JAGIELLONIAN UNIVERSITY IN KRAKÓW

J-PET
Jagiellonian Positron Emission Tomography

From J-PET prototype to total-body PET scanner

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on behalf of the J-PET Collaboration

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24.05.2022

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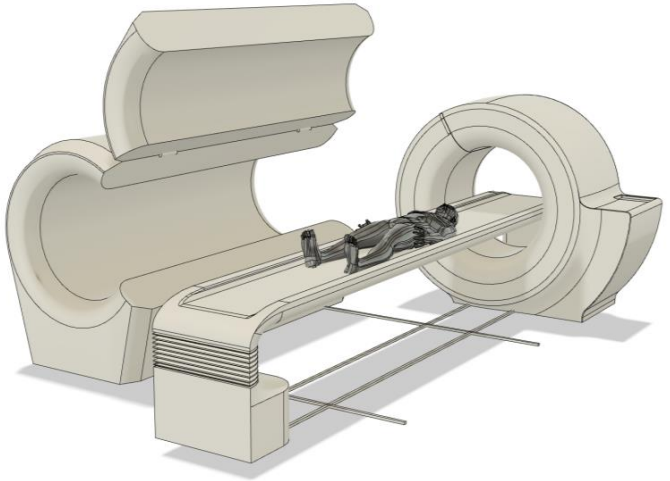
Outline

1) Motivation
2) J-PET: principle of operation
3) First J-PET prototypes
4) Total-body J-PET scanner
5) In-vitro positronium imaging
6) Conclusions

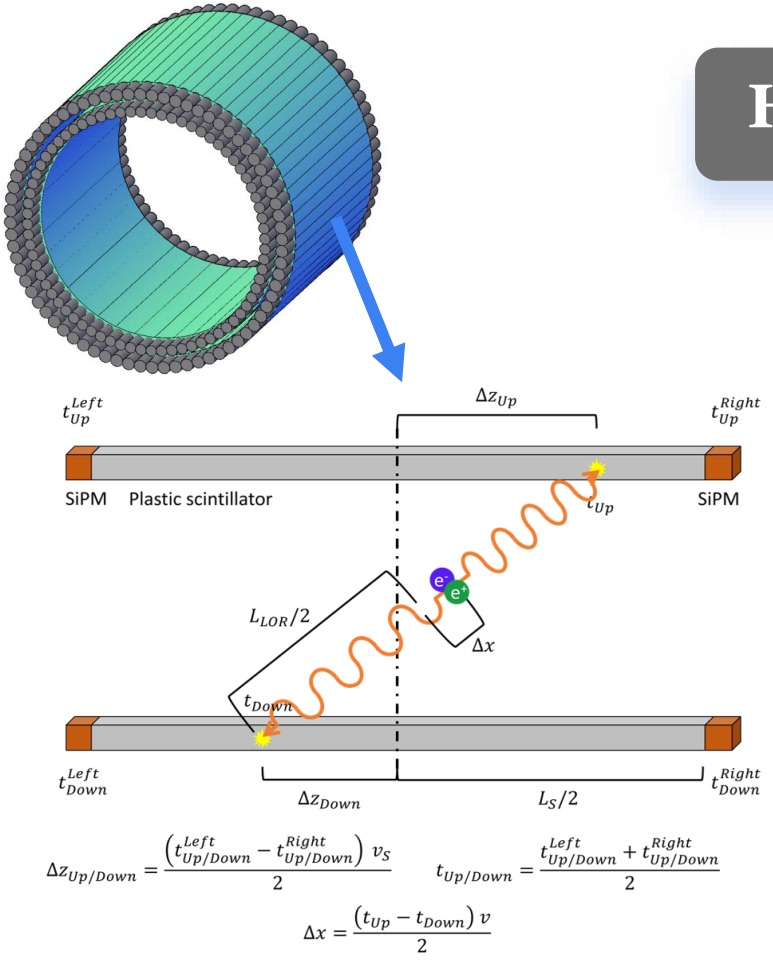


Motivation

The primary aim of the group is to elaborate a technology for:

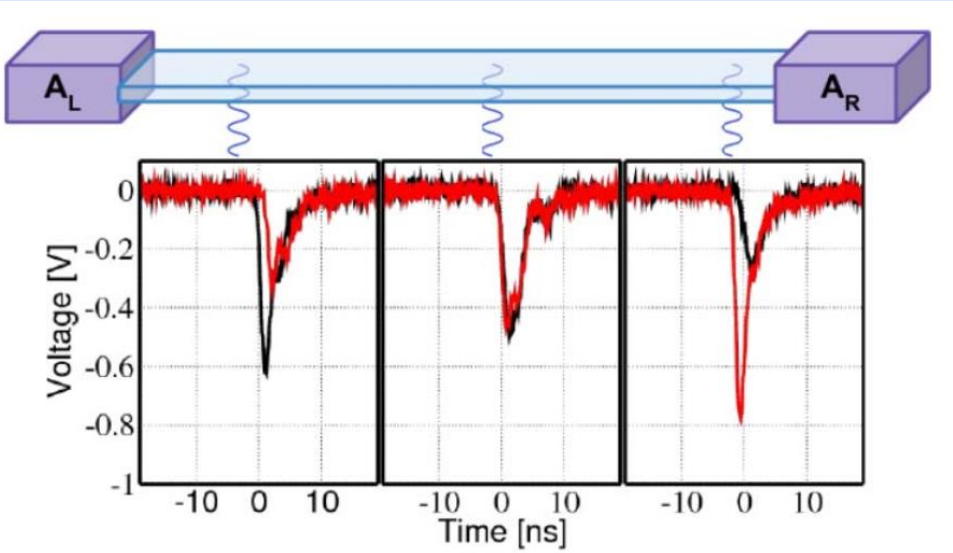
- **the cost-effective total-body PET scanner based on plastic scintillators;**
- **PET scanner with positronium and multiphoton imaging capabilities;**
- **modular and transportable PET scanner with the field of view adjustable to the patient size.**

Hit reconstruction along the strip



$$\Delta z_{Up/Down} = \frac{\left(t_{Up/Down}^{Left} - t_{Up/Down}^{Right}\right) v_S}{2} \qquad t_{Up/Down} = \frac{t_{Up/Down}^{Left} + t_{Up/Down}^{Right}}{2}$$

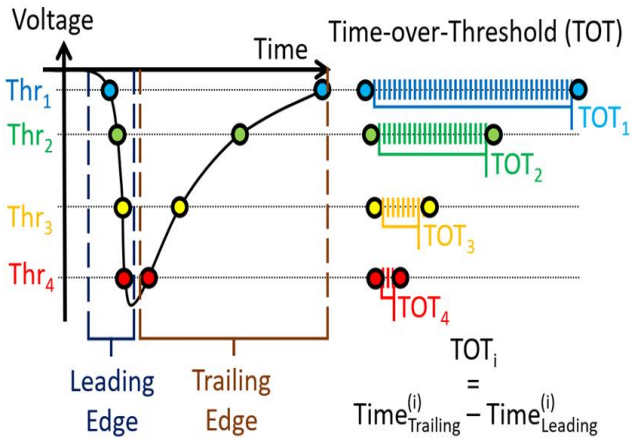
$$\Delta x = \frac{\left(t_{Up} - t_{Down}\right) v}{2}$$

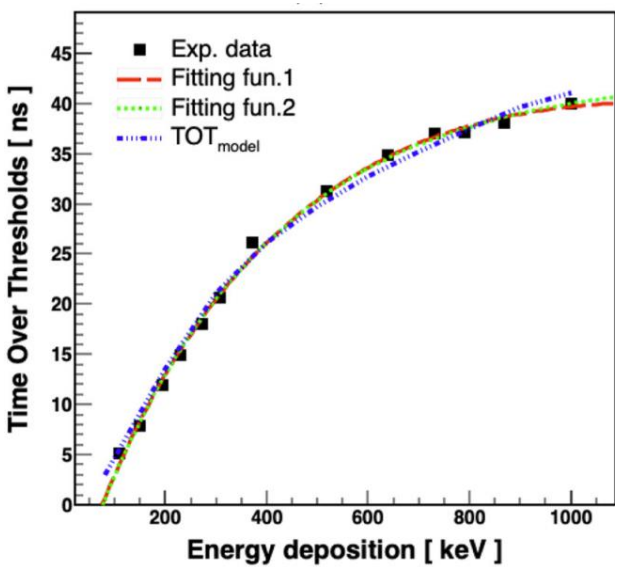


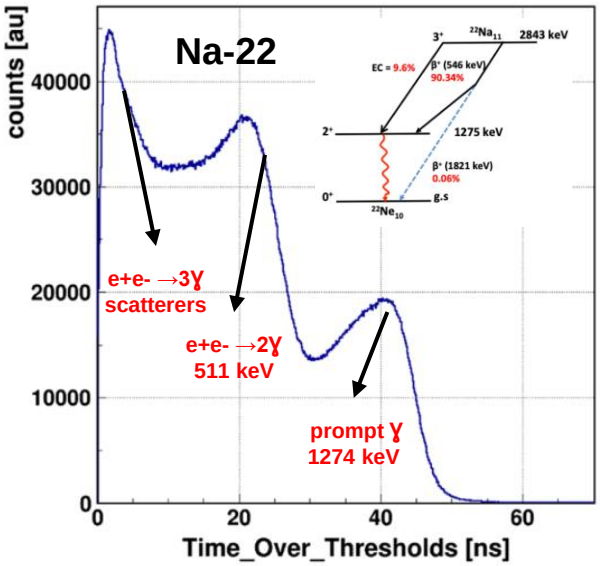
Hit along the strip → **Annihilation Point** → **3D image**

S. Sharma et al., Hit-Time and Hit-Position Reconstruction in Strips of Plastic Scintillators Using Multithreshold Readouts, IEEE Trans on Rad and Med. Sci (2020) 4:528

Time Over Threshold







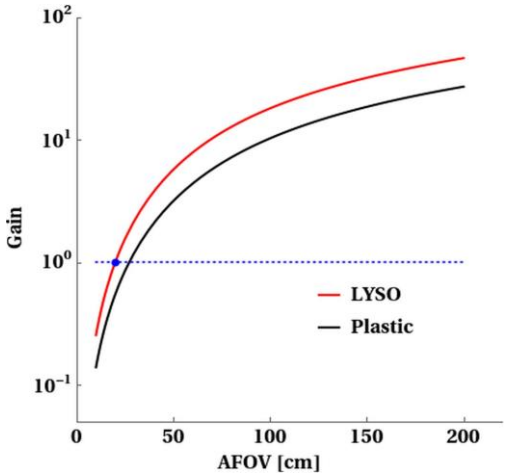
More information will be presented in poster session on Friday at 15:30:
Evaluation of data acquisition system based on FPGA and continuous readout of the J-PET detector.

S. Sharma et al., Estimating relationship between the Time Over Threshold and energy loss by photons in plastic scintillators used in the J-PET scanner, EJNMMI Physics (2020) 7:39

Differences between traditional PET and novel strip J-PET scanners

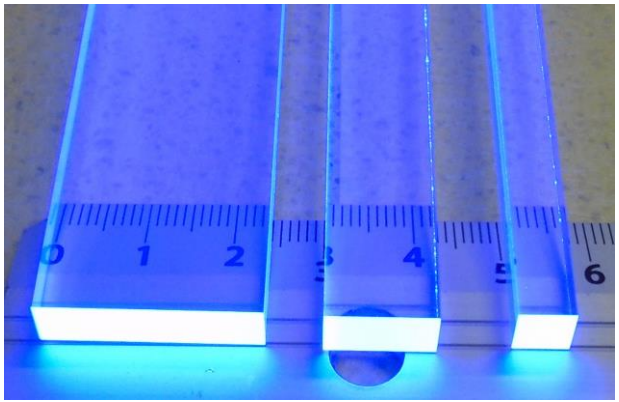
Parameters	Traditional PET	Strip J-PET
Type of scintillator	crystals LSO, LYSO, BGO	plastics BC-404, BC-420, EJ-230
Physical phenomenon	photoelectric effect	Compton scattering
Measured property	energy of gamma photon + time of flight	time of flight
Granularity of detector	high	low
Number of scintillators	13,824 to 32,444 crystals	192 strips
Scintillator size [mm^3]	e.g. 4x4x20; 6.3x6.3x30	e.g. 6x24x500; 5x19x300
Photo-detector	PMT, SiPM, dSiPM, APD	PMT, SiPM
Number of PMTs	256 to 768	384
Detection efficiency	high	low
Detector's acceptance	low	high
Axial length [mm]	157 to 260	500
Used electronics	analog	digital
Signal triggering	triggering	triggerless data acquisition
TOF resolution* [ps]	345 to 550	320
Simultaneous imaging of the whole human body	no	yes
Simultaneous imaging of PET-MRI	yes	yes
Simultaneous imaging of PET-CT	no	yes

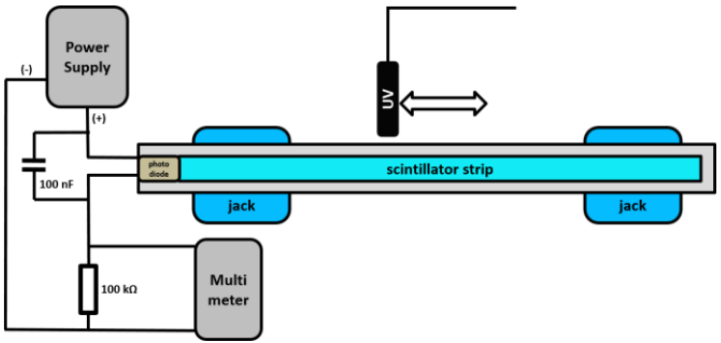
Scintillator	Light output (photons/Mev)	Decay time (ns)	Density (g/cm^3)	Light attenuation length (cm)
LYSO	32000	41	7.1	20.9
BGO	8500	300	7.13	22.8
GSO	7600	30-60	6.71	22.2
$LaBr_3$	65000	15	5.29	16.0
BC-408 (plastic)	11000	2.1	1.023	380



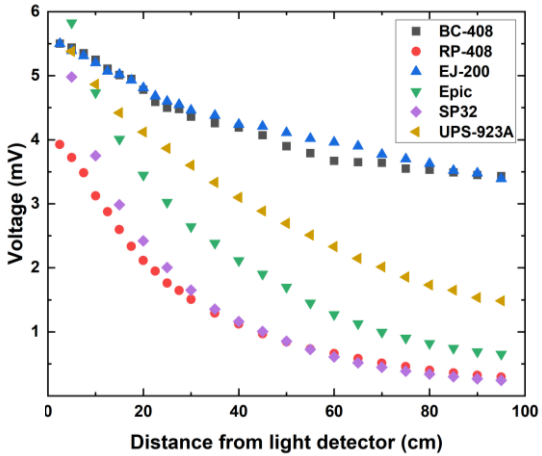
S. Vandenberghe, P. Moskal, J. Karp, State of the art in total body PET, EJNMMI Physics (2020) 7:35

Technical attenuation length of plastic scintillators

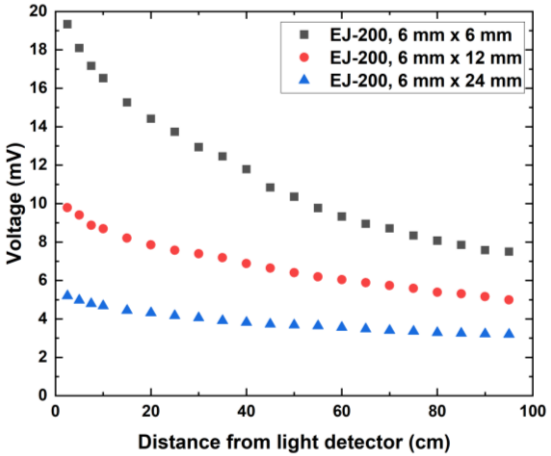




Scintillator types



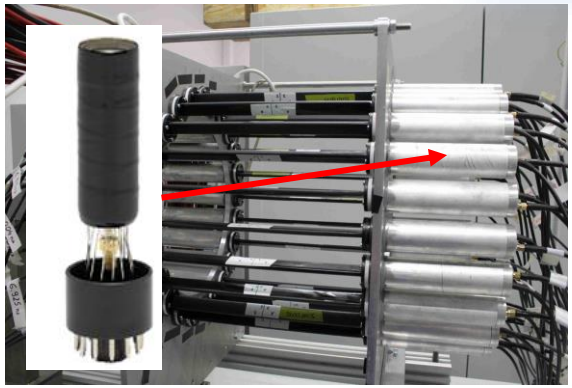
Scintillator cross-sections



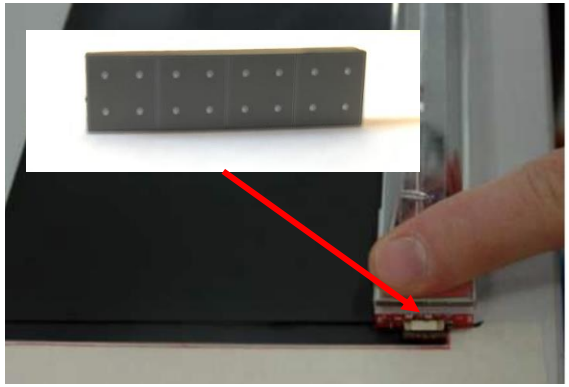
Scintillator	TAL (cm)	Scintillator	TAL (cm)
BC-408	228.4 ± 8.14	SP32	29.0 ± 0.41
EJ-200	194.1 ± 6.26	UPS-923A	68.8 ± 0.61
RP-408	55.8 ± 13.8	Epic	49.4 ± 2.30

Ł. Kapłon, Technical attenuation length measurement of plastic scintillator strips for the total-body J-PET scanner, IEEE Trans. Nucl. Sci. 2020; 67:2286-2289

Light detectors for J-PET



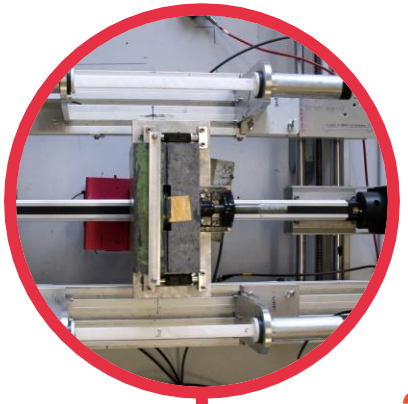
Mini J-PET

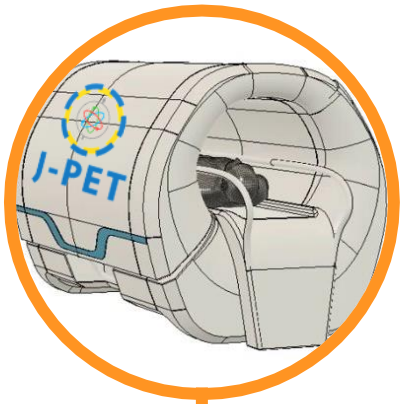


Modular J-PET

Parameter	PMT R4998	SiPM S13361
Effective photosensitive area (mm)	20 diameter	6 x 6
Spectral response range (nm)	300 - 650	320 - 900
Peak sensitivity wavelength (nm)	420	450
Gain	5.0 * 10^6	1.7 * 10^6
Photon detection efficiency (%)	25	40
Supply voltage (V)	2500	60

J-PET scanner prototypes: timeline





2009

2012

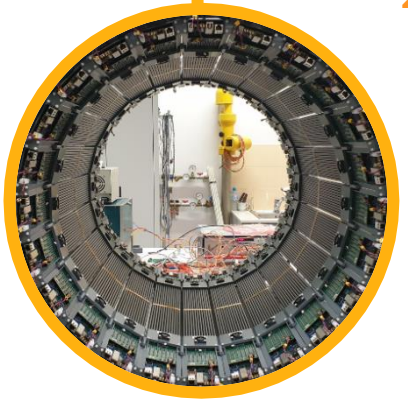
2014

2016

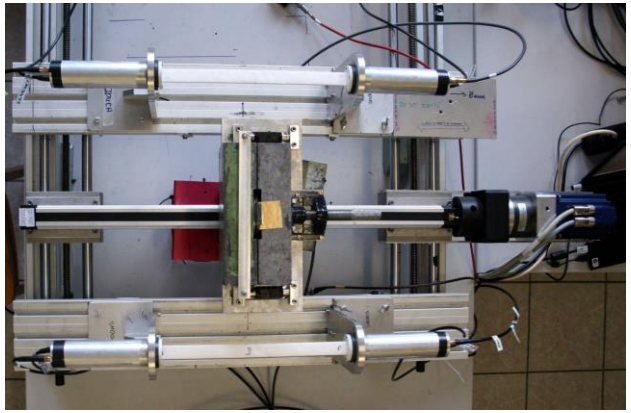
2021

2024

FIRST PATENT

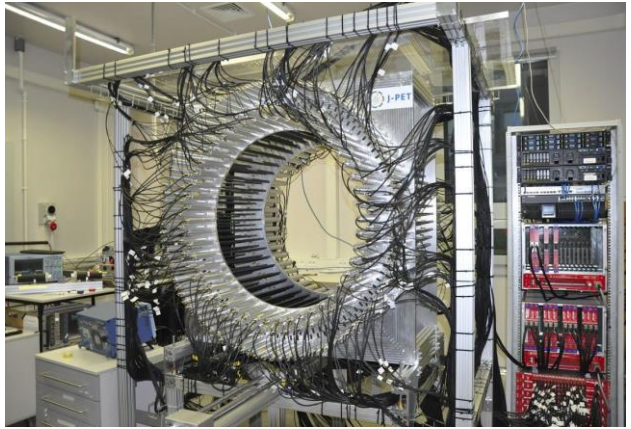


J-PET scanner prototypes: photos

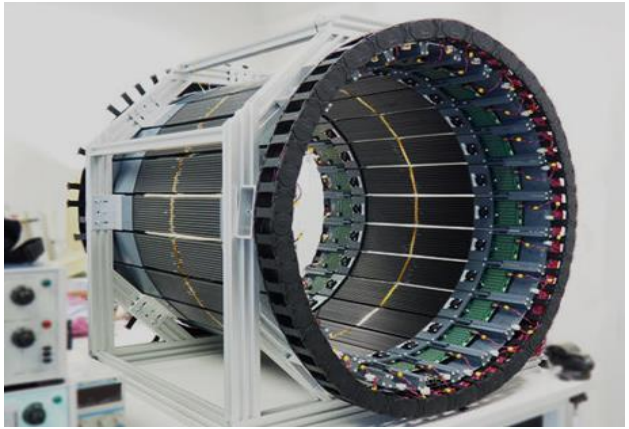


Two detector modules

Mini J-PET

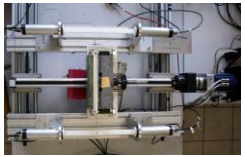


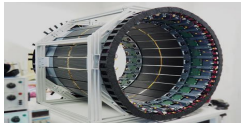
3 layers J-PET

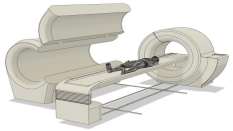


Modular J-PET

J-PET scanner prototypes: properties



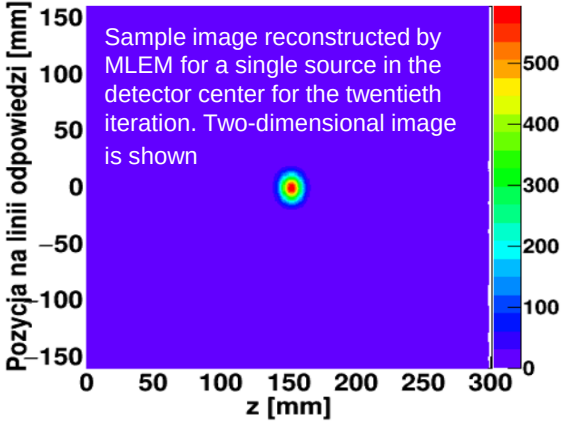




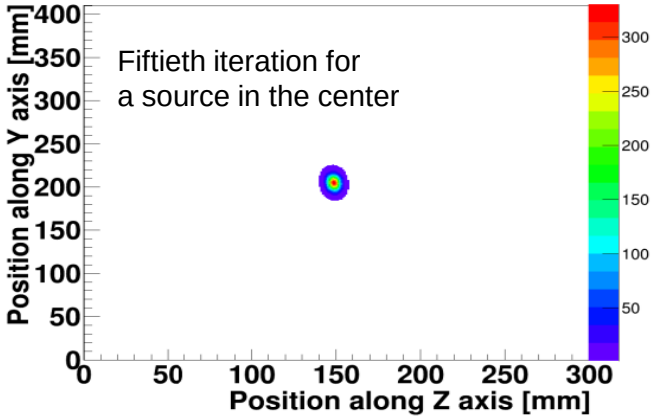
Prototype	Plastic scintillator	Light detector	Spatial resolution (FWHM, mm)	CRT (sigma, ps)
Two detector modules	2 pieces BC-420 5x19x300	4 pieces PMT R5320	6.7 MLEM	280
Mini J-PET	24 pieces BC-420 5x19x300	48 pieces PMT R4998	27 MLEM	490
3 layers J-PET	192 pieces EJ-230 7x19x500	384 pieces PMT R9800	11.4 3D MLEM	220
Modular J-PET	312 pieces BC-404 6x24x500	2496 pieces SiPM S13361-5797	5.4 QETIR	230
Total-Body J-PET	5400 pieces EJ-200 / BC-408 6x30x330	43 000 pieces SiPM S14	4.9 MLEM	240

Spatial resolution

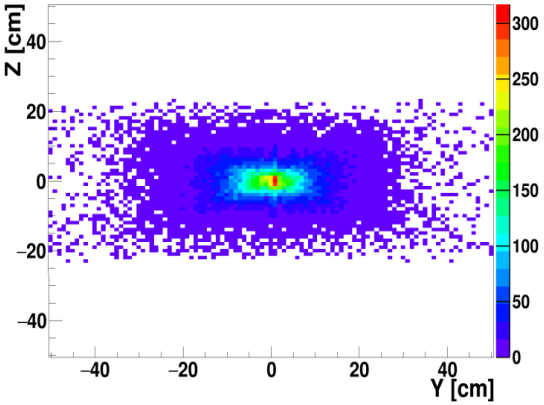
Two module

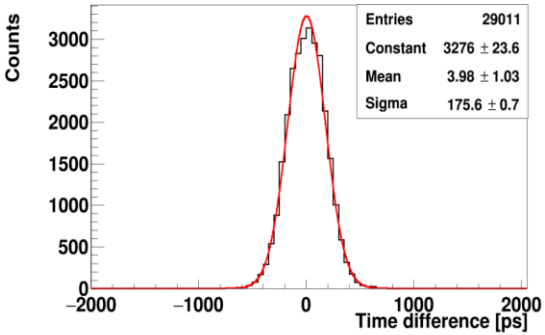


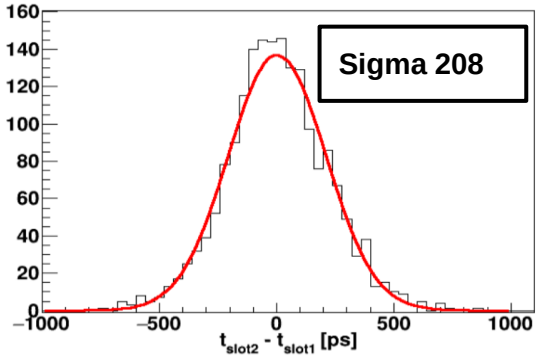
Mini J-PET

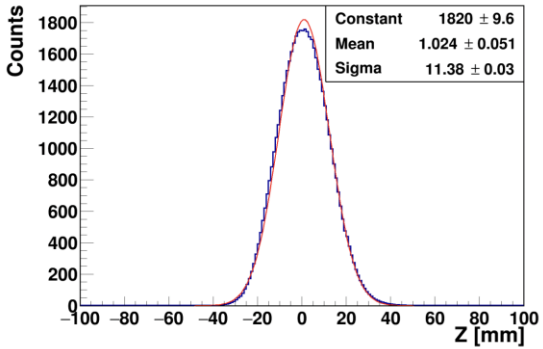


3 layers J-PET

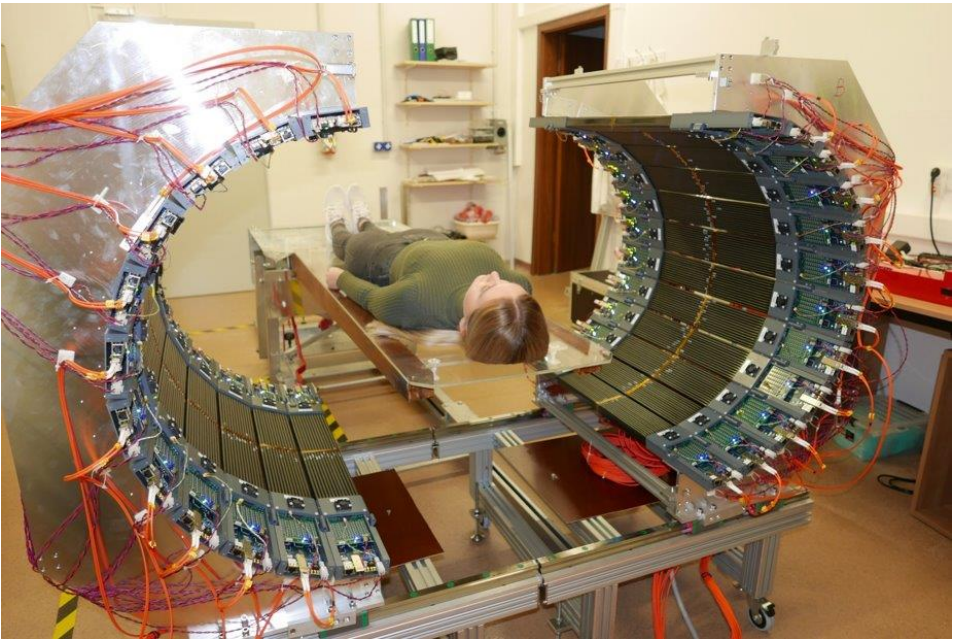


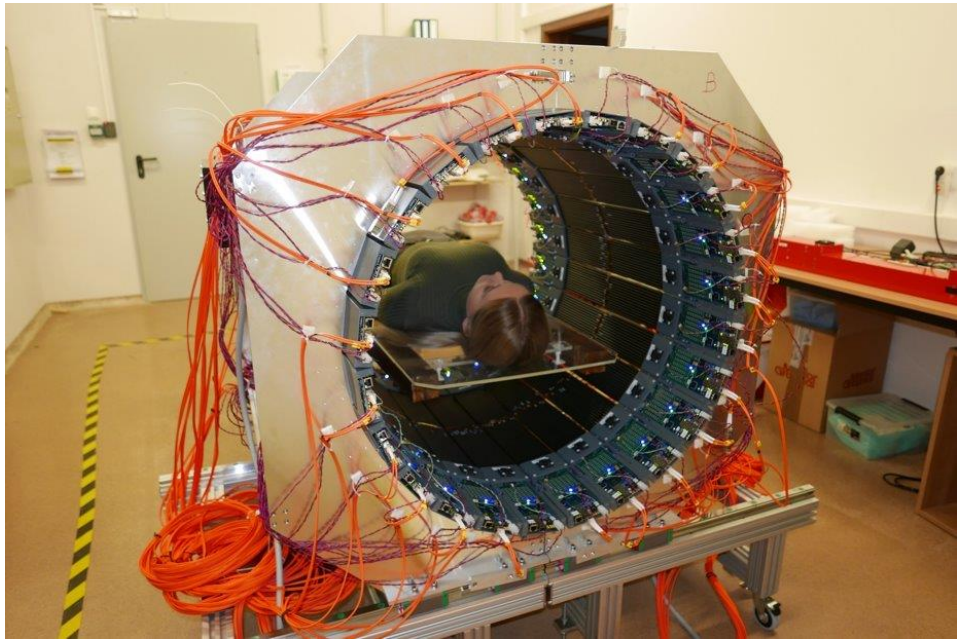






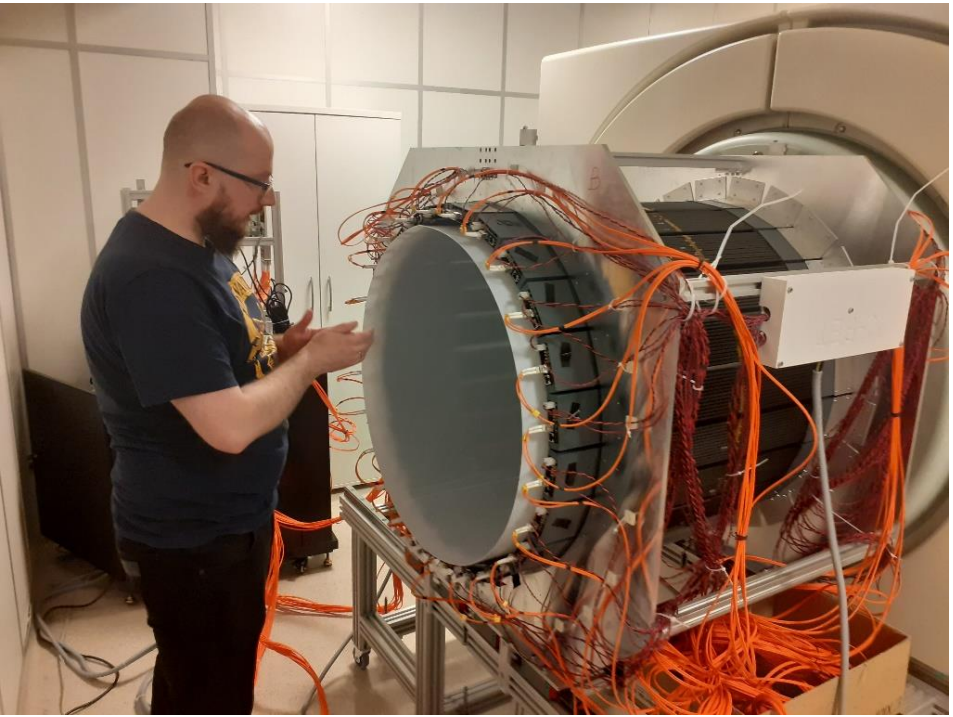
The world's first modular and portable positron emission tomography scanner

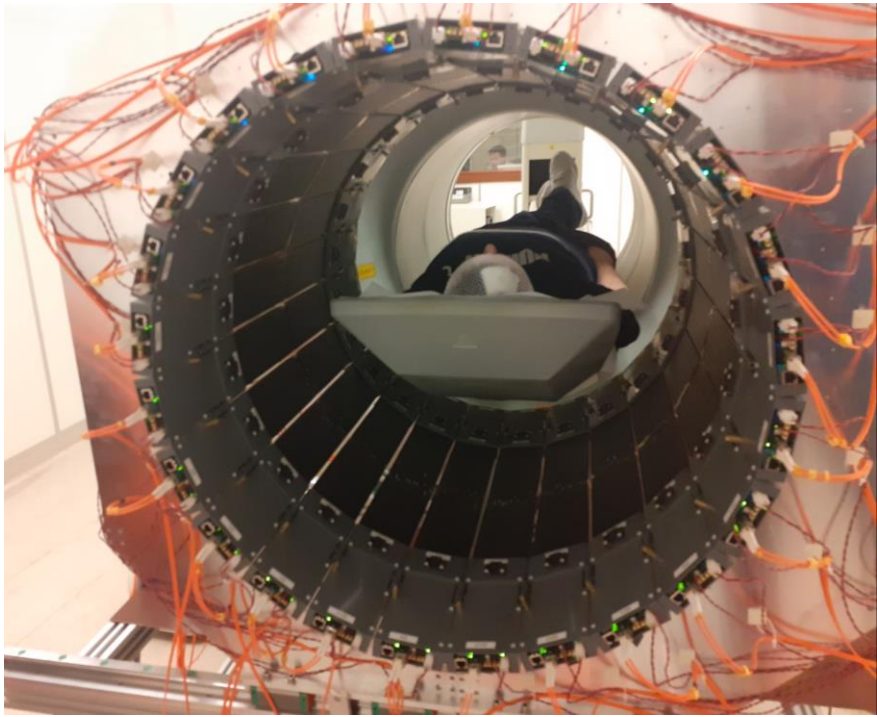




Total-Body Jagiellonian-PET Laboratory, Krakow

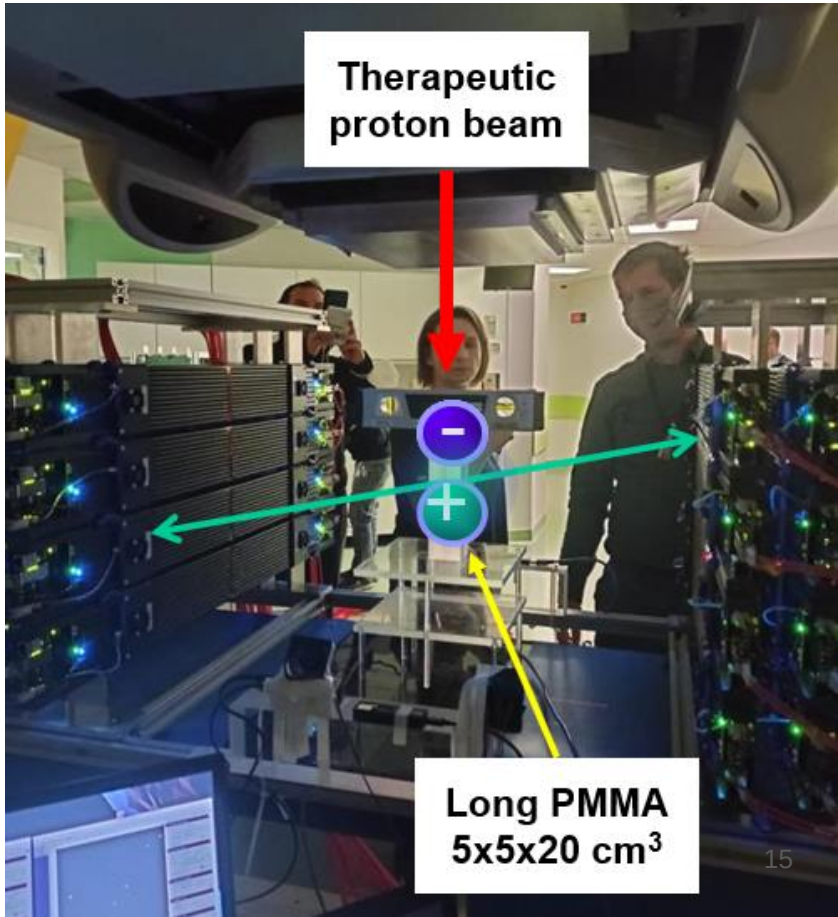
The world's first modular and portable positron emission tomography scanner





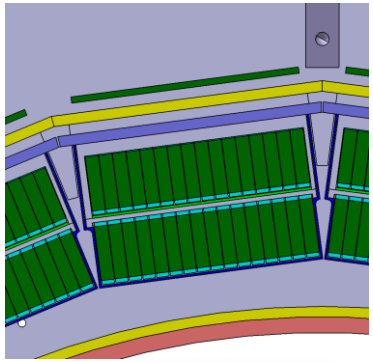
First imaging of patients with modular J-PET in Medical University of Warsaw

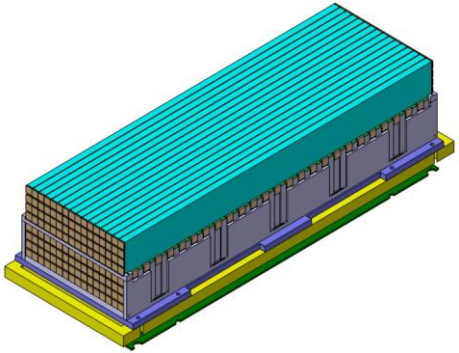
The world's first modular and portable positron emission tomography scanner

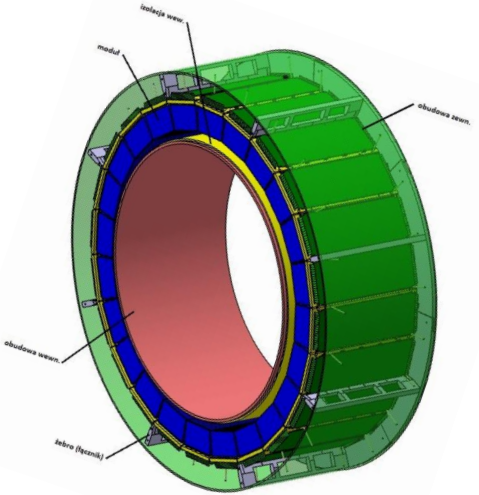


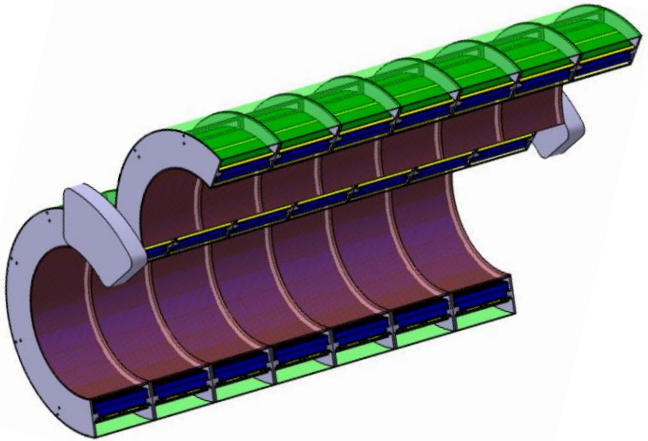
Imaging of PMMA fantoms irradiated with proton beam in Institute of Nuclear Physics Polish Academy of Sciences

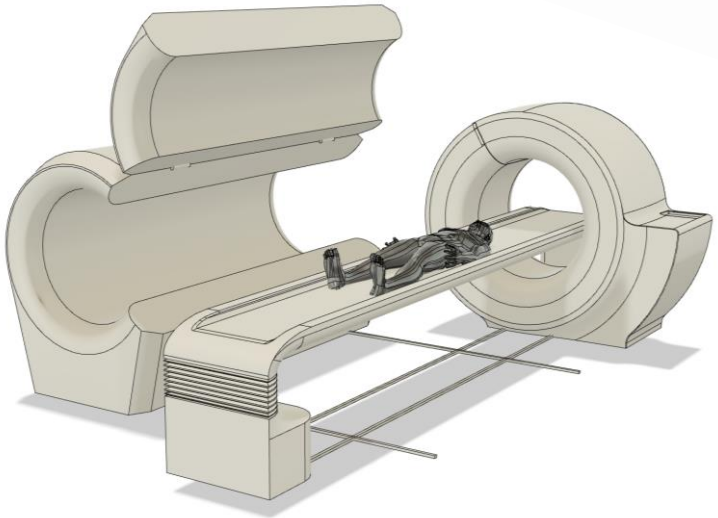
Total-body J-PET: design



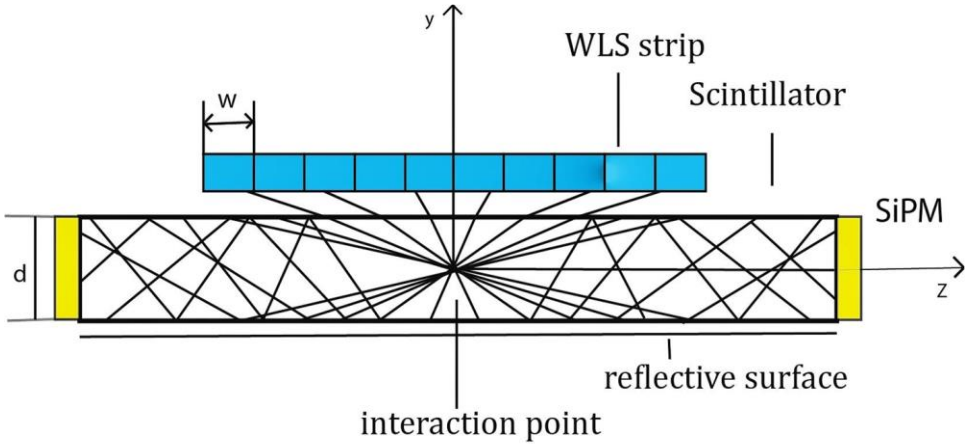


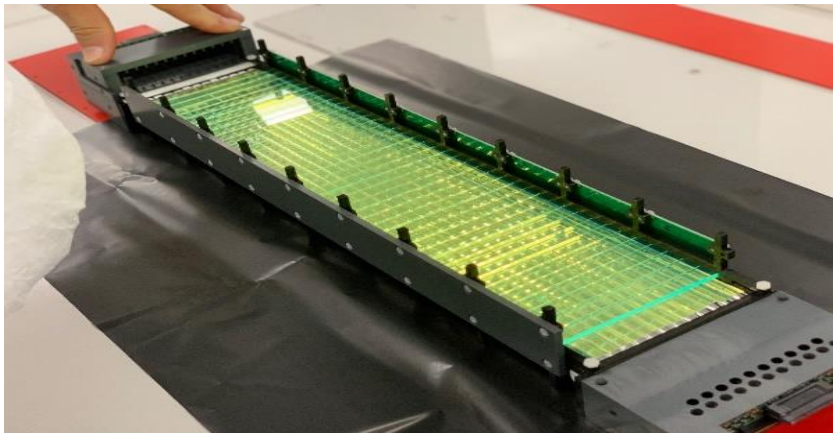


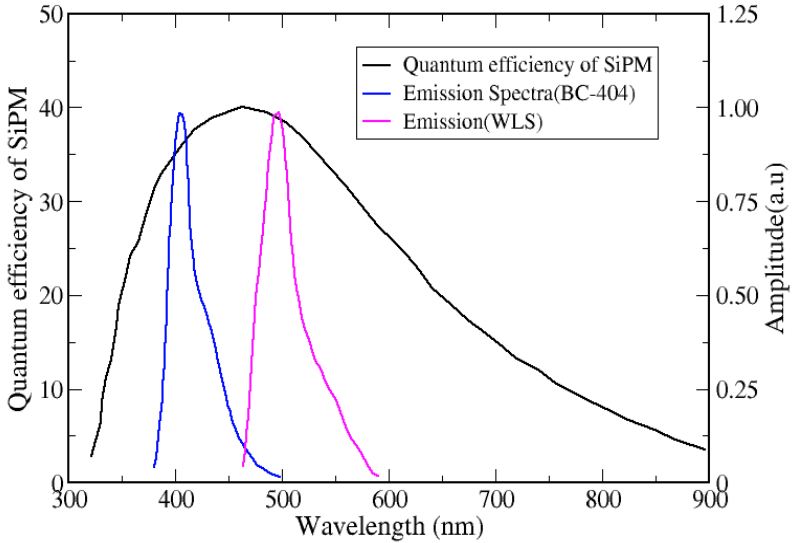




Total-body J-PET: plastic scintillators + wavelength shifters

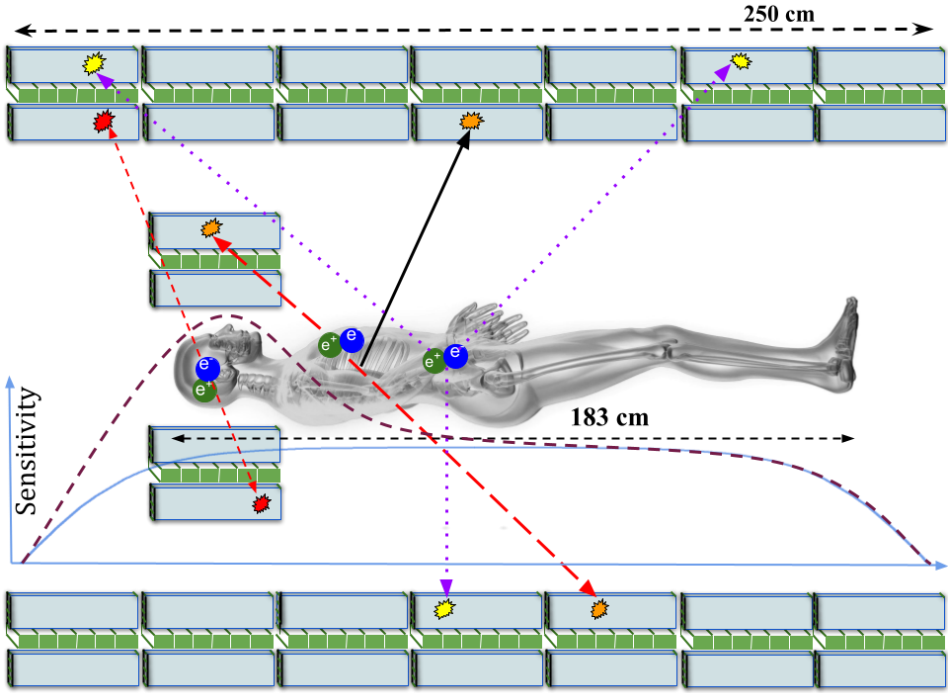


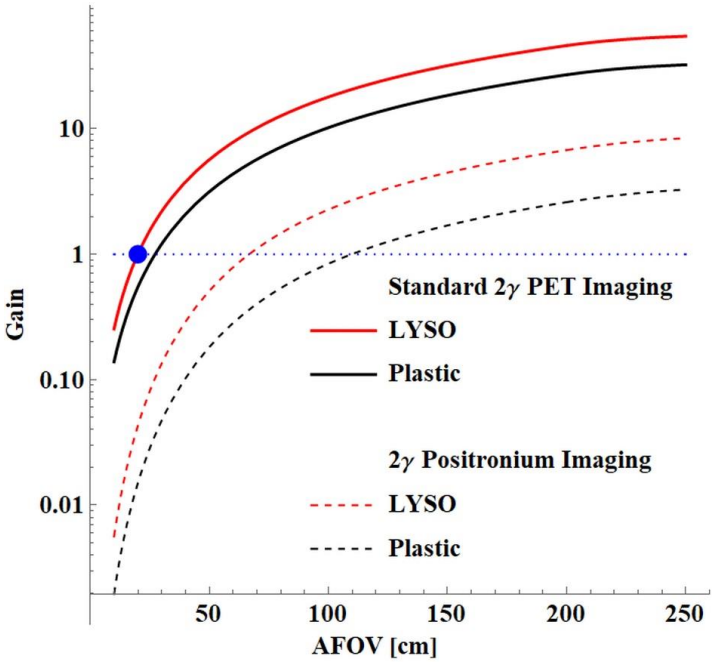




J. Smyrski et al., Measurement of gamma quantum interaction point in plastic scintillator with WLS strips, Nucl Instr and Meth in Phys Res A 851 (2017) 39–42

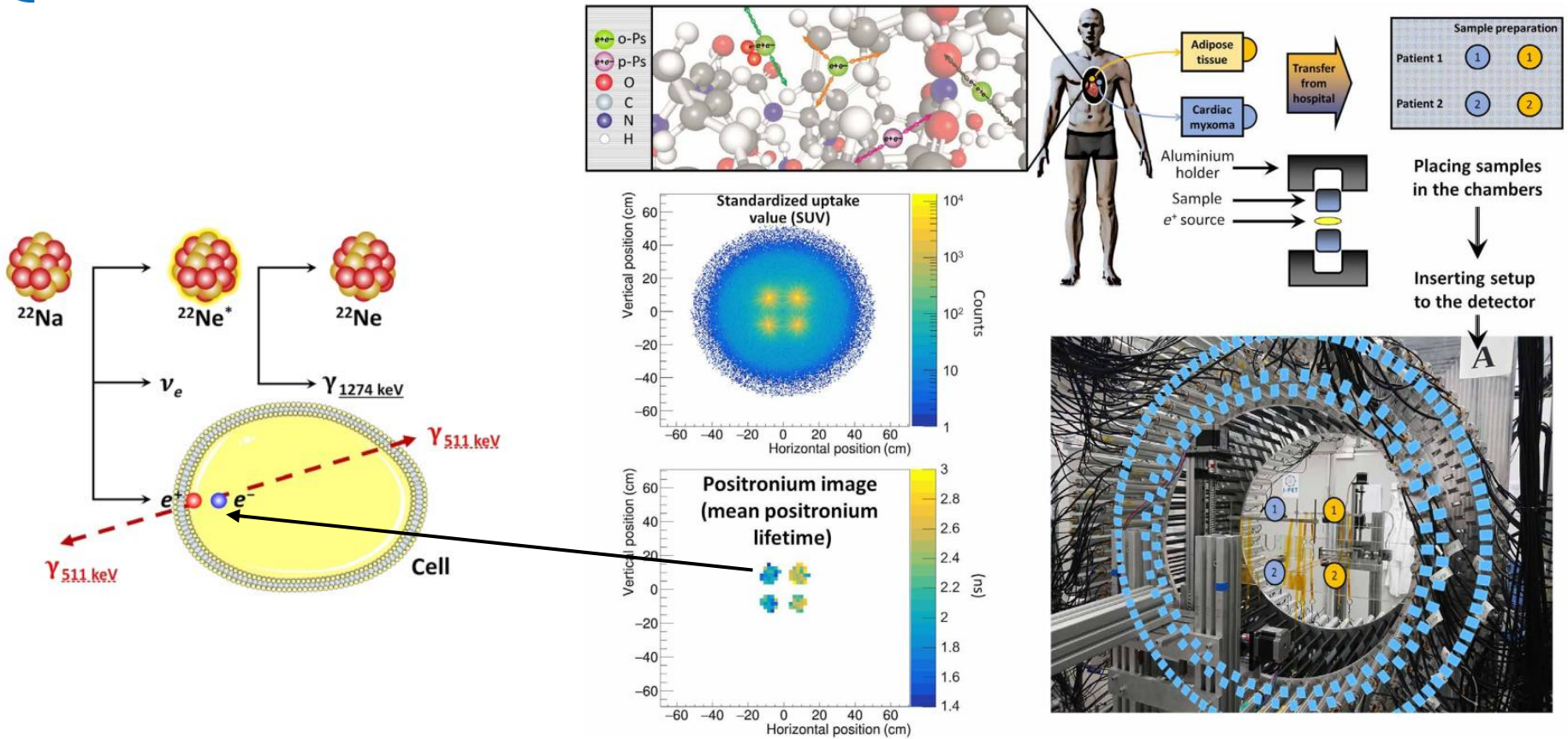
Total-body J-PET: sensitivity gain





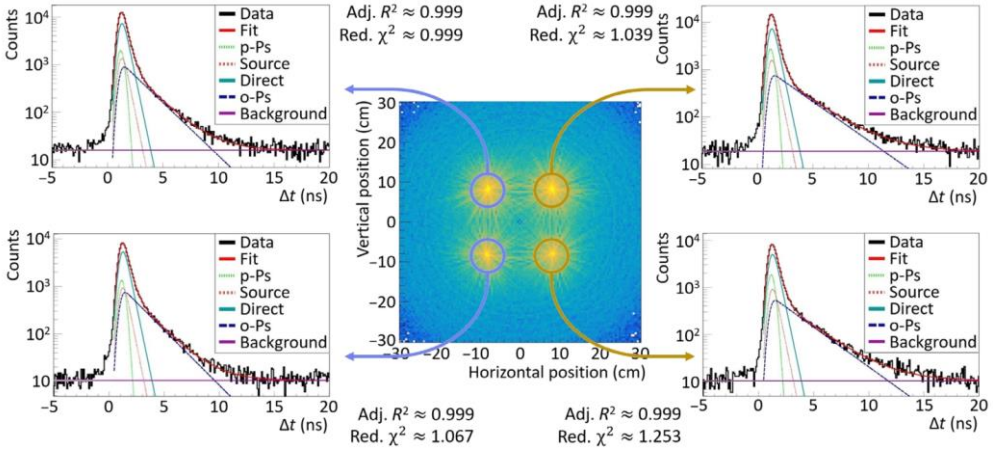
P. Moskal, E. Stępień, Prospects and clinical perspectives of total-body PET imaging using plastic scintillators, PET Clinics 15 (2020) 439

Total-body J-PET: in-vitro positronium imaging



P. Moskal et al., Positronium imaging with the novel multiphoton PET scanner, Science Advances 7 (2021) eabh4394

Total-body J-PET: in-vitro positronium imaging



$$\mathrm{Fit}(\Delta t) = \sum_{i=1}^{4} I_i \left(\exp\left(-\frac{\Delta t}{\tau_i}\right) * \mathrm{Gaussian}\,(\Delta t, t_0, \sigma) \right) + \mathrm{Background}$$

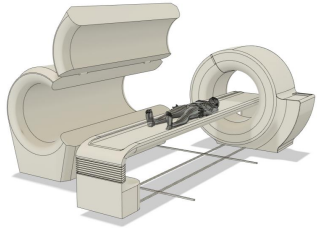
I_i – Intensity of ith component,
τ_i – Mean lifetime of ith component

$$\sum_{i=1}^{4} I_i = 100\%$$

Parameter name	Cardiac myxoma 1	Cardiac myxoma 2	Adipose tissue 1	Adipose tissue 2
Parapositronium mean lifetime (ns)		0.125 (fixed)		
Parapositronium intensity (%)	13.26 (18)	12.21 (21)	17.18 (16)	17.14 (20)
Direct annihilation mean lifetime (ns)		0.388 (fixed)		
Direct annihilation intensity (%)	65.35 (22)	64.52 (27)	61.34 (20)	61.31 (23)
o-Ps mean lifetime (ns)	1.950 (19)	1.874 (20)	2.645 (27)	2.581 (30)
o-Ps intensity (%)	21.39 (47)	23.27 (45)	21.49 (41)	21.56 (54)
Adjusted R^2	0.999	0.999	0.999	0.999
Reduced χ^2	0.999	1.067	1.039	1.253

P. Moskal et al., Positronium imaging with the novel multiphoton PET scanner, Science Advances 7 (2021) eabh4394

Summary



We are developing the Jagiellonian Positron Emission Tomography scanner based on plastic scintillators:

- **is modular and transportable,**
- **have field of view 500 mm (modular version) and will have 2000 mm (total-body PET),**
- **is cost-effective in comparison with other total-body PET scanners,**
- **can image positronium and multi-photon isotopes labeled with biomolecules.**

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