Range monitoring in proton therapy using the J-PET scanner

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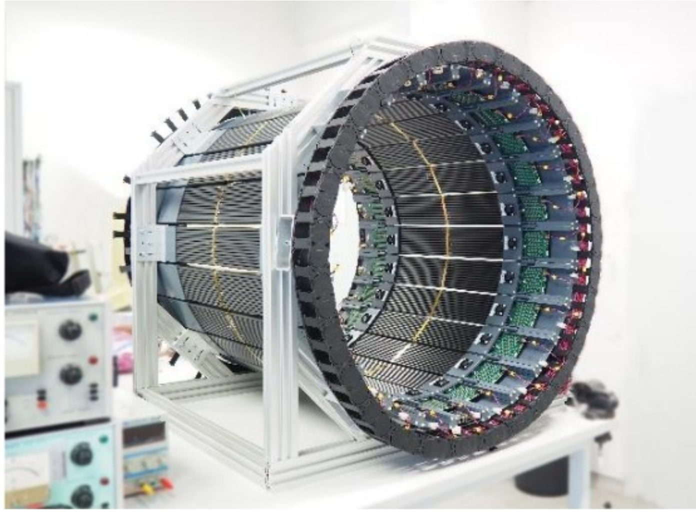
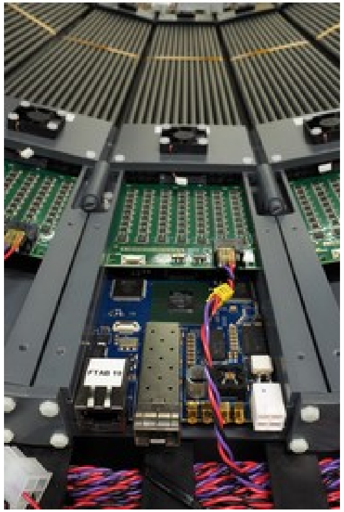
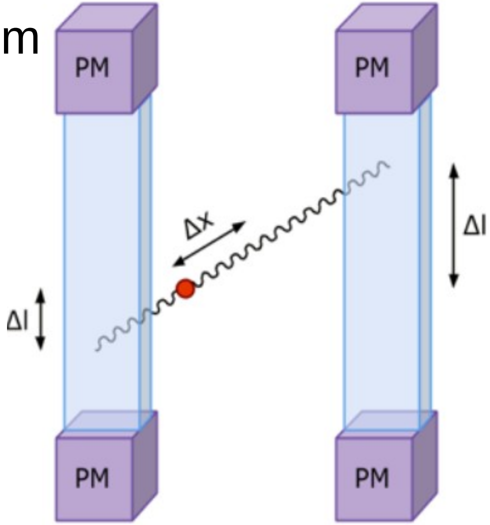
The Jagiellonian PET (J-PET) scanner

PET scanner based on plastic scintillators





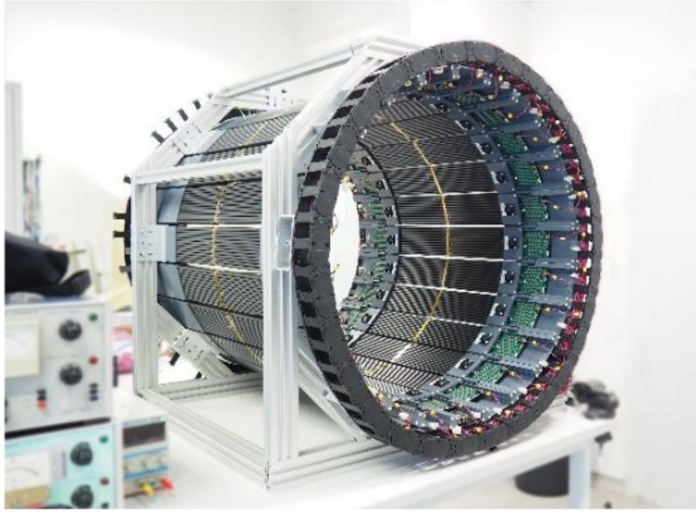
- 24 modules, of 13 BC-404 scintillator strips
- 6×24 mm^2 and 500 mm in length
- Read out at both sides by SiPM array
- Axial position through ToF along the strip
  - Wavelength shifters
  - Axial res. 5 mm
- 500 ps CRT



- Inexpensive technology for total-body diagnostic PET
- Capable of multi-photon and positronium imaging
- Compton instead of photoelectric absorption
  - P. Moskal et al., *Phys. Med. Biol.* **66** (2021) 175015
  - P. Moskal et al., *Science Advances* **7** (2021) eabh4394

The Jagiellonian PET (J-PET) scanner

A flexible, inexpensive tool for range monitoring in proton therapy



¤ Modular construction
¤ Simplified electronics

Easy adaptation to:
- ¤ Full-ring
- ¤ Dual-head

¤ Other geometries (*in situ*)

Timing performance expected with BC-408 scintillator strips (140 ps CRT - FWHM) should allow the possibility of beam-on imaging in the long-term.

P. Moskal et al., *Phys. Med. Biol.* **66** (2021) 175015
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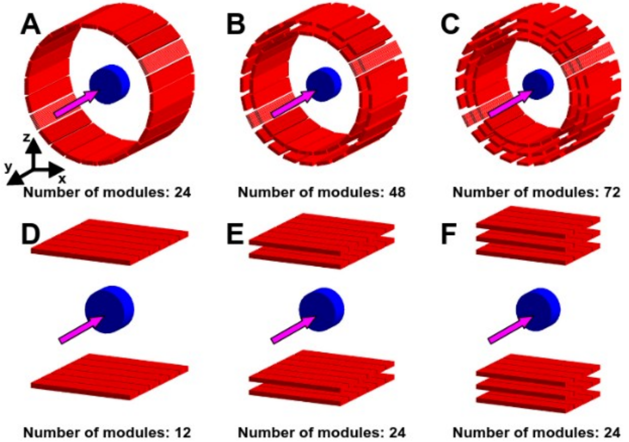
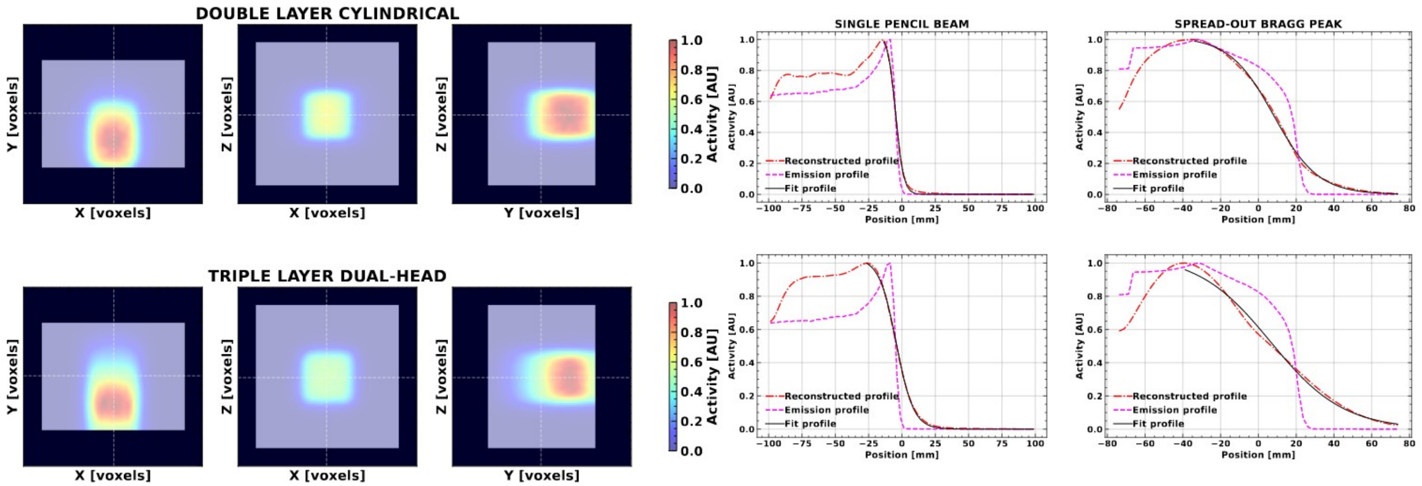
Initial simulation studies

Six proposed J-PET geometries





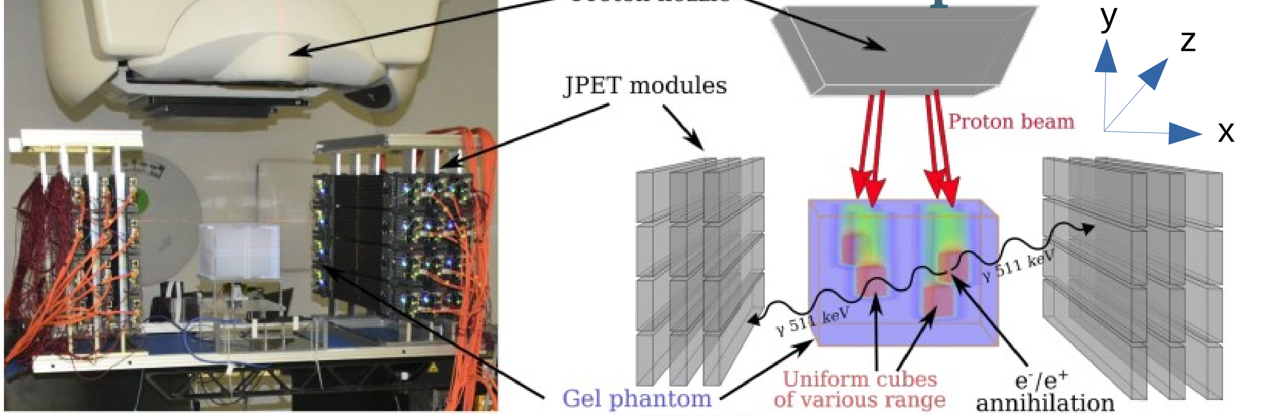
A. single layer ring
B. double layer ring
C. triple layer ring
D. single layer dual-head
E. double layer dual-head
F. triple layer dual-head

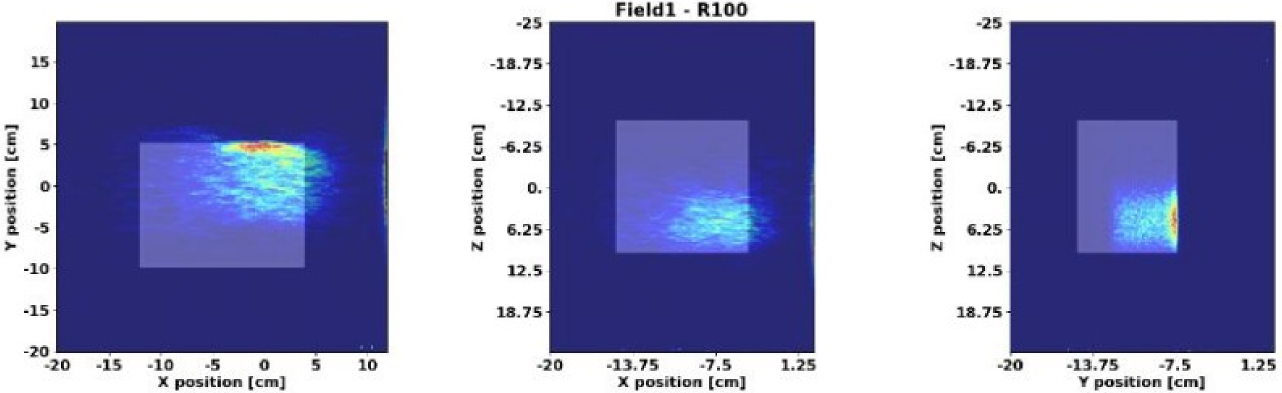
¤ SPB and SOBP irradiations
¤ Six range shifts (2,3,4,5,7,9 mm)
δRD = shift in dose
δRA = shift measured from PET image
$\Delta R = \delta RD - \delta RA$
$\sigma \Delta R < 1$ mm for all geometries

Setup	SPB study		SOBP study	
	$\overline{\Delta R}$ [mm]	$\sigma_{\Delta R}$ [mm]	$\overline{\Delta R}$ [mm]	$\sigma_{\Delta R}$ [mm]
Single layer cylindrical	0.22	0.26	0.10	0.50
Double layer cylindrical	0.45	0.27	0.17	0.36
Triple layer cylindrical	0.40	0.27	0.31	0.64
Single layer dual-head	0.79	0.58	0.07	0.83
Double layer dual-head	0.33	0.42	-0.37	0.43
Triple layer dual-head	-0.06	0.04	-0.05	0.56

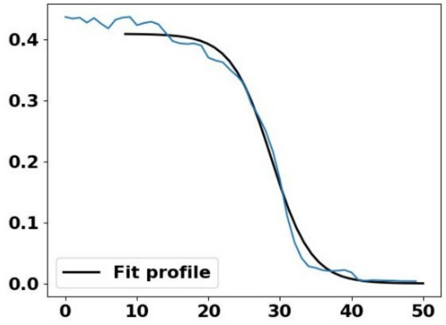
Experimental validation in water phantom

Set-up and Method





- ¤ Eight SOBPs irradiated (100 mm – 103 mm depth)
- ¤ Distal edge fitted (Sigmoid)



Preliminary results

Five out of eight range differences measured with precision < 1mm

A patient simulation study

Simulation Framework (ProTheRaMon)

Complete processing of:

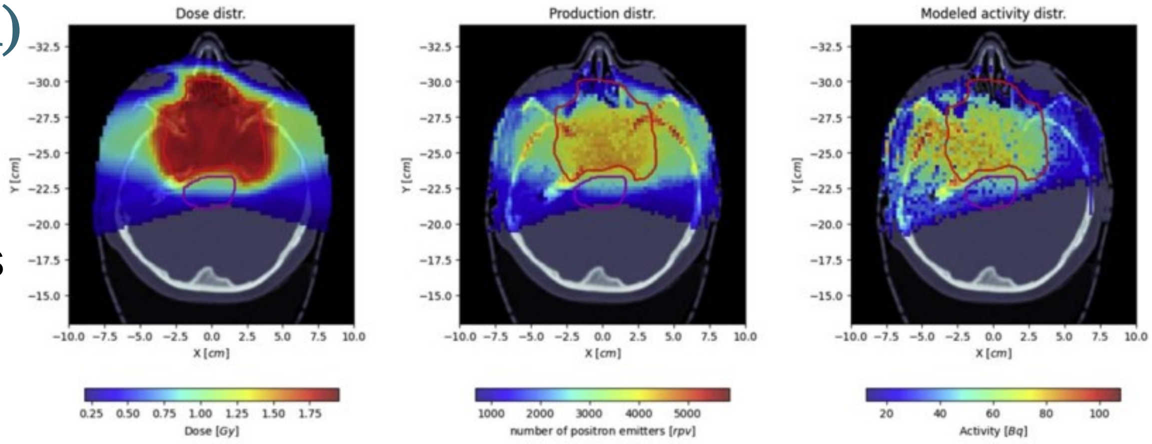
¤ Proton therapy treatment plans

¤ Patient CT geometries

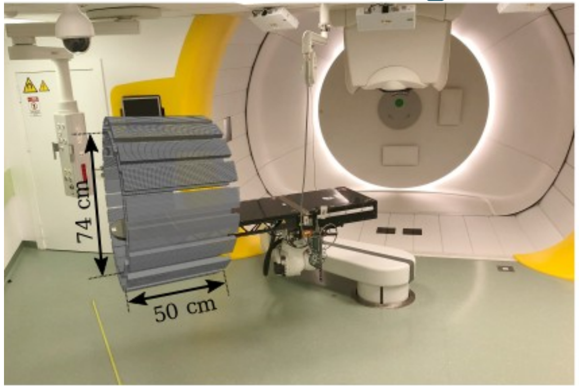
¤ Treatment & imaging coordinate systems

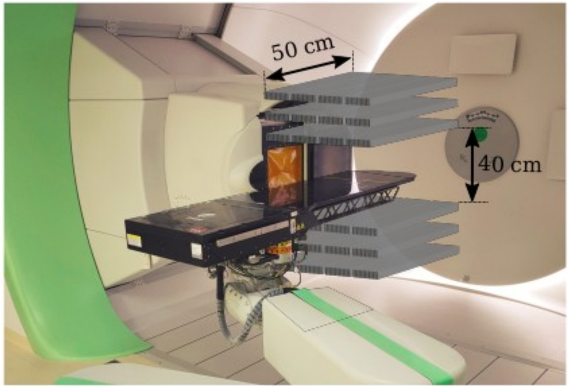
¤ Protocol-specific activity decay

D. Borys et al 2022 *Phys. Med. Biol.* **67** 224002



Simulated J-PET geometries





¤ Treatment plans from 95 patients.

¤ Each in 27 imaging scenarios (positioning and calibration errors)

In-room protocol

¤ Ring geometry, 1 min after last field

In-beam protocol

¤ Dual-head geometry, right after first field

A patient simulation study

Single patient example

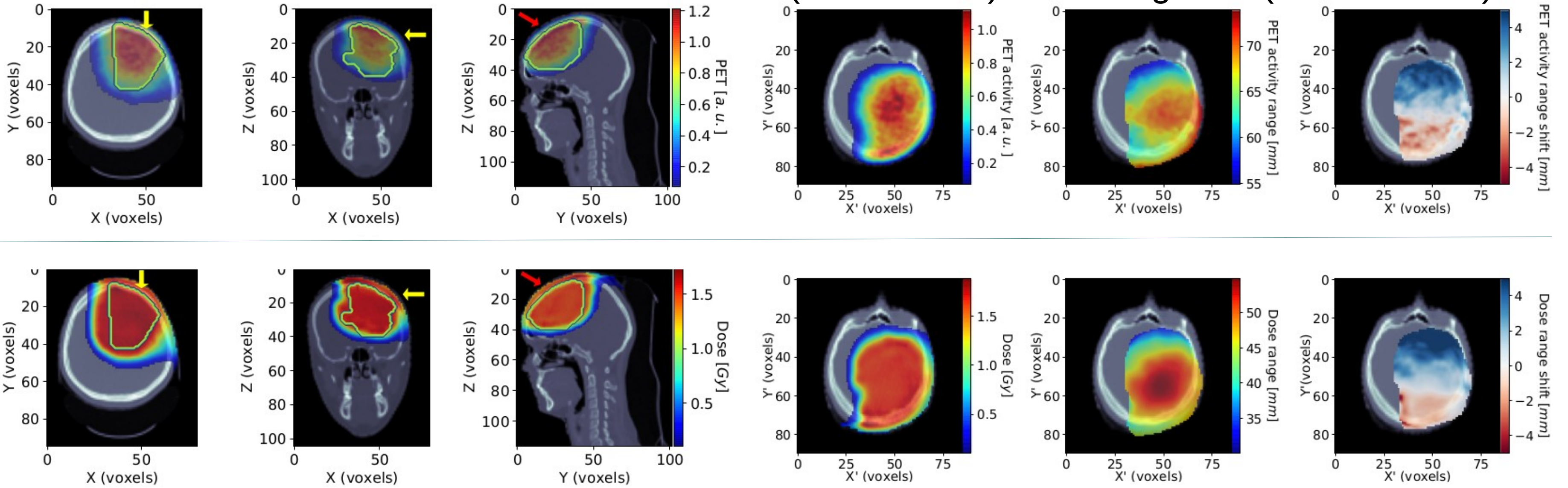
J-PET Image (In-room)

Dose (1 fraction)

Distributions (at isocentre)

Range

Range diff. (z-10mm shift)



isotope	half-time [s]
^{15}O	122.2
^{14}O	70.6
^{13}N	597.9
^{11}C	1223.4
^{10}C	19.2
^{30}P	149.9
^{38}K	458.2

Rotation to beam's eye view (BEV) of last delivered field and range measurement

K. Brzezinski 2023 *Phys. Med. Biol.* (accepted)

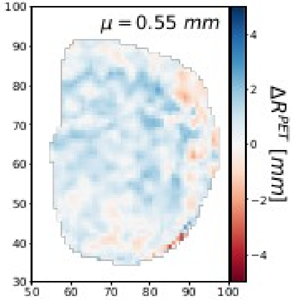
A patient simulation study

Analysis of patient cohort

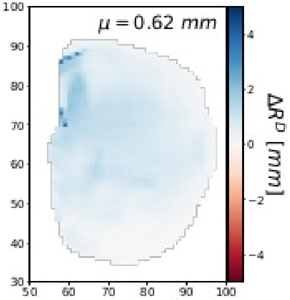
Statistical prediction model:

Measure of overall proton range shift:
¤ Mean dose range difference with respect to reference

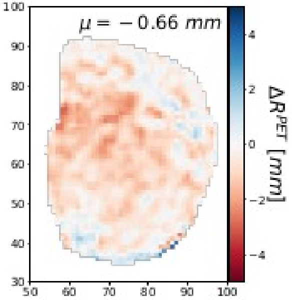
PET-based predictor for overall proton range shift:
¤ Mean range difference of the reconstructed PET activity with respect to reference



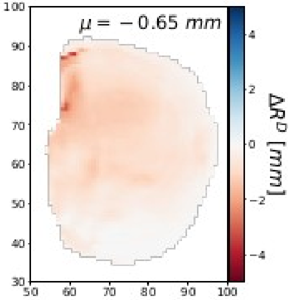
PET range (HU+2%)



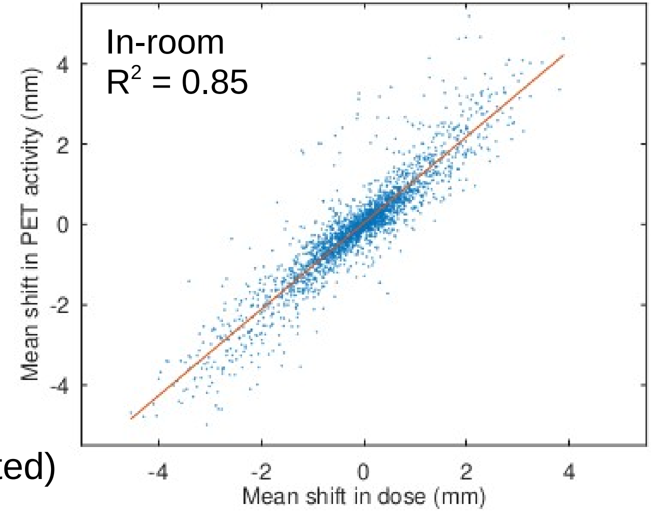
Dose range (HU+2%)

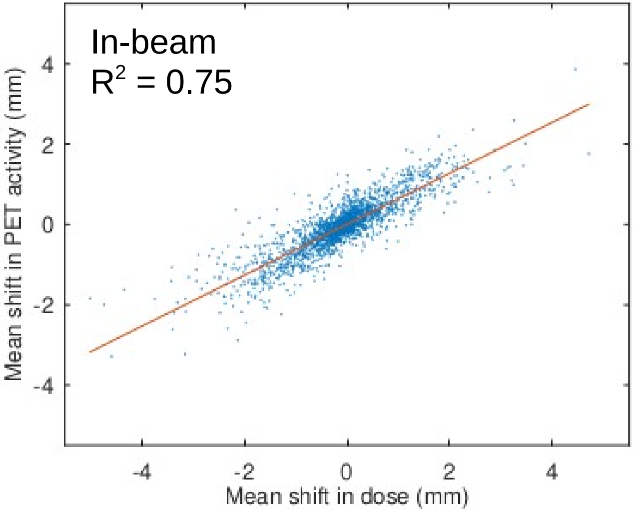


PET range (HU-2%)



Dose range (HU-2%)





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Conclusions

¤ Simulation studies of SPB and SOBP irradiations of a PMMA phantom show the capability of the J-PET scanner to measure proton range shifts with precision < 1 mm.

¤ Preliminary experimental results using SOBP irradiations suggest that the J-PET scanner can measure proton range shifts with precision < 1 mm in a clinical setting.

¤ BEV maps of range shifts in PET activity, created using reconstructed J-PET images, offer a visual tool for identifying proton range deviations.

¤ Using J-PET images, a model has been constructed for predicting overall proton range deviations using range shifts in reconstructed PET activity.

¤ The results motivate the use of PET-based models as a tool for predicting proton range deviations, as well as clinical metrics that aid in the assessment of the quality of the delivered treatment.

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Backup slides

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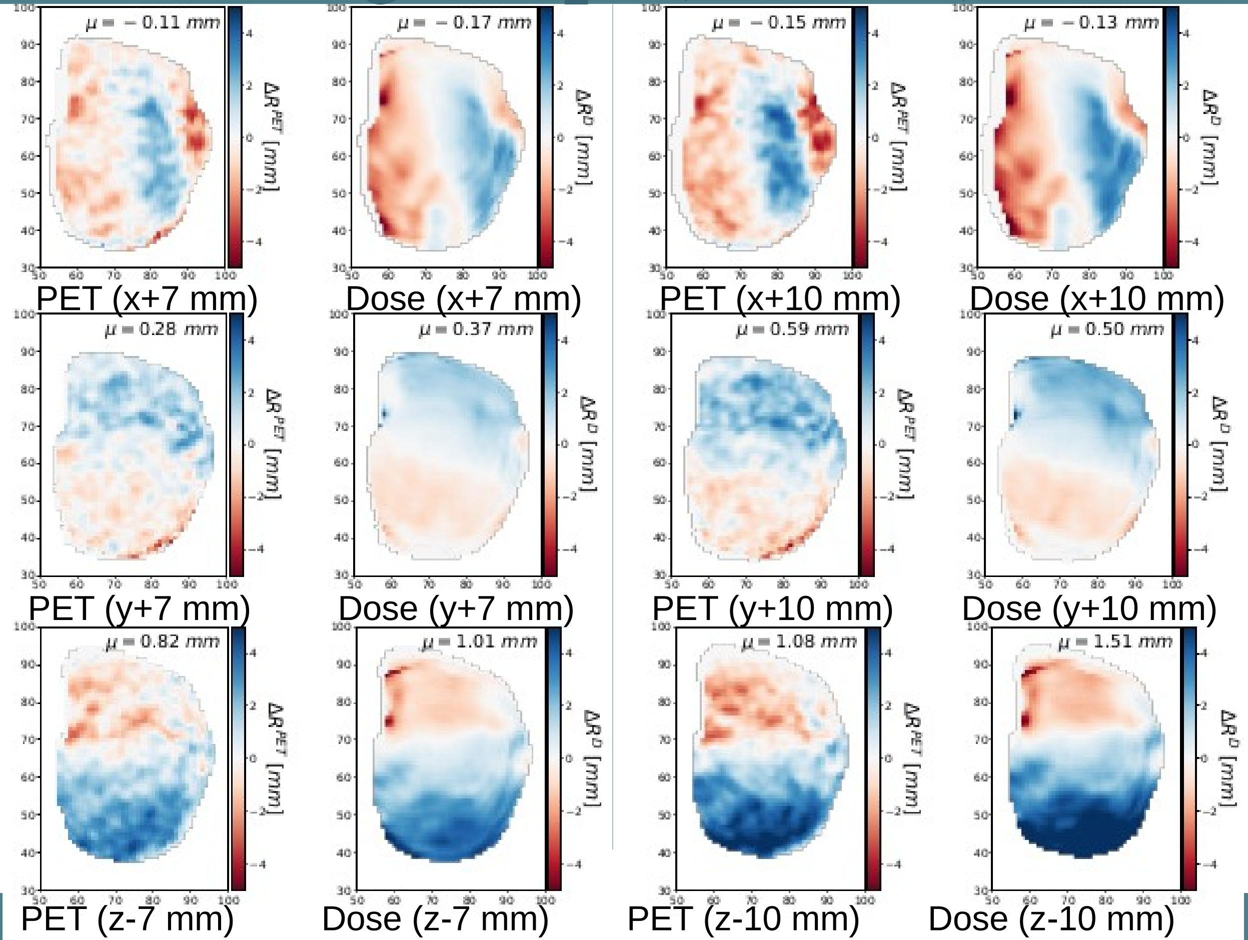
Beam’s-eye-view range maps (in-room)



Beam’s-eye-view range maps (in-beam)