-Niedźwiecka[2], J Raj[2], K Rakoczy[2], Z Rudy[2], S Sharma[2], S Shivani[2], M Silarski[2], M Skurzok[2], B Zgardzińska[4], M Zieliński[2] and P Moskal[2]

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Keywords: NEMA norms, J-PET, positron emission tomography, plastic scintillators

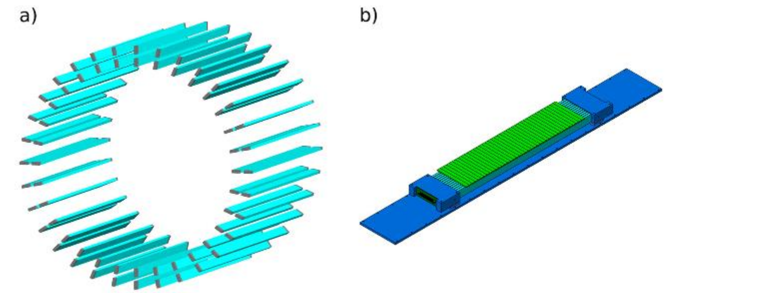


Figure 2. (a) The exemplary geometry of the two-layer J-PET scanner. For better visualization, only 32 strips in each layer are shown. Simulations of the completely filled cylinder were performed. (b) The geometry of the prototype module for the scanner based on both SiPM photomultipliers and WLS strips. Scintillator strips (light blue) in the prototype module are arranged into clusters consisting of over a dozen of strips. The WLS strips (green) are arranged perpendicularly to the scintillator strips. The results of the first experimental tests performed for the single plastic strip with an array of WLS strips are reported in Smyrski *et al* (2017).

Table 2. Configurations of simulated detecting systems which may differ with number of layers of the detector and their diameters, thickness, length of the scintillator strip and type of readout.

Layers		Thickness		L (cm)		D (cm)		Readout
1		4 mm		20		75		PMT
2	×	7 mm	×	50	×	85	×	SiPM
				100		95		SiPM + WLS

DIAGNOSTIC SCANNER PERFORMANCE

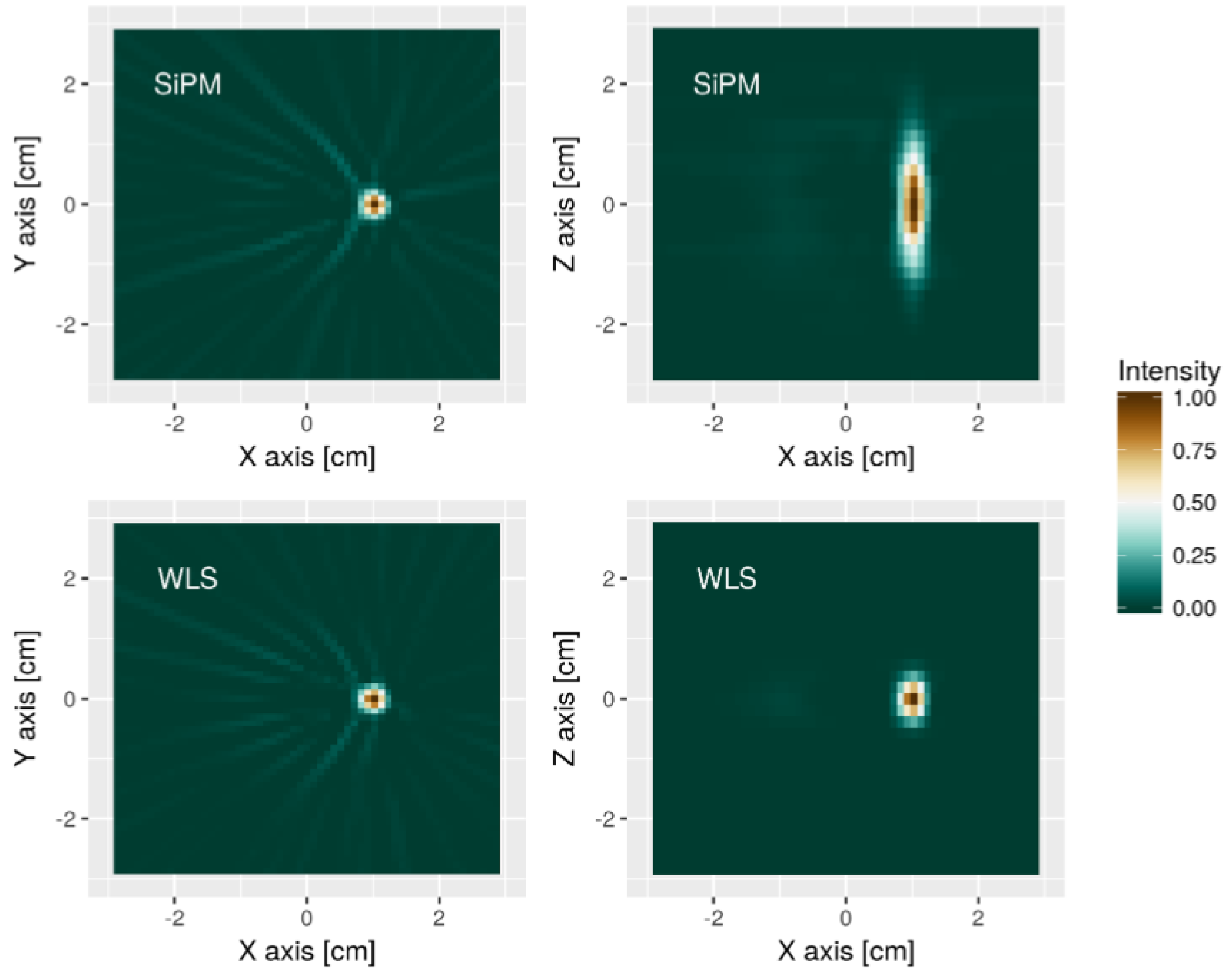
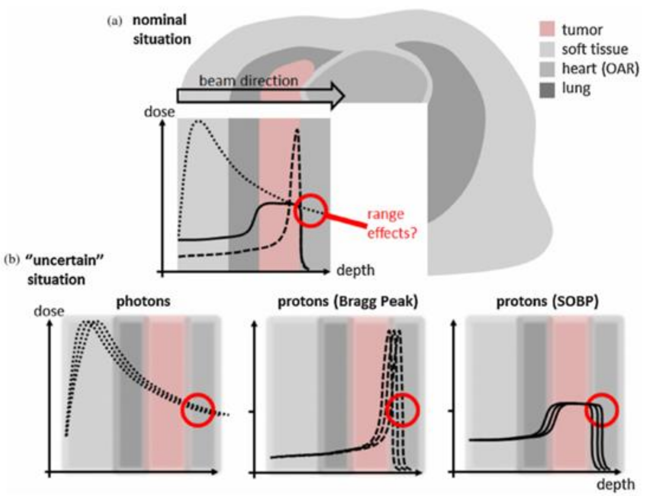
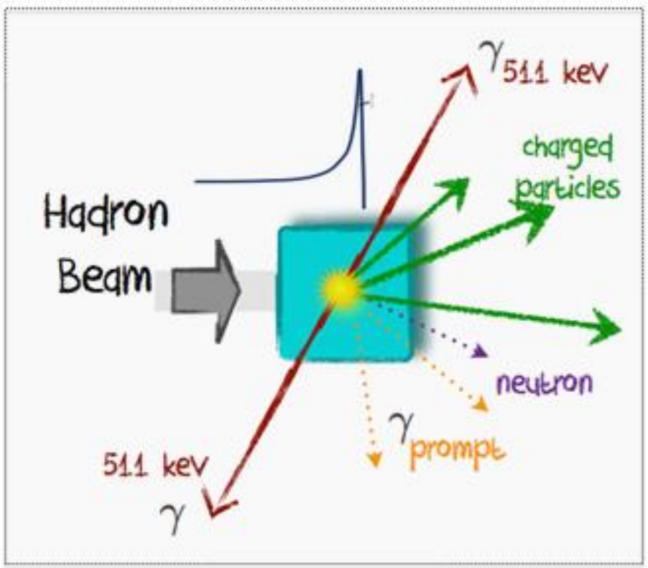


Figure 15. Example reconstruction of the source placed in the central position [(1,0,0) cm] of the detecting chamber. The geometry consisted of the single layer chamber of diameter 85 cm and strips of length 50 cm and thickness 4 mm. Silicon photomultipliers (SiPM) were used as photodetectors in the upper images, WLS strips were used in the bottom images. The left column corresponds to the cross-section perpendicular to the axis, the right column to the cross-section along the axis of the scanner.

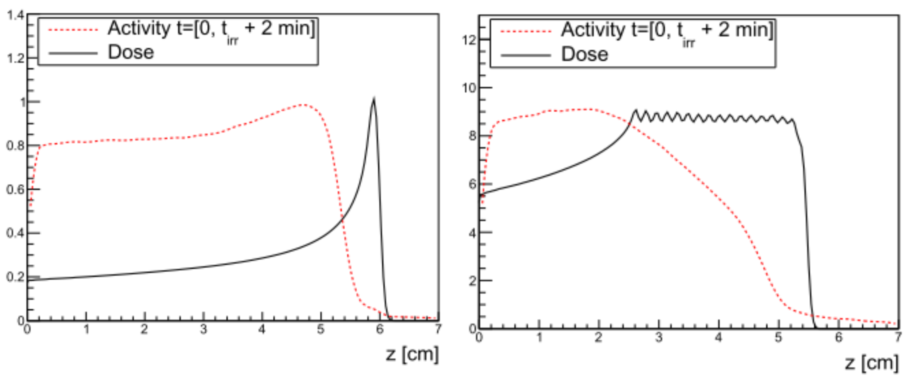
PROTON RANGE MONITORING



Dose distribution profiles for conventional photon radiotherapy vs proton radiotherapy (Knopf and Lomax, PMB 2013)



Secondary radiation produced during the protons interactions with matter (courtesy of Antoni Ruciński)



Dose and β^+ profiles from Monte Carlo simulations for 95 MeV protons (left) and 2Gy irradiation plan (Krann AC. et al. JINST 2010)

PROTON RANGE MONITORING

Simulated setups are as follows:

A. **single layer barrel – 24 modules**

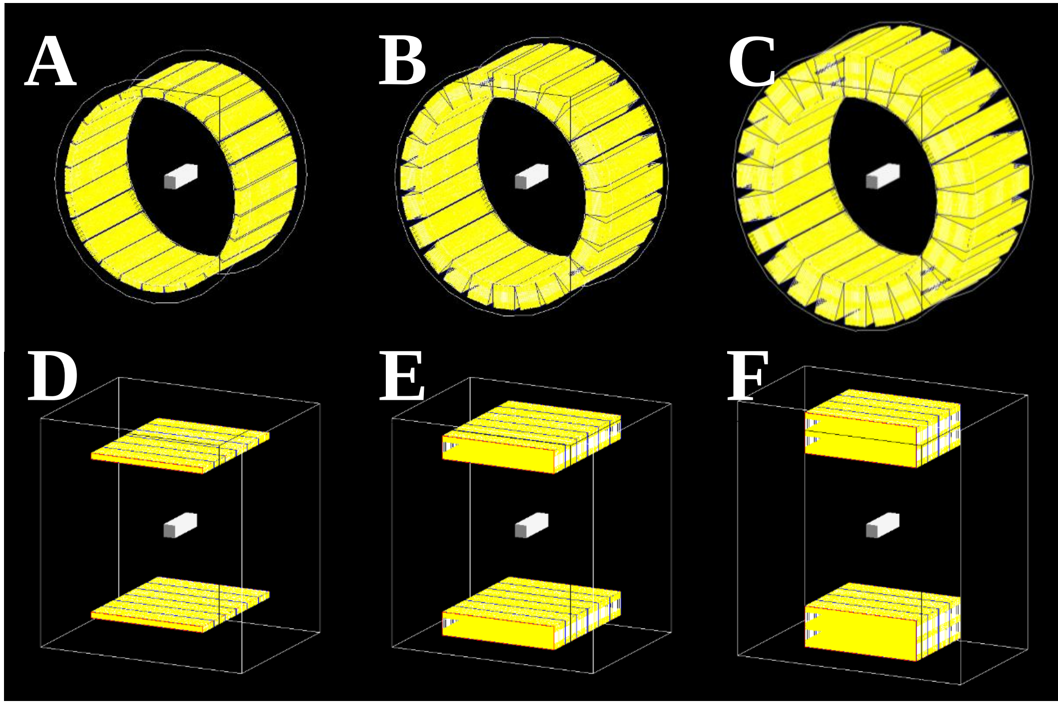
B. **double layer barrel – 48 modules**

C. **triple layer barrel – 72 modules**

D. **single layer dual-head – 12 modules**

E. **double layer dual-head – 24 modules**

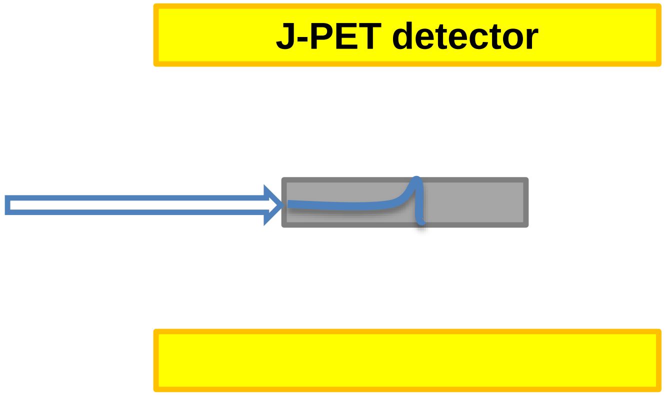
F. **triple layer dual-head – 24 modules**



Simulated J-PET configurations: single layer barrel (A), double layer barrel (B), triple layer barrel (C), single layer dual-head (D), double layer dual-head (E), triple layer dual-head (F)

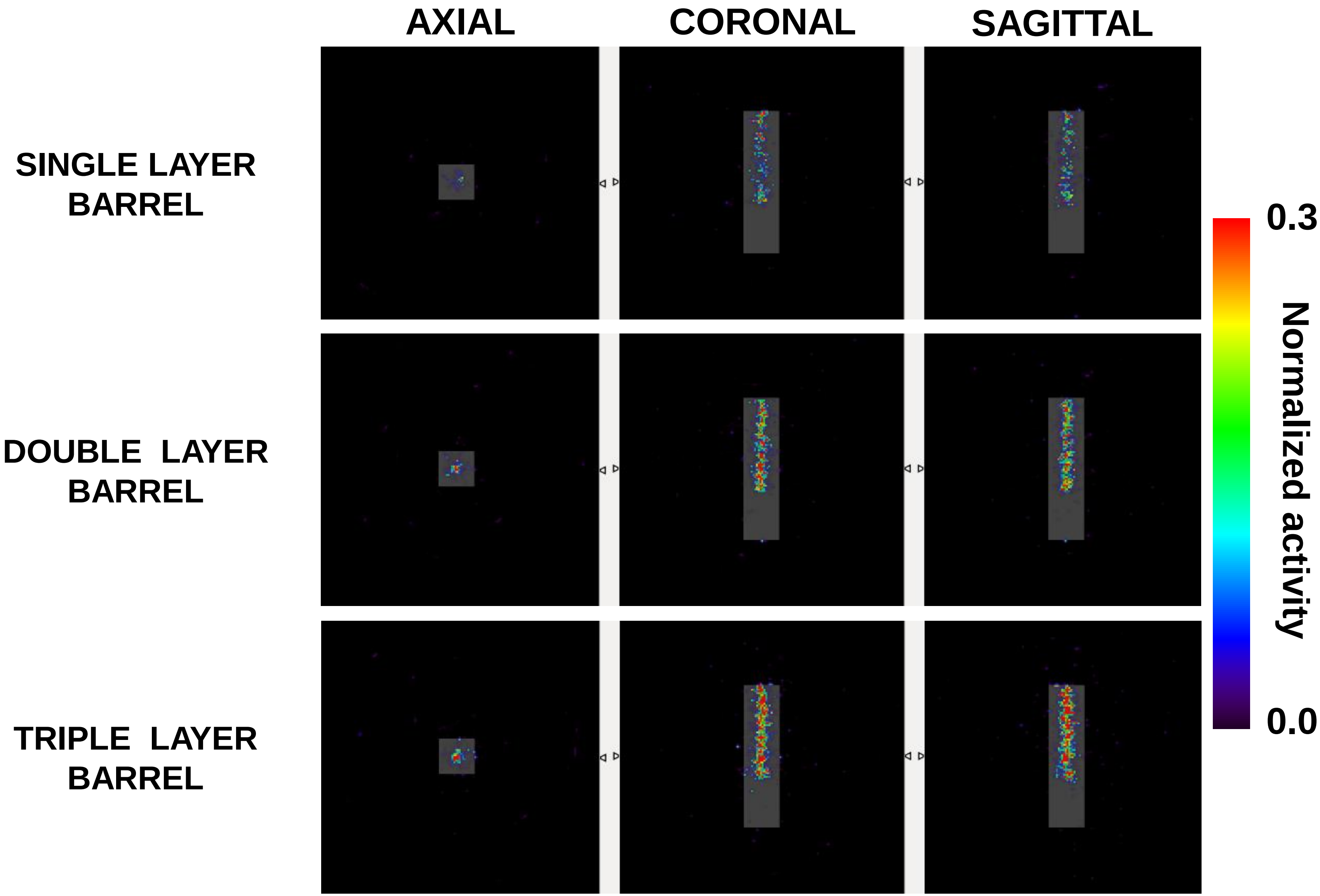
PROTON RANGE MONITORING

- 10^8 primary protons with the therapeutic beam model of the CCB (150 MeV)
- PMMA phantom 5x5x20 cm3
- QGSP_BIC_HP_EMY physics list
- CASToR software for the reconstruction
- TOF resolution: 500 ps
- Time window: 3 ns, energy window: 200 keV
- Applied corrections: sensitivity, attenuation, post-smoothing



Schematic view on the simulation setup cross section.

PROTON BEAM RANGE MONITORING



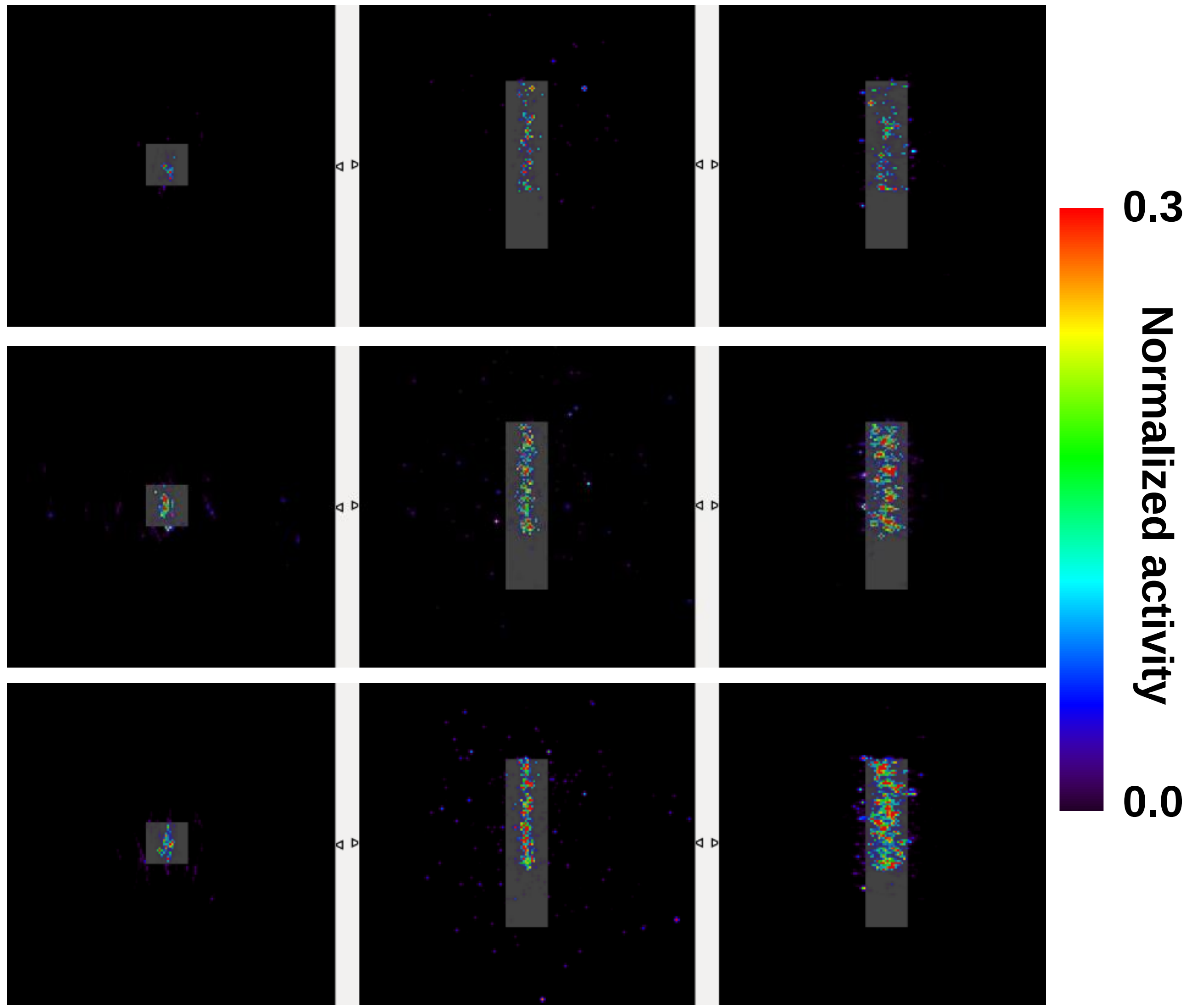
PROTON BEAM RANGE MONITORING

AXIAL | CORONAL | SAGITTAL

SINGLE LAYER DUAL-HEAD

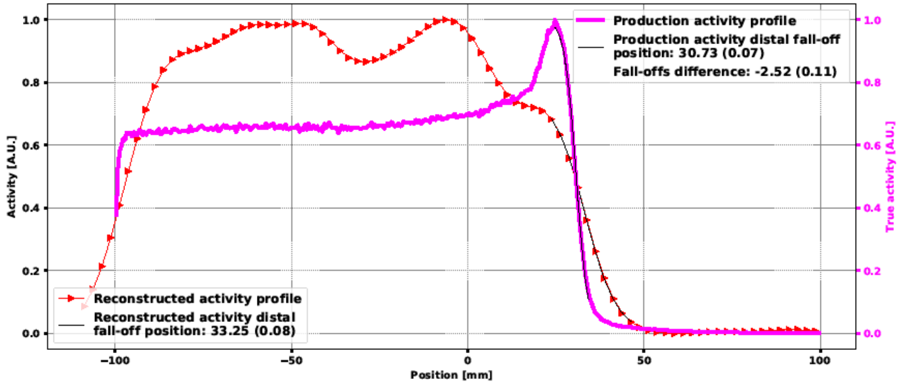
DOUBLE LAYER DUAL-HEAD

TRIPLE LAYER DUAL-HEAD

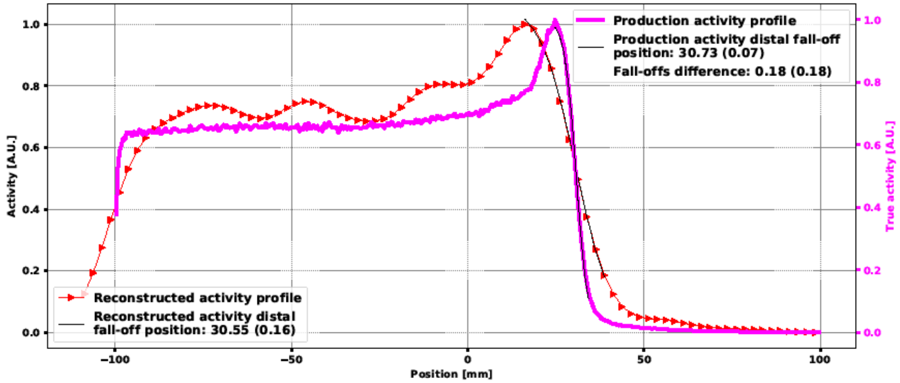


PROTON BEAM RANGE MONITORING

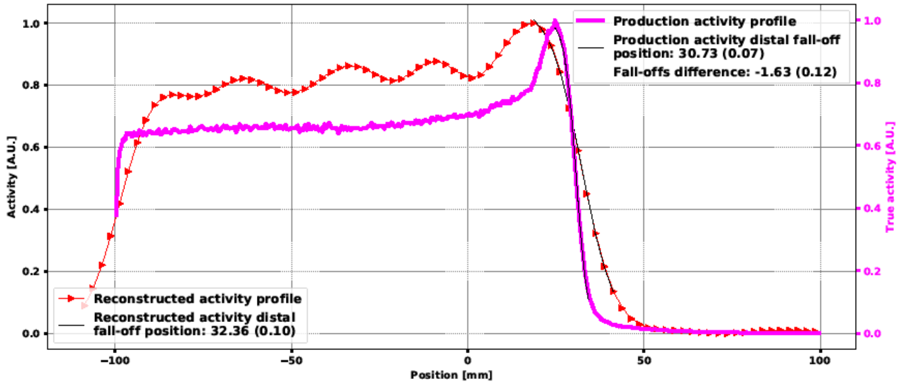
SINGLE LAYER BARREL



DOUBLE LAYER BARREL

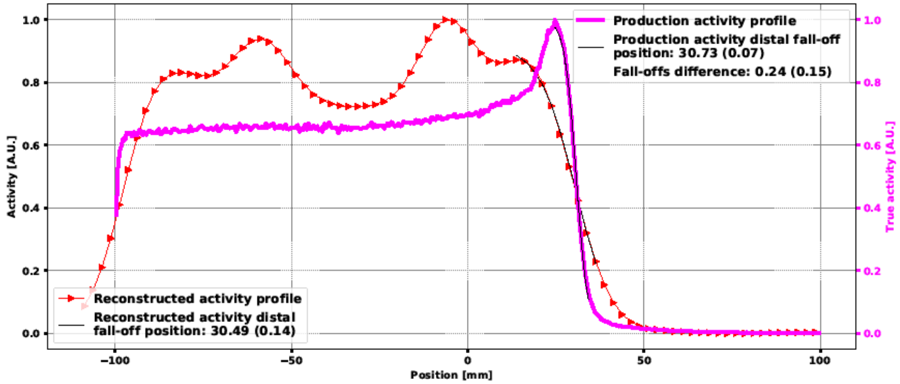


TRIPLE LAYER BARREL

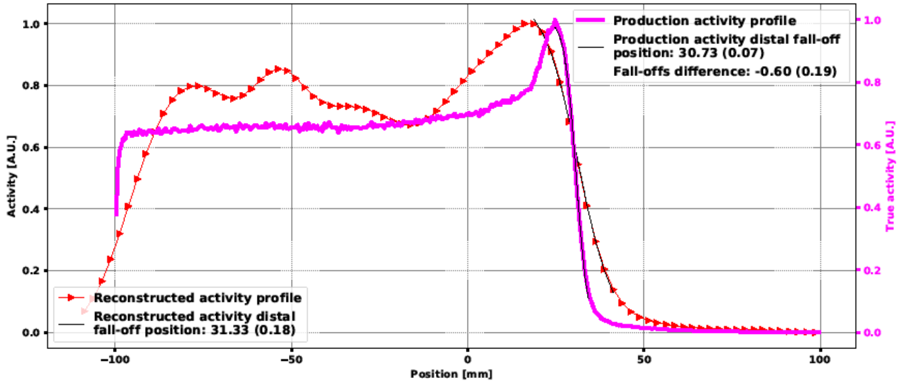


PROTON BEAM RANGE MONITORING

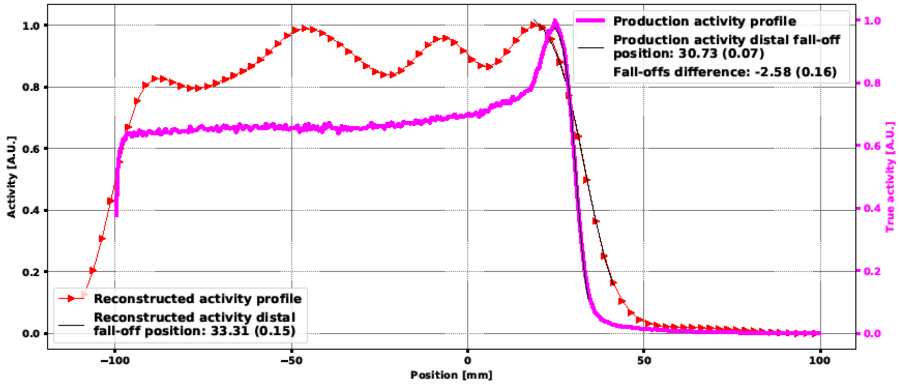
SINGLE LAYER DUAL-HEAD



DOUBLE LAYER DUAL-HEAD

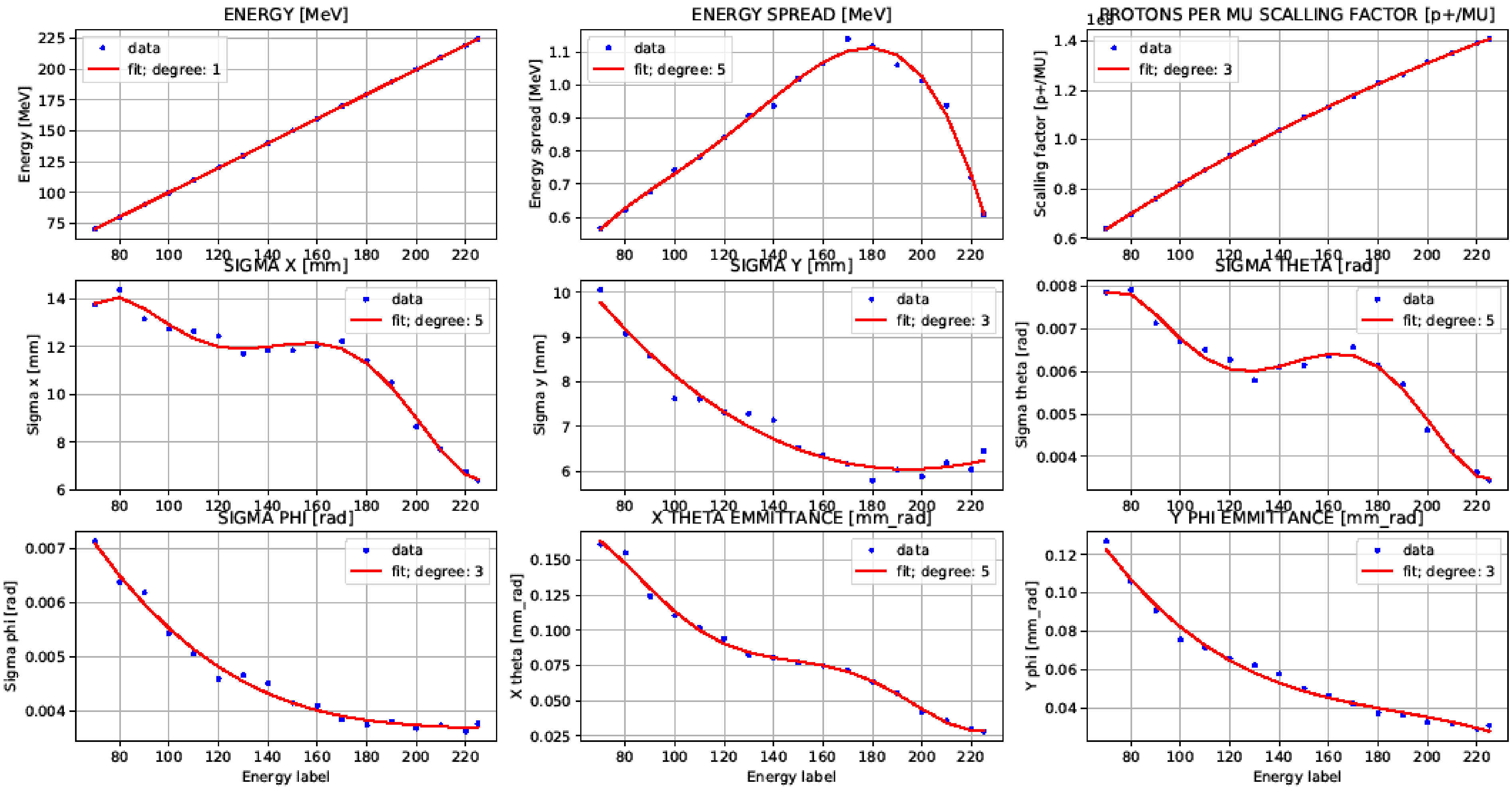


TRIPLE LAYER DUAL-HEAD



TREATMENT PLAN VERIFICATION

BEAM MODEL OF A GANTRY AT CYCLOTRON CENTRE BRONOWICE (CCB) IN CRACOW

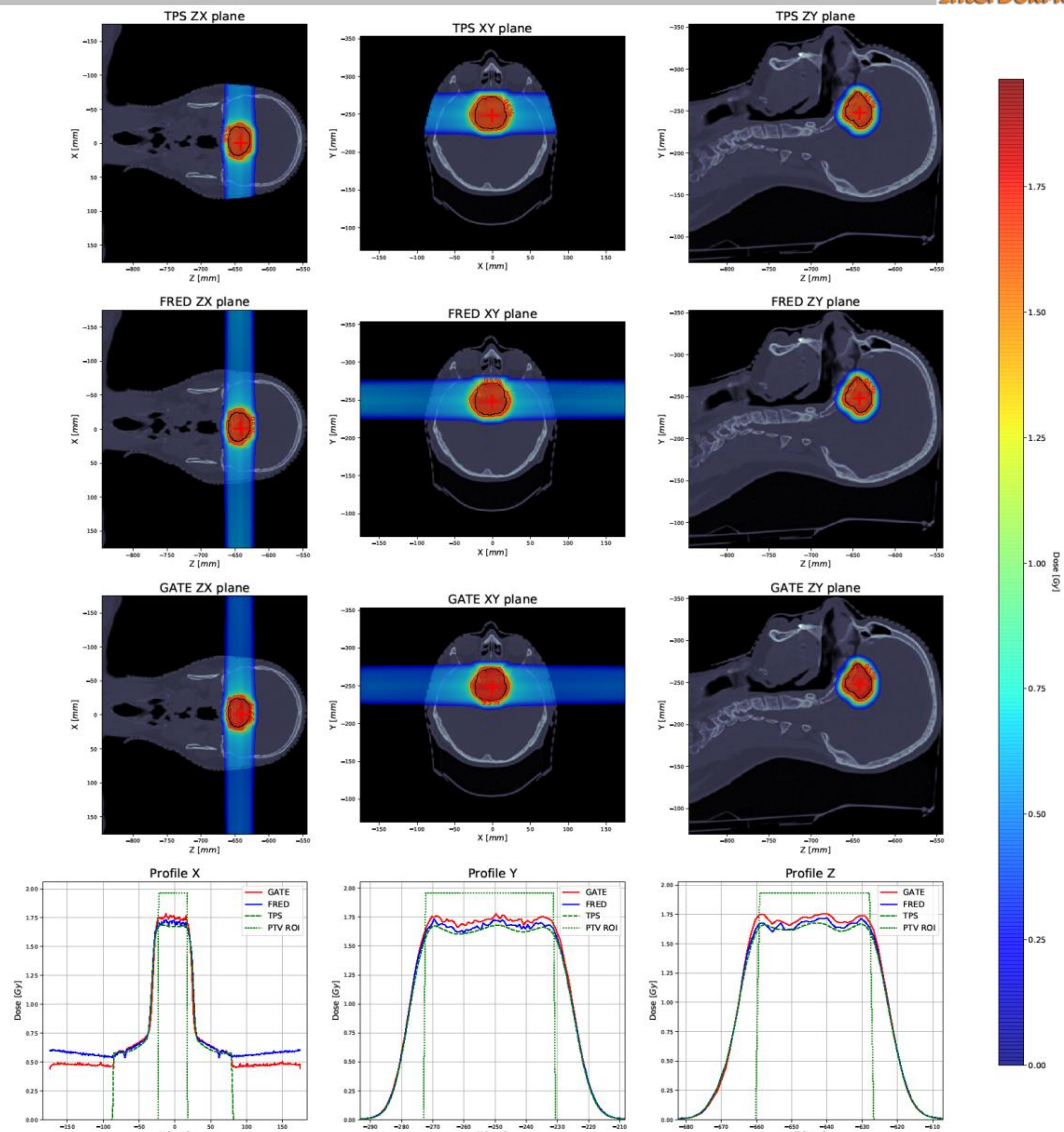


TREATMENT PLAN VERIFICATION

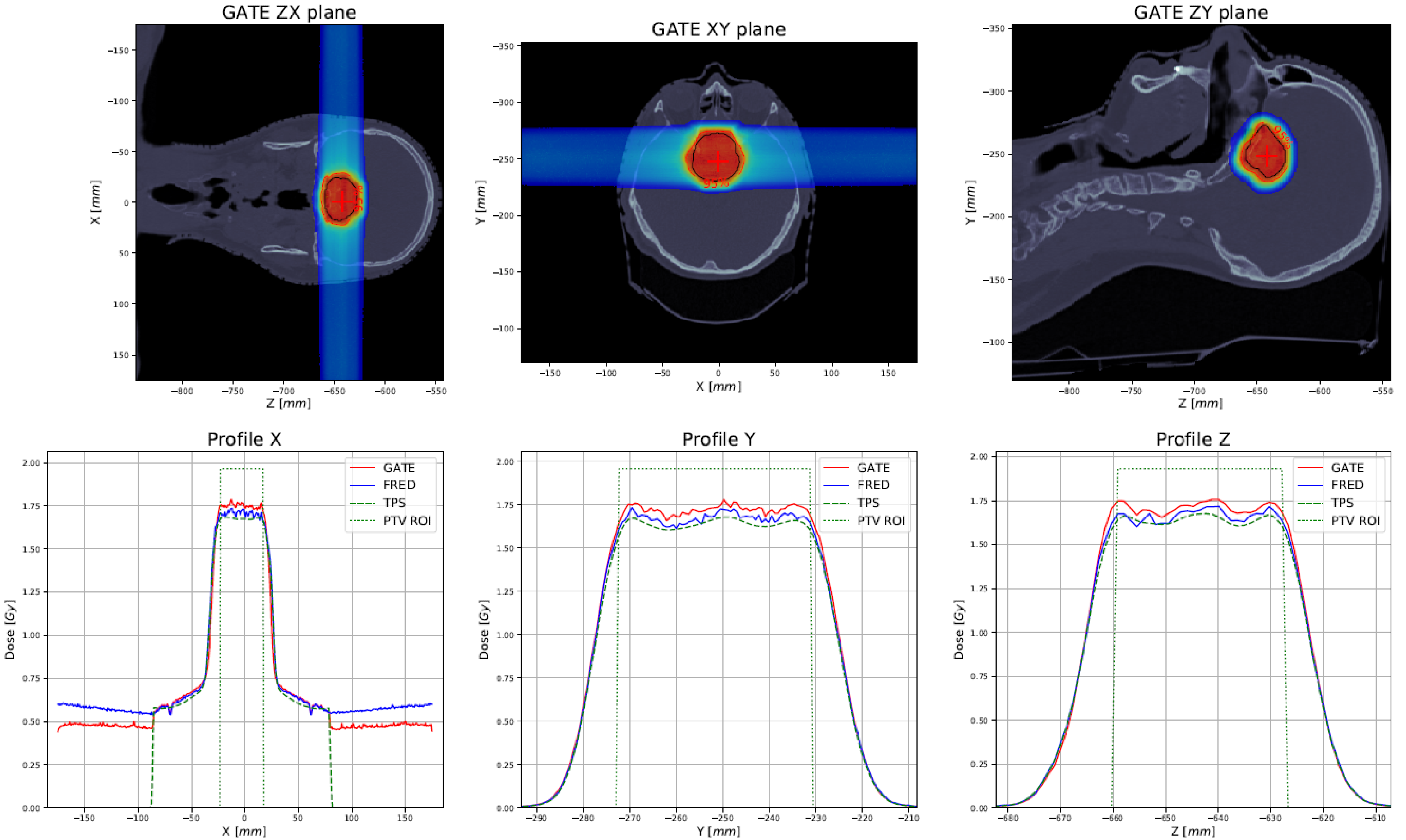
TREATMENT PLAN VERIFICATION:

- **Beam model**
- **CT calibration**
- **~10^5 primary protons/spot simulated**
- **Dose comparison between GATE, TPS and FRED GPU Monte Carlo software**

RANGE MONITORING WITH J-PET



TREATMENT PLAN VERIFICATION



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