THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

InterDokMed

An update on J-PET for the beam range monitoring in proton radiotherapy

Jakub Baran

PhD student
Institute of Nuclear Physics PAN

The 6th Annual Loma Linda workshop 2020 on Particle Imaging and Radiation Treatment Planning

Presentation overview

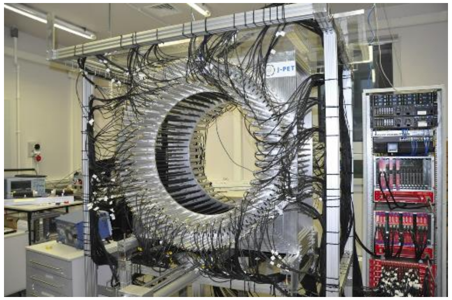
1. J-PET technology
2. Proton beam range monitoring
3. Project aim
4. PMMA phantom studies
5. Patient studies

J-PET technology

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

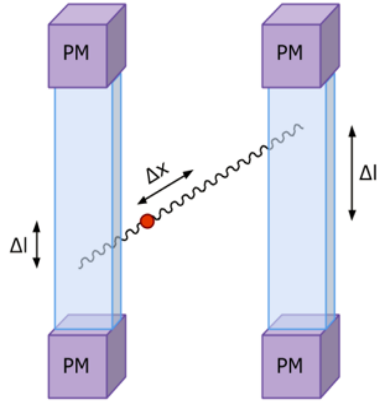
Photos by courtesy of J-PET team

J-PET tomograph prototype (2016)



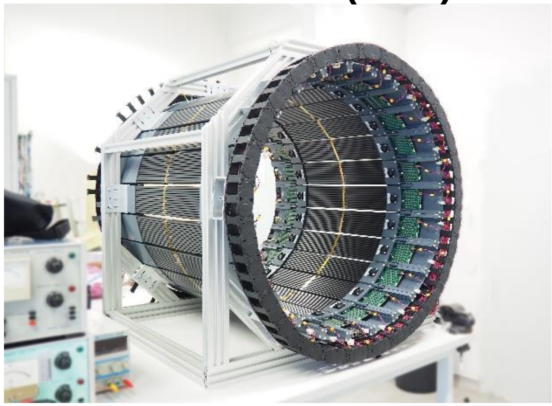
3-layer scanner consists of 192 EJ-230 plastic scintillators (7x19x500mm^3)

J-PET tomograph principle



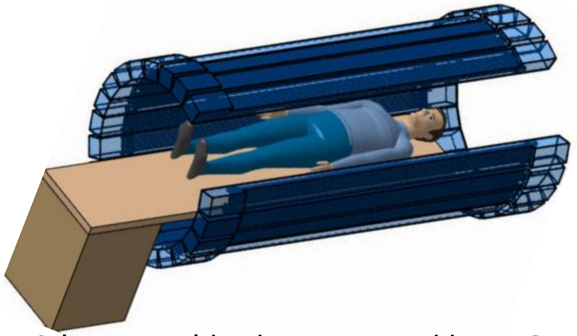
- **Compton scattering instead of photoelectric absorbtion**
- **Two TOFs: in plastic and at the LOR level**
- **TOF resolution = 500 ps**

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).

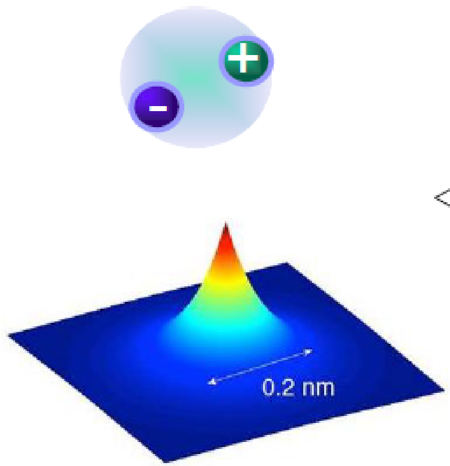
Total-body J-PET (202X)



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**

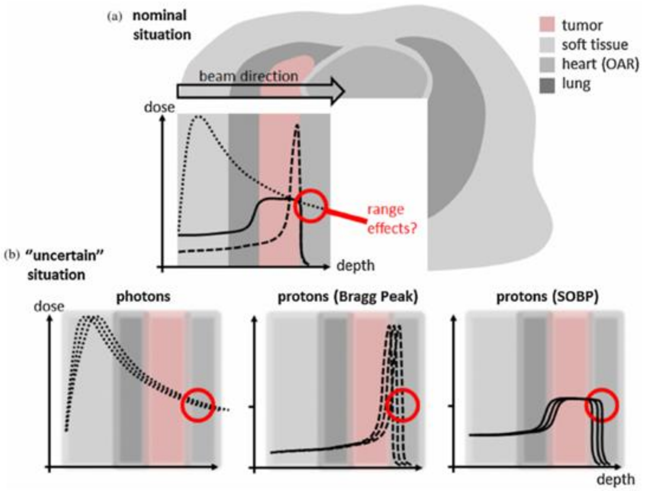
Positronium tomography

Fundamental physics studies (symmetries)

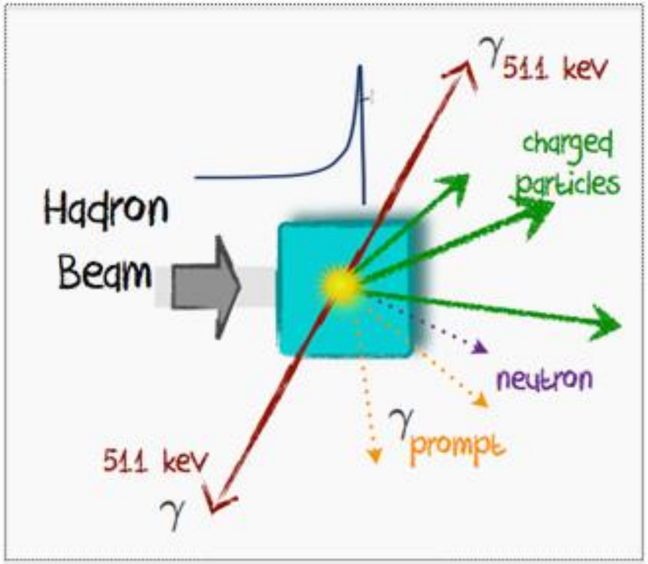
Quantum entanglement tomography

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

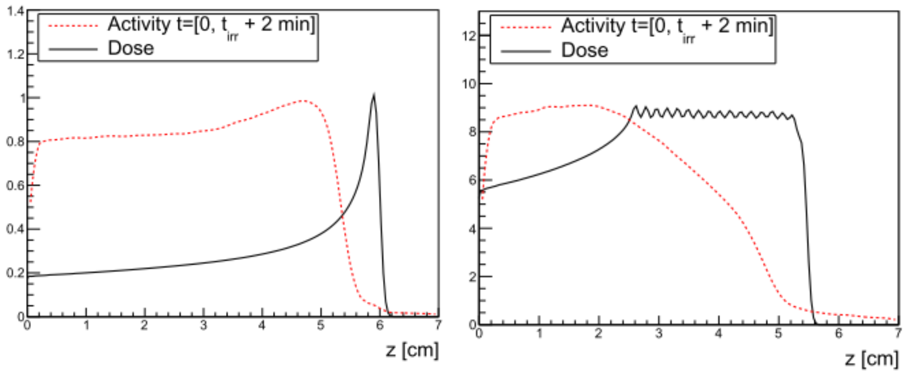
Proton range monitoring



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)

Project aim

Establish and test a methodology for application of set of J-PET detectors for proton beam range verification using Monte Carlo simulations

<u>Main tasks:</u>

1. Development of the dedicated Monte Carlo simulations for J-PET detector characterization using GATE and PET data reconstruction framework validation with CASToR.

2. Monte Carlo based study of the response to proton beam induced annihilation gammas of various J-PET systems in a PMMA phantom.

3. Preparation of the Monte Carlo based simulations methodology of the patient treatment at CCB (Krakow proton therapy facility) and investigation of the various J-PET detectors response on annihilation gammas produced in patient body during the after-treatment (in-room) phase.

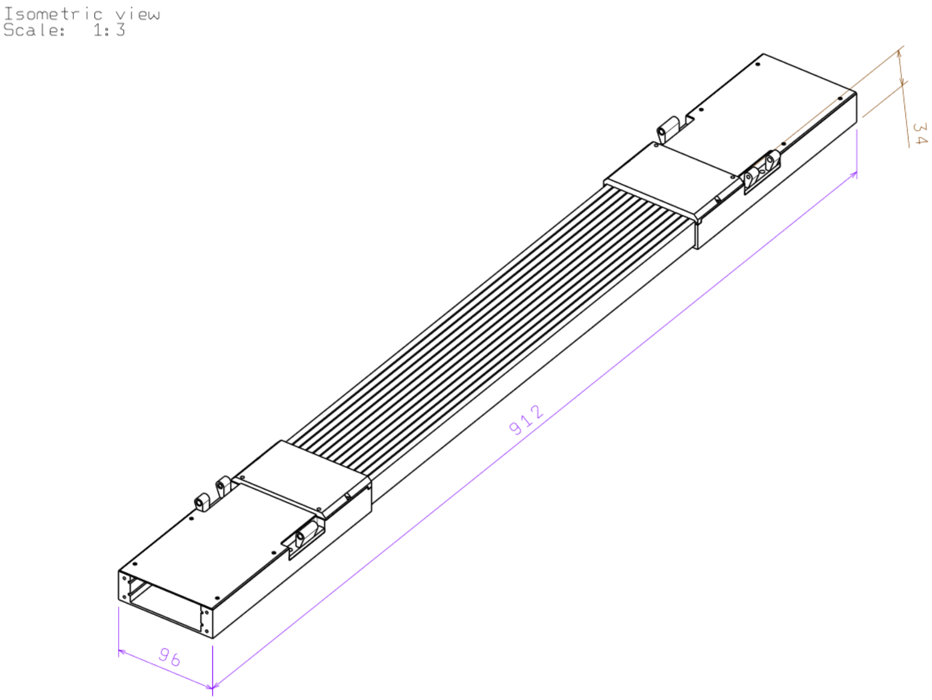
J-PET module

- Digital J-PET modules based configurations are considered

- Each module consists out of thirteen 50-cm long plastic scintilators (cross section: 6x24 mm^2)

- In simulations only scintilators were considered, covers were not implemented

- All setups are constructed out of modules

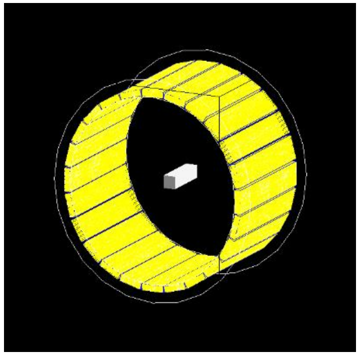


Digital PET – single module

J-PET based setups

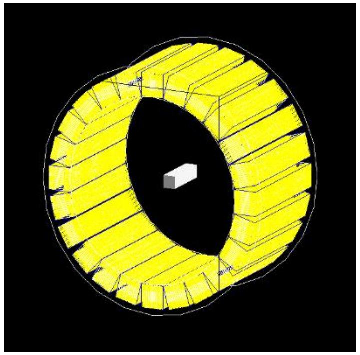
6 diffferent setups are considered for in-room/off-beam proton beam range monitoring

SINGLE LAYER BARREL



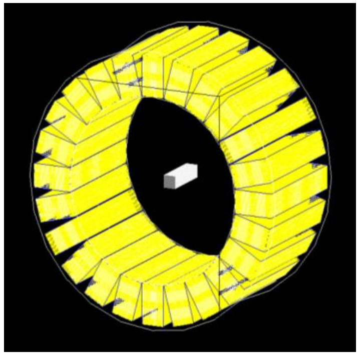
24 modules

DOUBLE LAYER BARREL



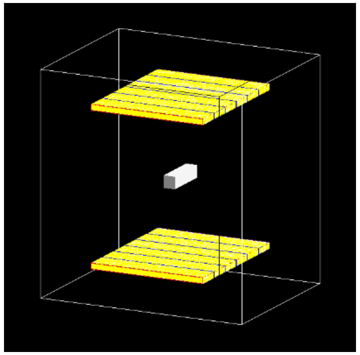
48 modules

TRIPLE LAYER BARREL



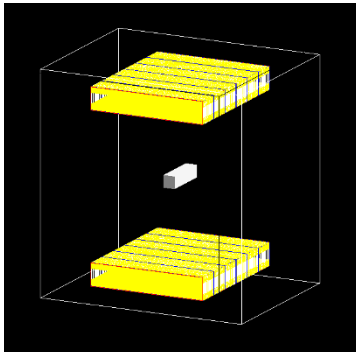
72 modules

SINGLE LAYER DUAL-HEAD



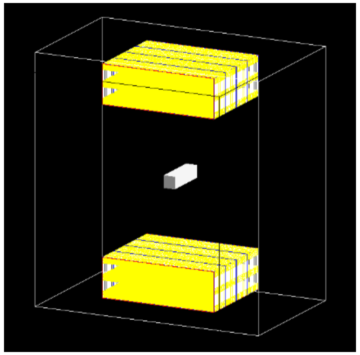
12 modules

SINGLE LAYER DUAL-HEAD



24 modules

TRIPLE LAYER DUAL-HEAD

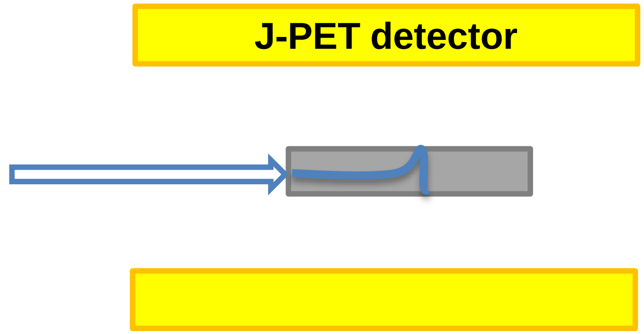


24 modules

Dual-head setups could be potentially considered for in-beam proton range monitoring

Simulation setup - phantom

Krakow proton therapy facility beam model implemented by Jan Gajewski (Wednesday morning session talk)

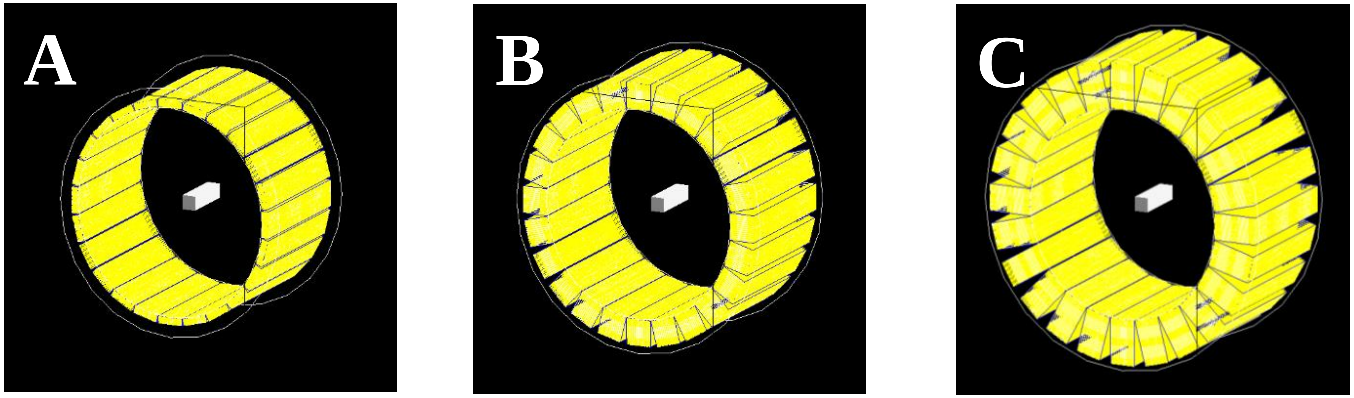


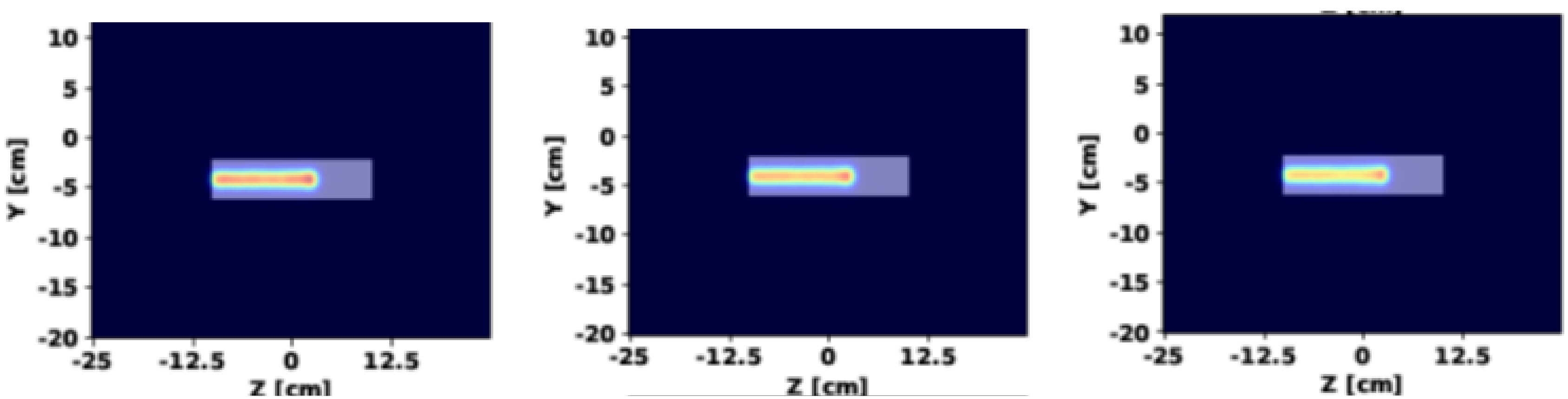
- $5 \cdot 10^9$ primary protons (150 MeV) irradiated PMMA phantom
- Efficiency factor (EF) defined as a number of registered coincidences per primary proton
- PMMA phantom: 5x5x20 cm^3
- Time structure of the beam was considered
- QGSP_BIC_HP_EMY physics list + Radioactive Decay physics
- Coincidences were integrated over time

PET data reconstruction

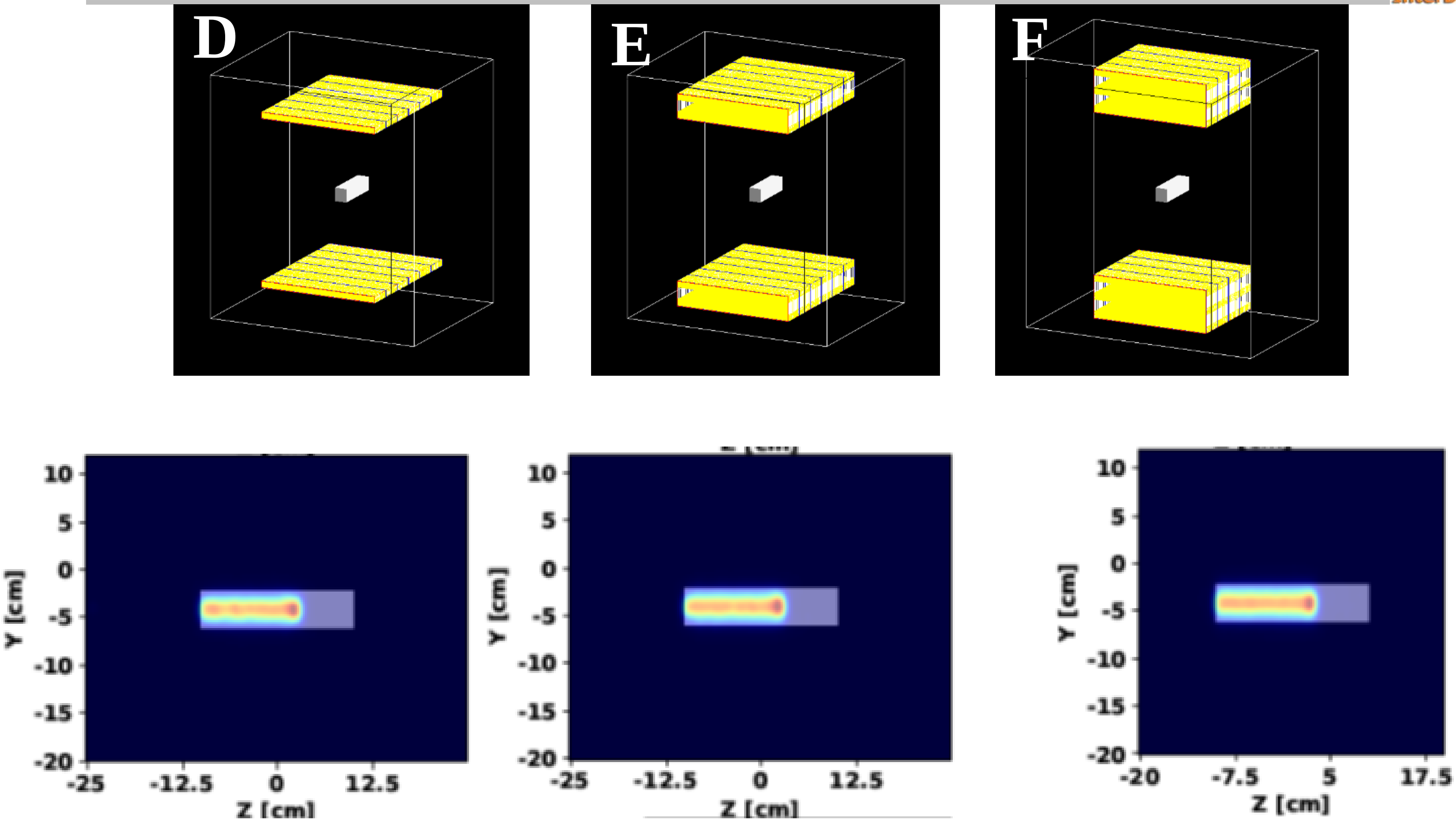
- **PET reconstruction grid: 2.5 mm^3 isotropic**
- **TOF List Mode MLEM algorithm was used**
- **TOF resolution: 500 ps**
- **Coincidence time window: 3 ns; energy window: 200 keV**
- **Applied corrections: sensitivity, attenuation, post-smoothing (3D Gaussian σ = 2voxels)**

Patient setup – reconstructed images

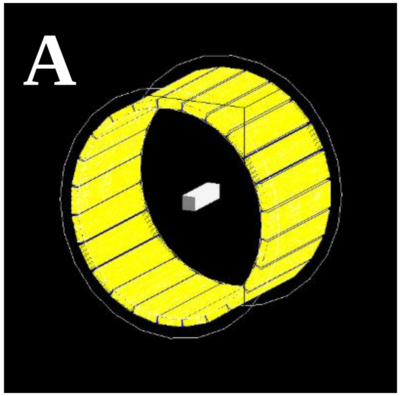


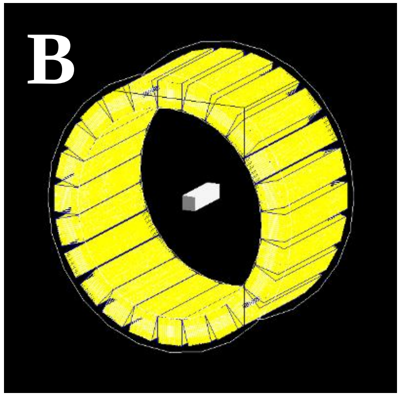


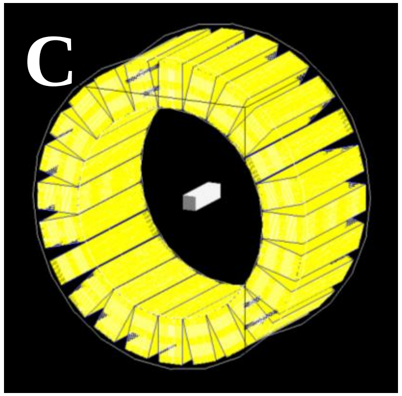
Patient setup – reconstructed images

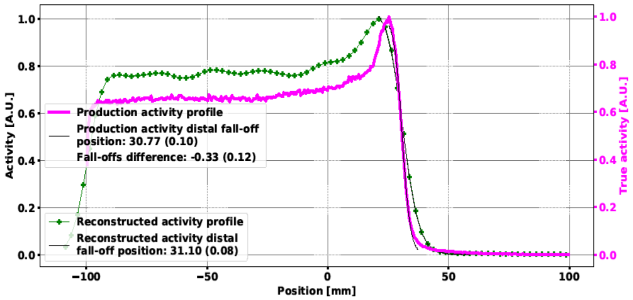


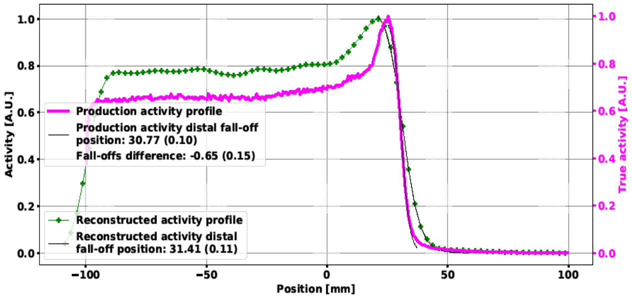
Patient setup – activity profiles

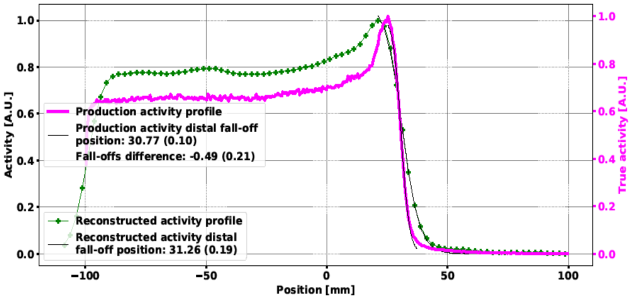






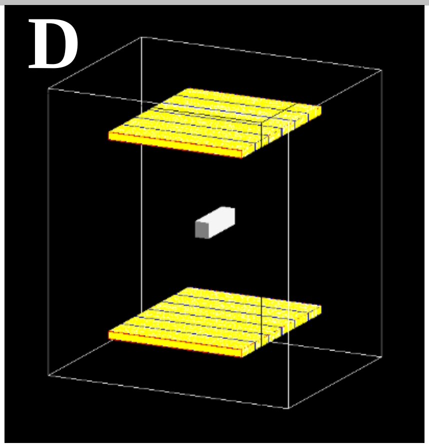


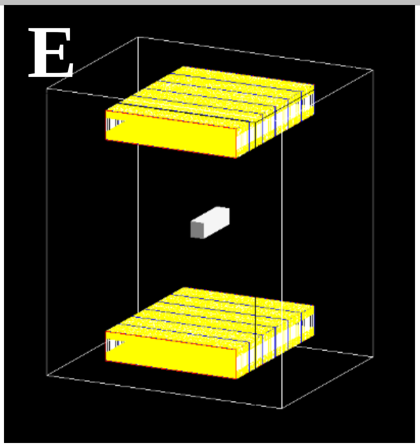


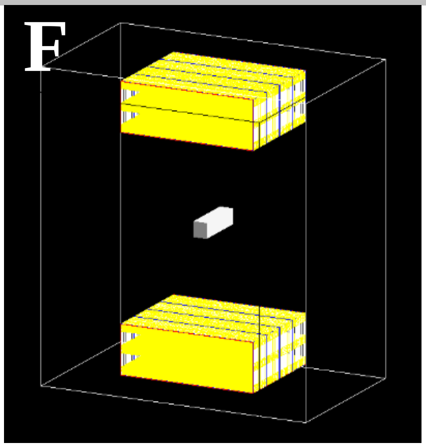


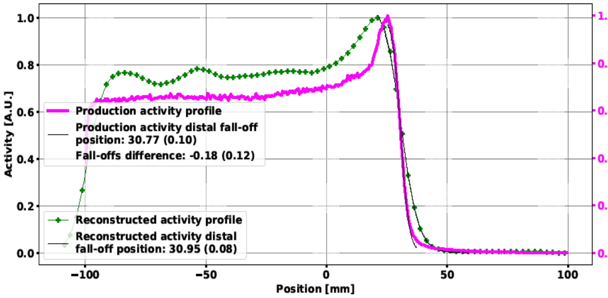
EF	$6.00 * 10^{-6}$	$11.60 * 10^{-6}$	$16.18 * 10^{-6}$
Number of coincidences	$3.00 * 10^{4}$	$5.80 * 10^{4}$	$8.09 * 10^{4}$

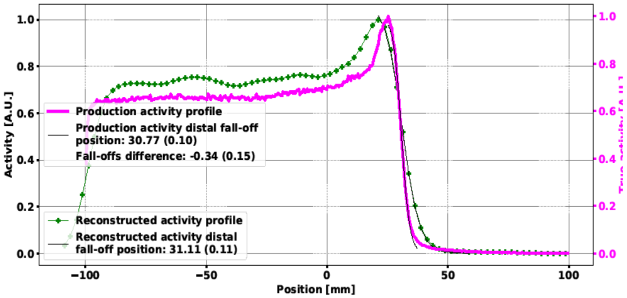
Patient setup – activity profiles

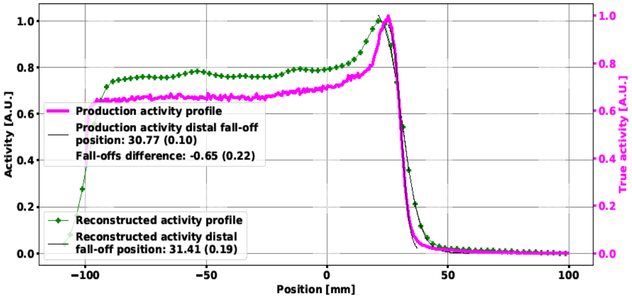










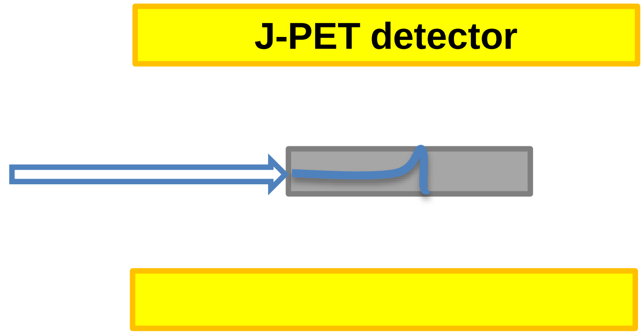


EF	$4.8 * 10^{-6}$	$9.1 * 10^{-6}$	$10.4 * 10^{-6}$
Number of coincidences	$2.42 * 10^{4}$	$4.56 * 10^{4}$	$5.25 * 10^{4}$

The EF for the DoPET study isexpected to be about 5 – 20 times greater than examined J-PET setups

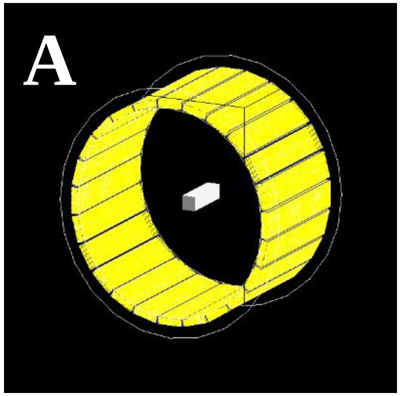
Simulation setup - phantom

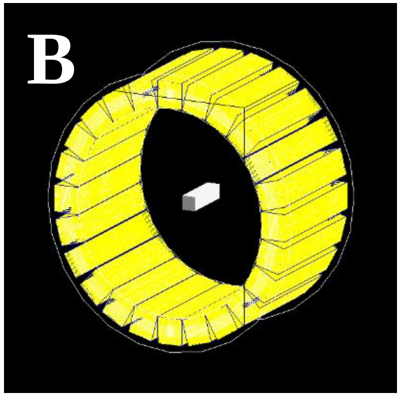
CCB (Krakow proton therapy facility) beam model implemented by Jan Gajewski (Wednesday morning session)

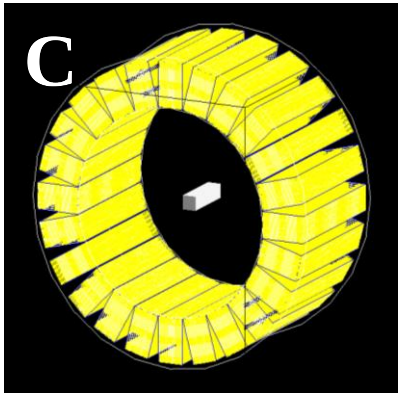


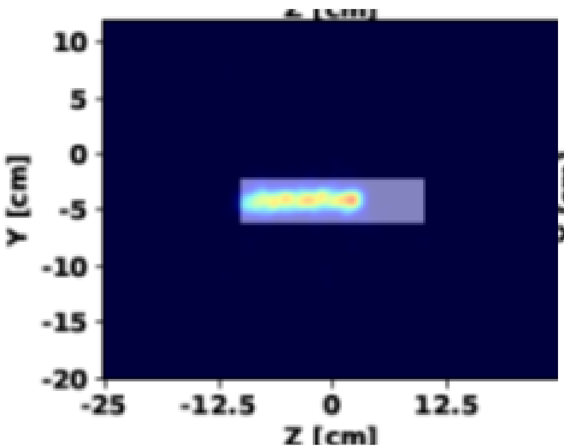
- **10^8 primary protons (150 MeV) irradiated PMMA phantom**
- **PMMA phantom: 5x5x20 cm^3**
- **Time structure of the beam was considered**
- **QGSP_BIC_HP_EMY physics list + Radioactive Decay physics**
- **Coincidences were integrated over time**

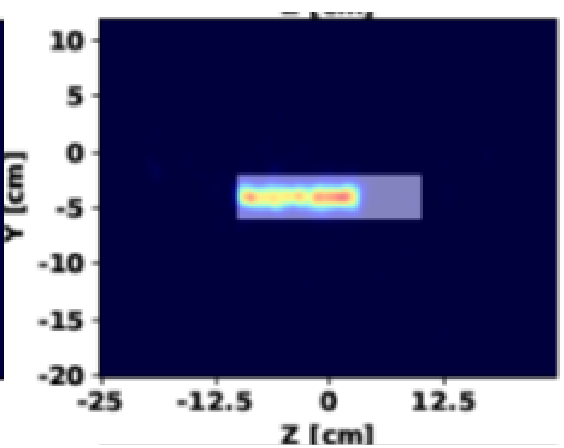
Patient setup – reconstructed images

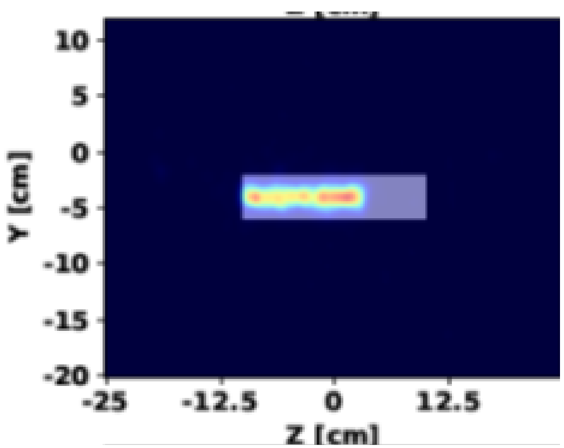




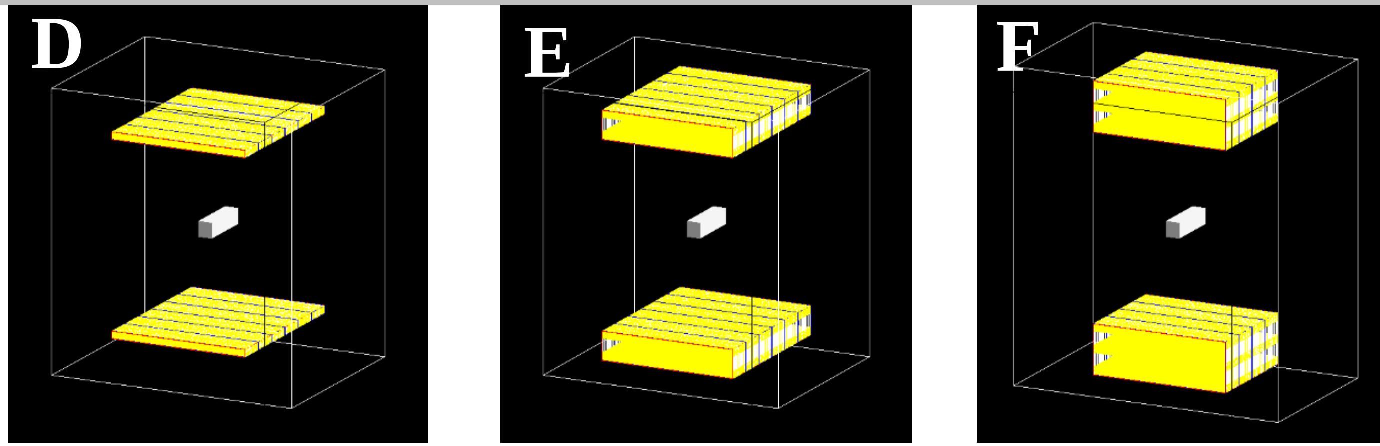


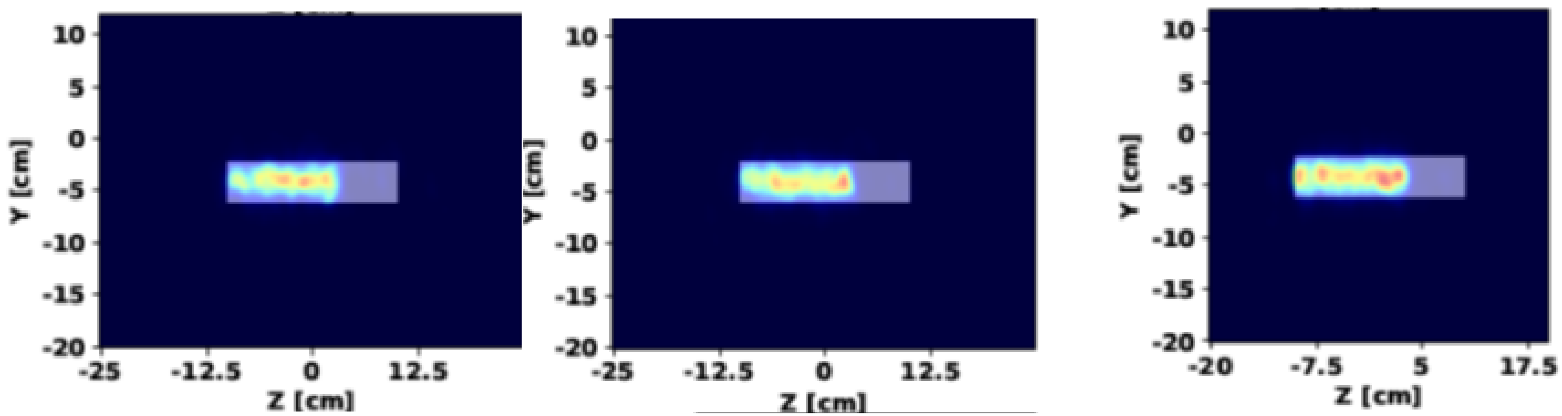




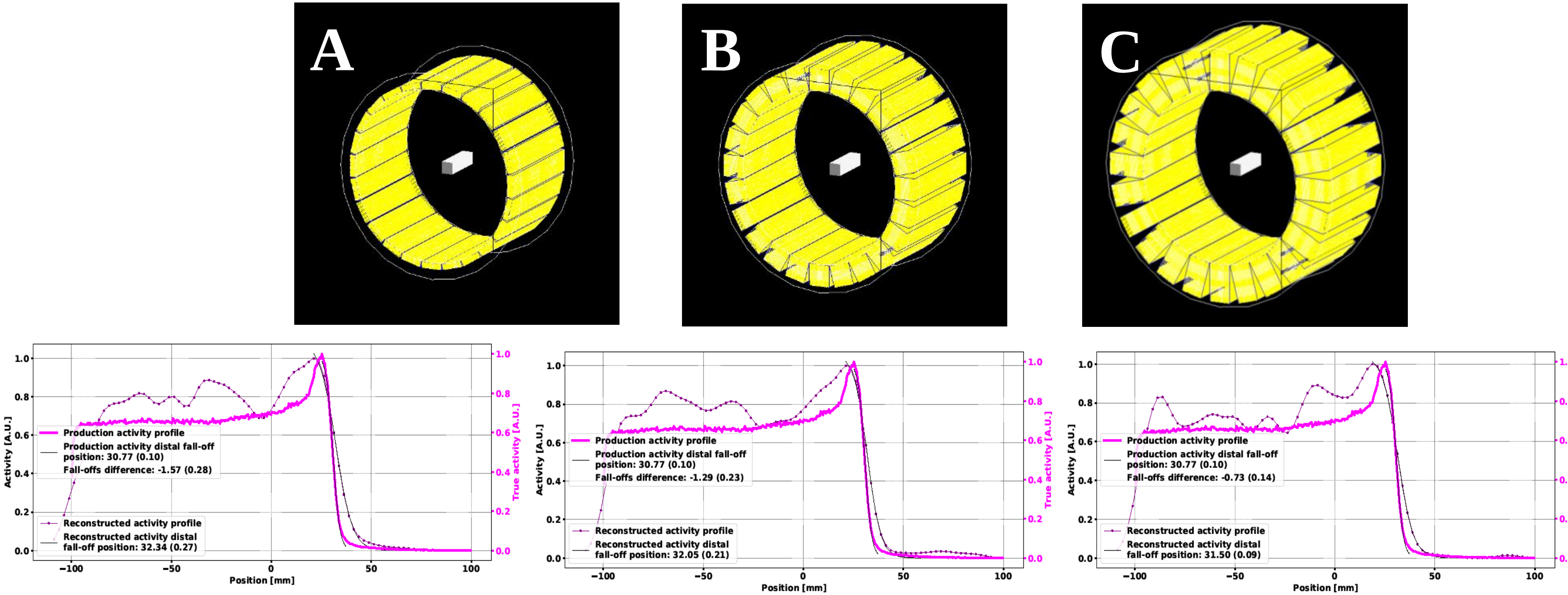


Patient setup – reconstructed images

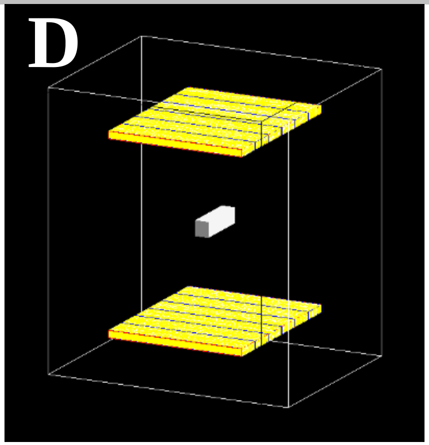


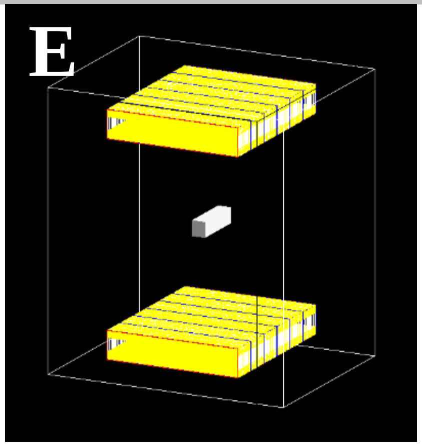


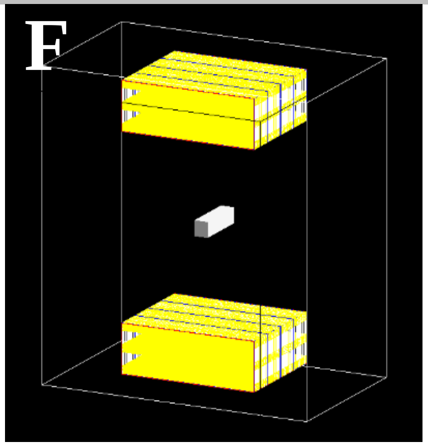
Patient setup – activity profiles

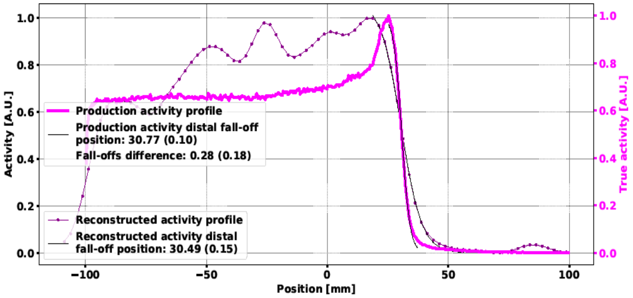


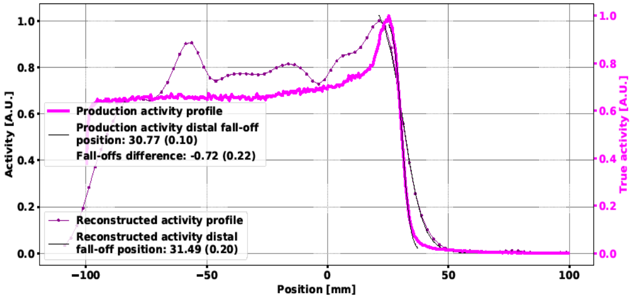
Patient setup – activity profiles

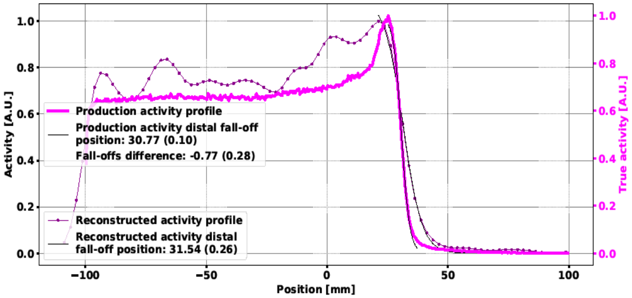












Simulation setup - patient

- Full treatment plan simulation with beam model and CT calibration implemented
- Head patient treated in CCB centre (Magdalena Garbacz Wednesday morning talk)
- $1.5E10^{10}$ primary protons - 1380 pencil beams
- In-room range monitoring scenario (10 minutes of irradiation, 1 minute of preparation, 5 minutes of PET data acquisition)
- PCC (Pearson Correlation Coefficient) was calculated for two masks and two different filters to determine potentially the best post-processing procedure to compare the reconstructed and true activity distributions

Range monitoring with J-PET

1^{st} STEP

Full treatment plan simulation in order to obtain:

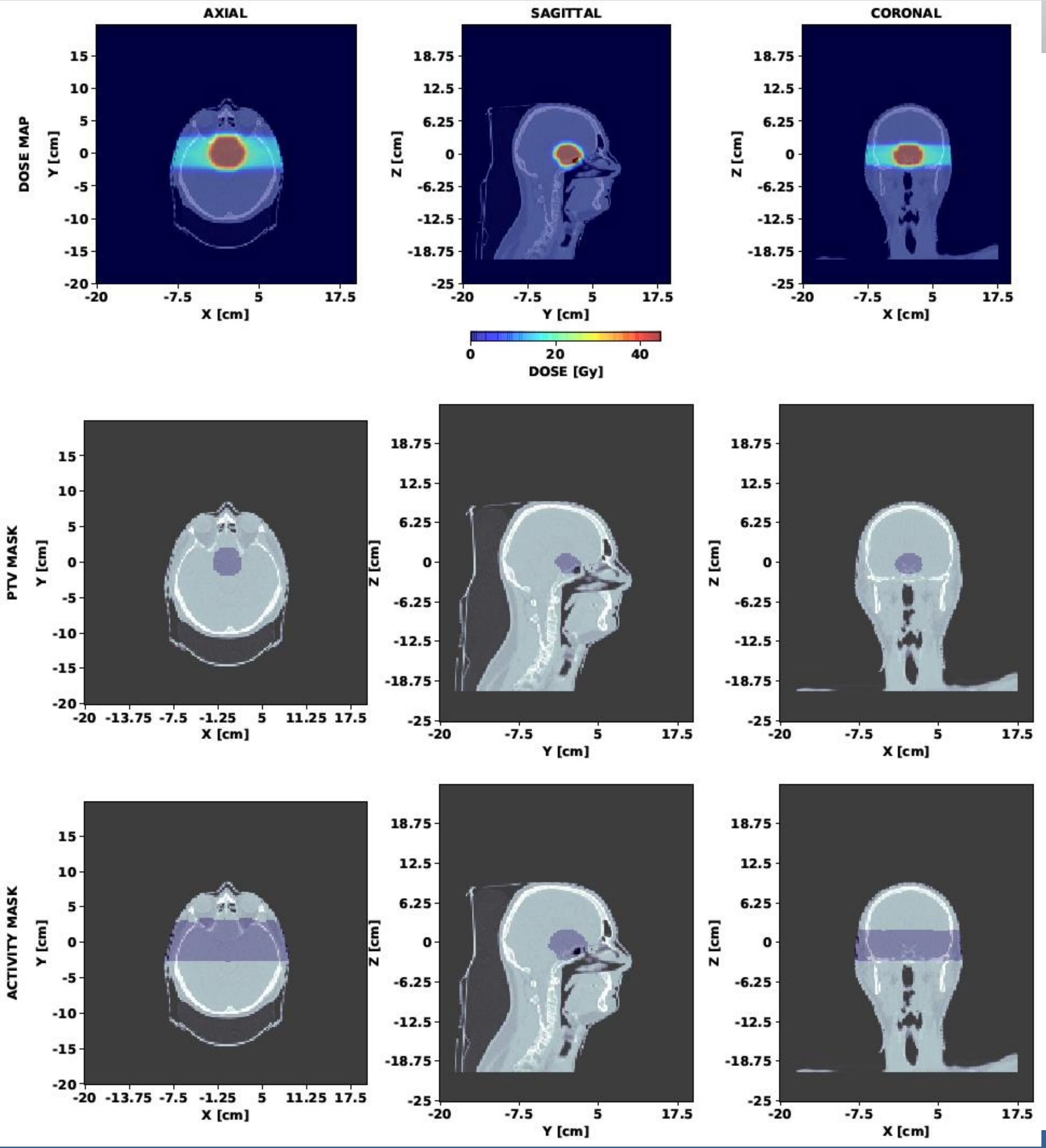
- β^+ PRODUCTION MAP

2^{nd} STEP

PET standalone simulation using β^+ PRODUCTION MAP obtained in 1st step with different J-PET configurations in order to obtain:

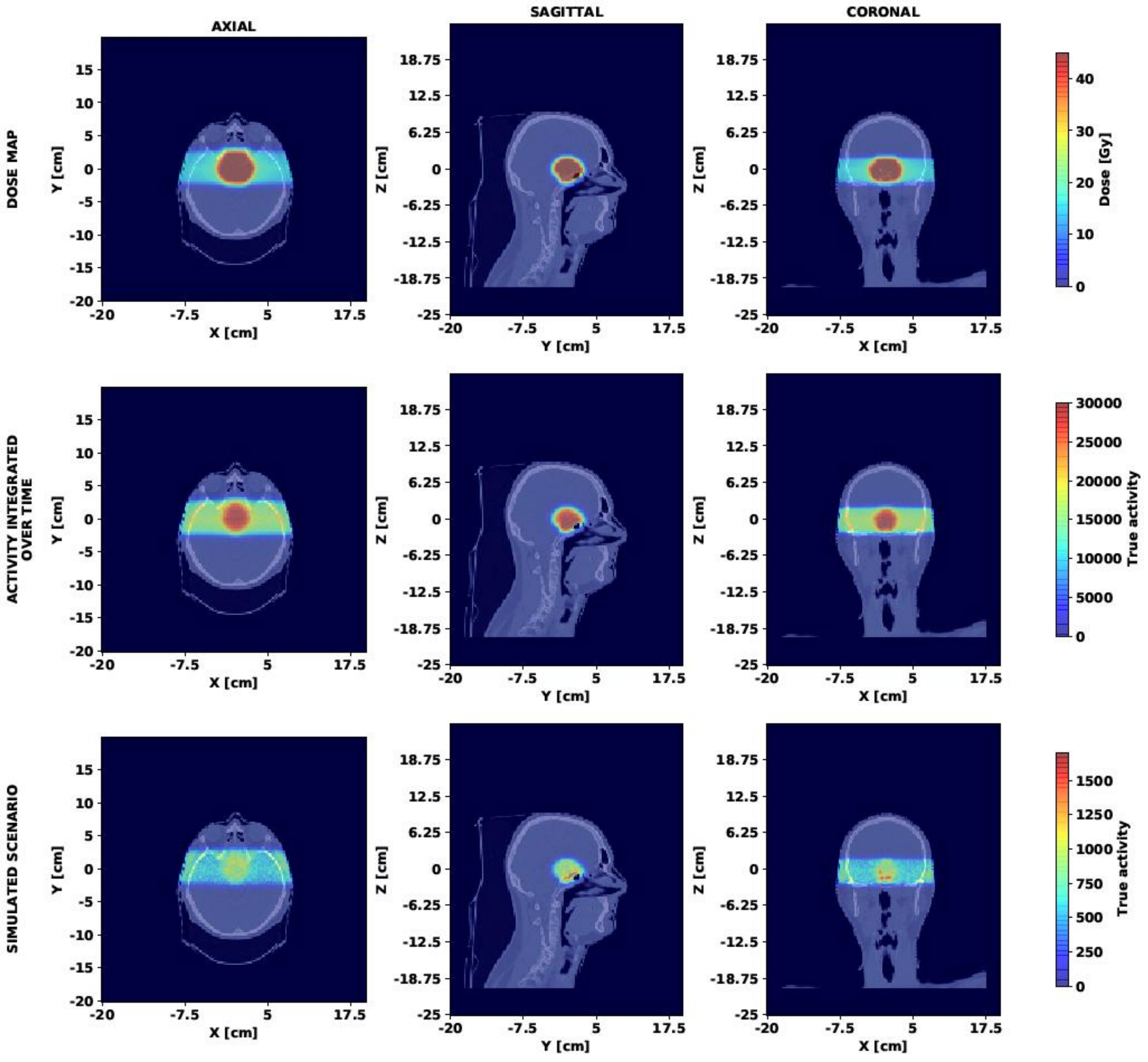
- IN-ROOM RECONSTRUCTED IMAGES

PCC masks

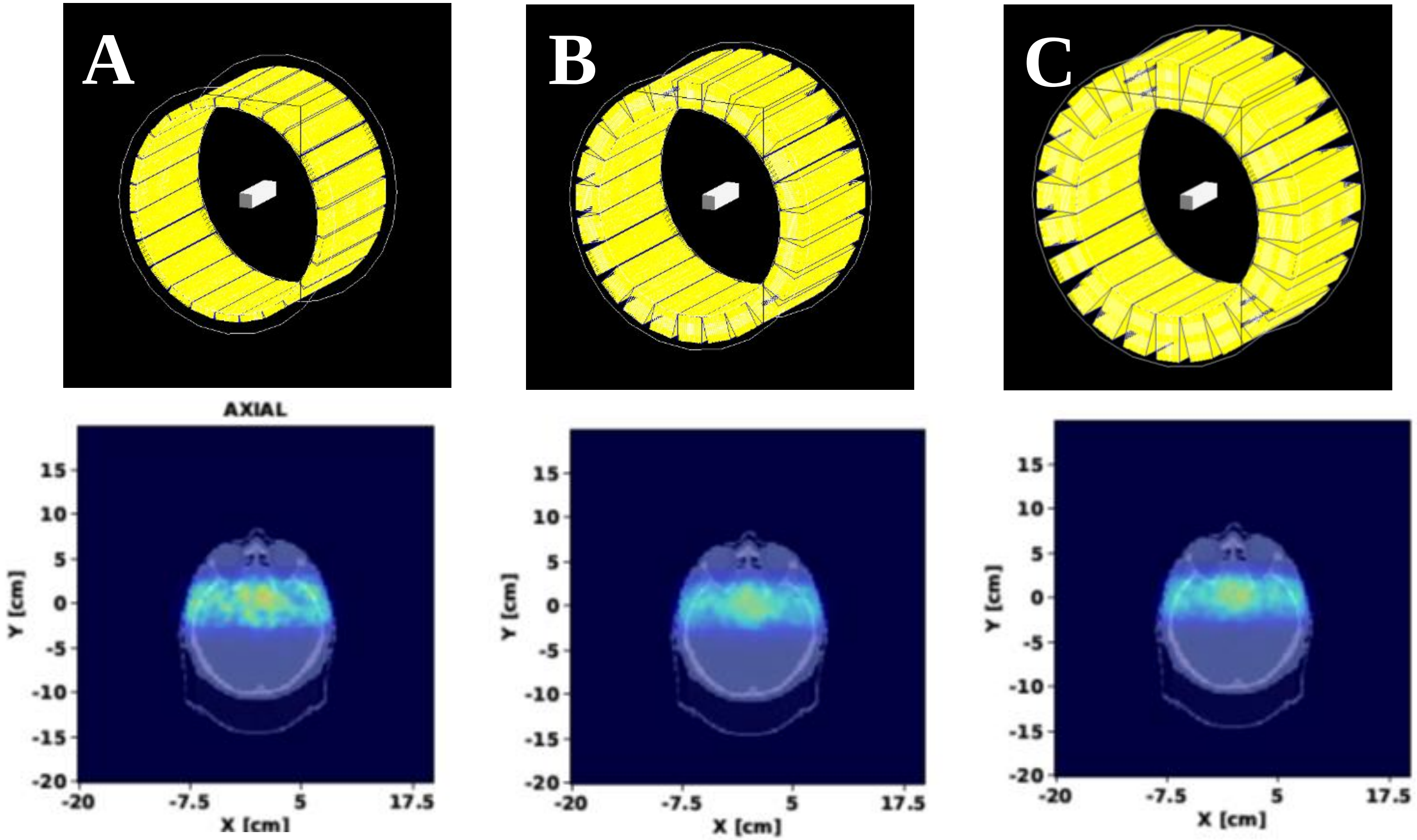


AXIAL
SAGITTAL
CORONAL
DOSE MAP
PTV MASK
ACTIVITY MASK
X [cm]
Y [cm]
Z [cm]
DOSE [Gy]
0
20
40

Activity maps

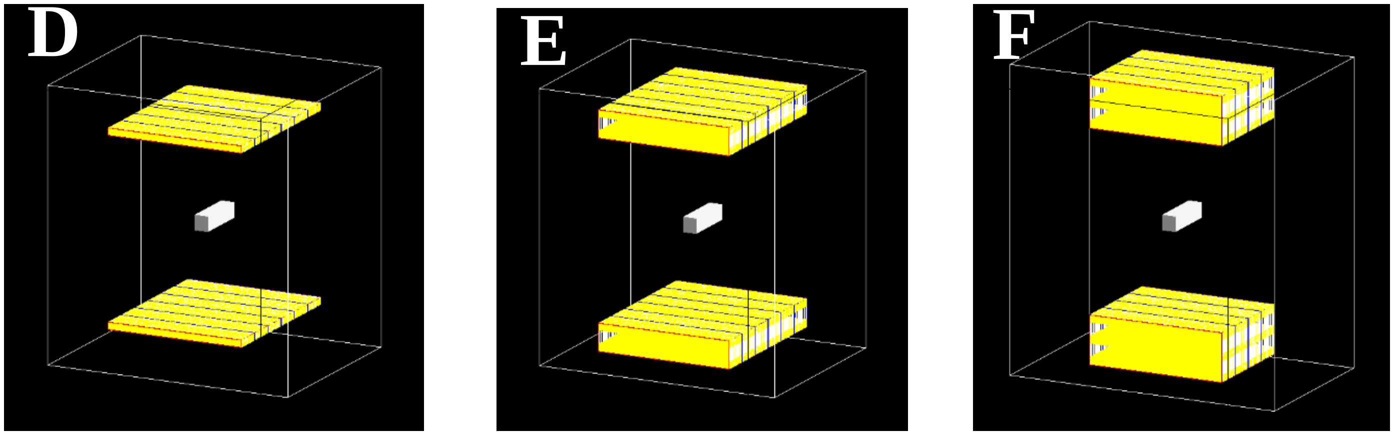


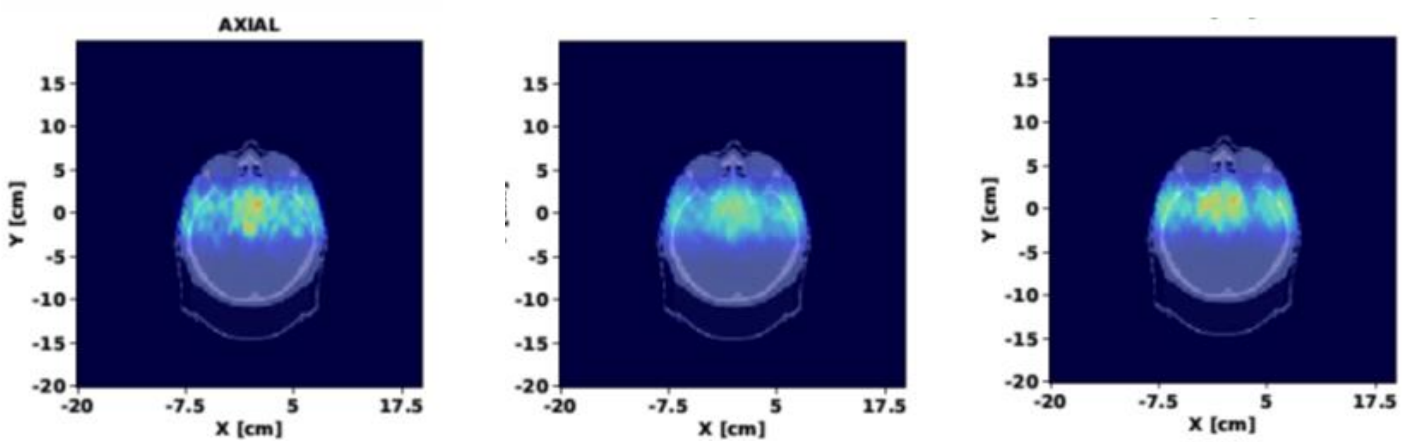
Patient setup – reconstructed images



EF	$0.90 * 10^{-6}$	$2.60 * 10^{-6}$	$4.34 * 10^{-6}$
Number of coincidences	$1.35 * 10^{4}$	$3.89 * 10^{4}$	$6.52 * 10^{4}$

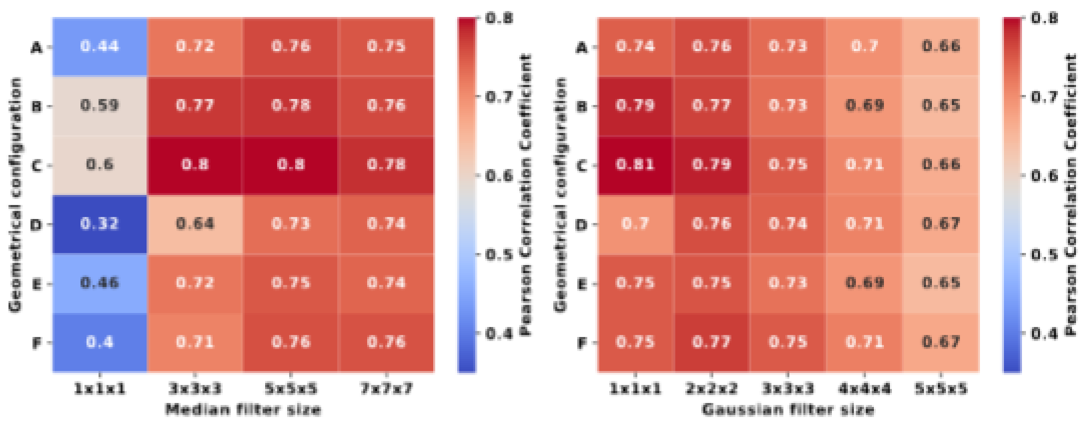
Patient setup – reconstructed images



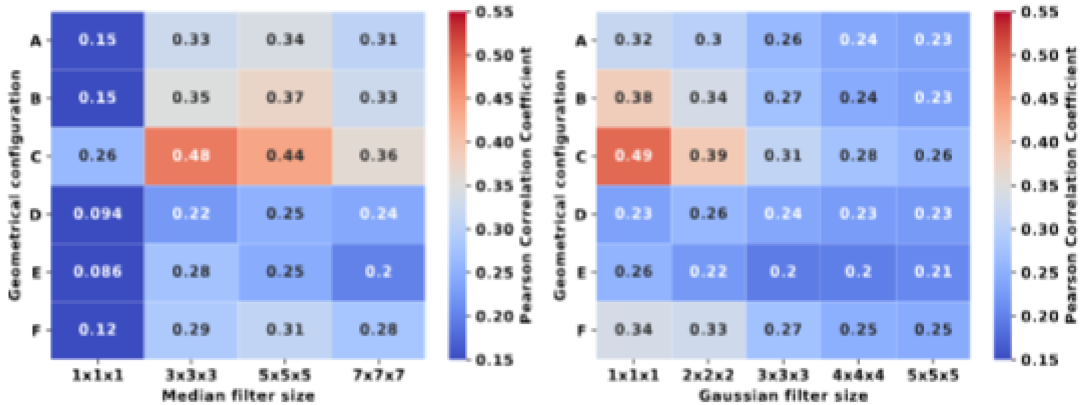


EF	$0.48 * 10^{-6}$	$1.40 * 10^{-6}$	$1.57 * 10^{-6}$
Number of coincidences	$0.72 * 10^{4}$	$2.10 * 10^{4}$	$2.36 * 10^{4}$

Patient setup – PCC analysis



(a) ROI: ACTIVITY; filter: median (b) ROI: ACTIVITY; filter: Gaussian



(c) ROI: PTV; filter: median (d) ROI: PTV; filter: Gaussian

Gaussian (1x1x1 and 2x2x2) and median (5x5x5 and 7x7x7) filtering gives the best results between reconstructed and true activity distributions.
Experimental validation is needed to determine the best post-reconstruction analysis.

Conclusions & Discussion

1. J-PET detector is feasible to acquire the β^+ activity produced during proton therapy treatment and the offline 3D reconstruction of PET activity images is possible using CASToR toolkit. Works towards reconstruction parameters optimization (algorithm, projector etc.) is needed.

2. Barrel based setups are prefered for the in-room/off-beam setups whereas the dual-head setups could be potentially considered for the in-beam applications.

3. Among setups with 24 modules, the best image quality were obtained with single layer barrel but the best statistics were observed for the triple layer dual-head setup.

Conclusions & Discussion

4. Works towards in-beam is needed. Incorporate the dual-head not to the nozzle but to the panels which rotates with the nozzle (perpendicular to the beam axis) using a length adaptive solution to assure the constant distance between the heads and distance from the isocenter.

5. A lot of work has to be done from the software side. Especially ‘’in-fly” reconstruction and normalization are very challenging. However use of the FPGA electronics gives hope to utilize the J-PET technology for the in-beam proton beam range verification.

6. Experimental validation of the simulations is needed and planned later this year.

Acknowledgment

J. Baran acknowledge the support of **InterDokMed** project no. **POWR.03.02.00-00-I013/16**

The National Centre for Research and Development

LIDER

Research was supported by: the National Centre for Research and Development (NCBiR), grant no. **LIDER/26/0157/L-8/16/NCBR/2017**

CASToR developpers:

Thibault Merlin, PhD
Simon Stute, PhD

This research was supported in part by **PL-Grid Infrastructure**.

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

Prof. Paweł Olko
Jan Swakoń, PhD
Leszek Grzanka, PhD
Antoni Ruciński, PhD
Jan Gajewski, PhD
Monika Pawlik-Niedźwiecka
Magdalena Garbacz
Agata Skrzypek

J-PET

Prof. Paweł Moskal
Wojciech Krzemień, PhD
Szymon Niedźwiecki, PhD
Nikodem Krawczyk
Mateusz Bała

Centrum Cyklotronowe Bronowice

Dawid Krzempek
Katarzyna Krzempek
Marzena Rydygier, PhD