J-PET

modułowy detektor szerokiego zastosowania,

czyli jak w Polsce łączyć badania podstawowe i stosowane

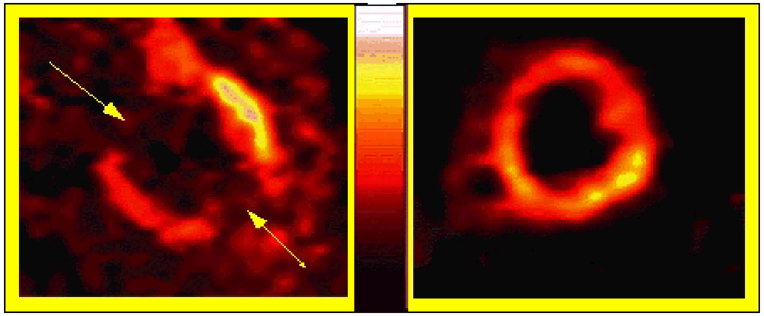
Eryk Czerwiński w imieniu grupy J-PET

11 V 2017
Wydział Fizyki
Uniwersytet Warszawski

Plan

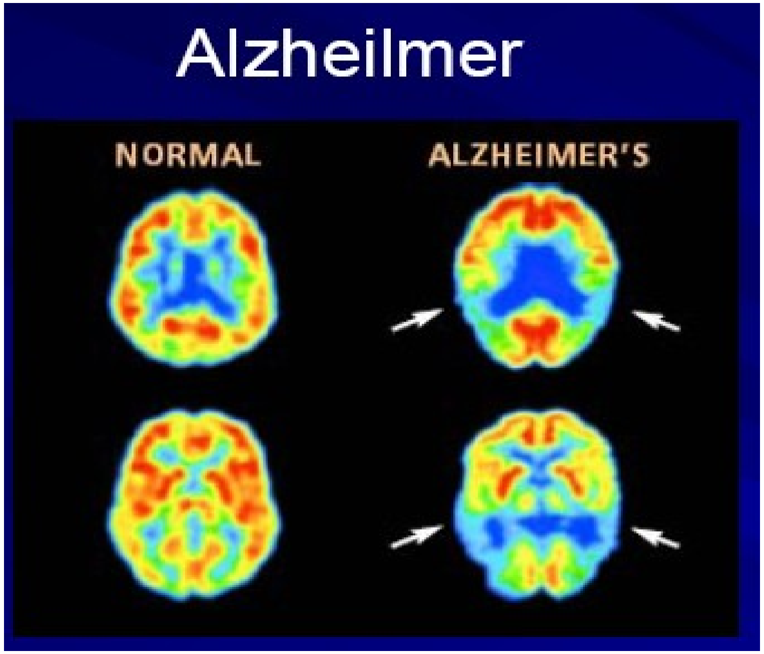
1. *Klasyczny* TOF-PET
2. Nowy pomysł
3. Realizacja
4. Wyniki

Obrazowanie PET



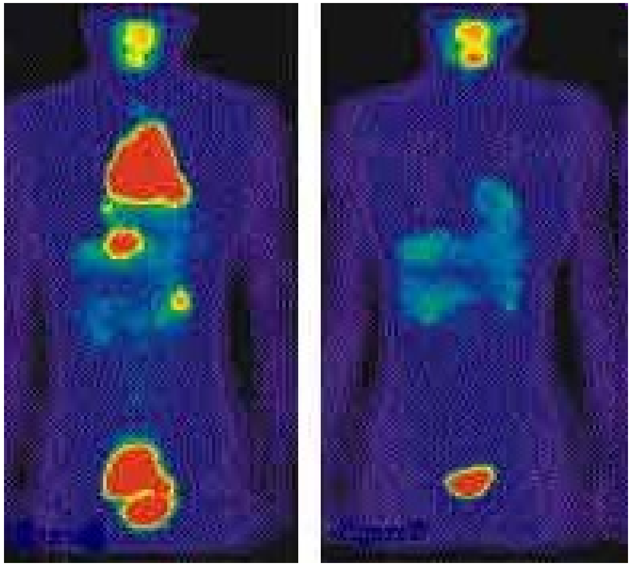
Serce po zawale

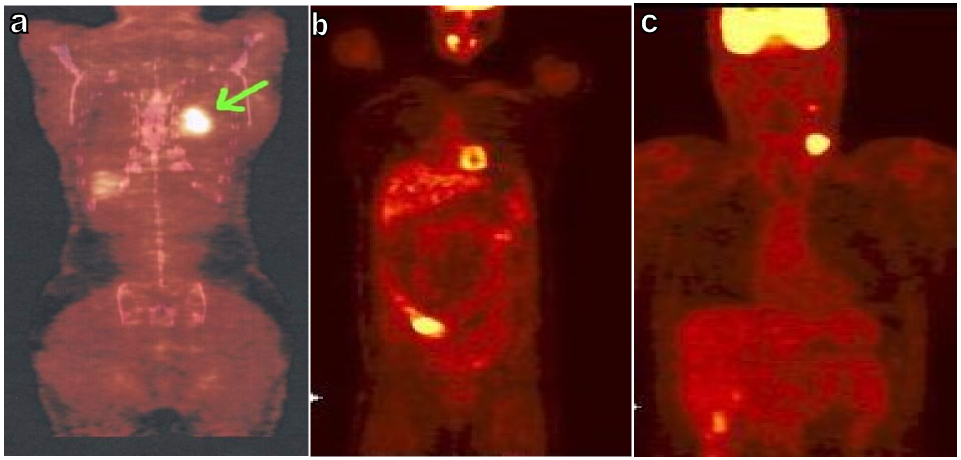
Serce zdrowego człowieka



Nowotwór przed (po lewej) i

- ***po terapii (po prawej)***





Nowotwór a) płuca b) jelita grubego c) szyi

www.radiologyregional.com/imagesfolder/Photos...

www.londonpetcentre.com/images/heart.gif

Procedura PET

Increased glycolysis in tumor cells
-Warburg phenomenon-
20-30 time higher glucose metabolism

Due to the structure differences between glucose and FDG, FDG is trapped In malignant cells.

RADIOACTIVE SUGER

Fluoro–deoxy-glucose
(F-18 FDG)

$$^{18}F \rightarrow {}^{18}O + e^{+} + \nu_e$$

$$e^{+} + e^{-} \rightarrow \gamma\,\gamma$$

Przygotować radiofarmaceutyk

-- wytworzyć odpowiedni izotop promieniotwórczy (fizyk)

-- dokonać syntezy farmaceutyku wykorzystując przygotowany izotop promieniotwórczy (chemik)

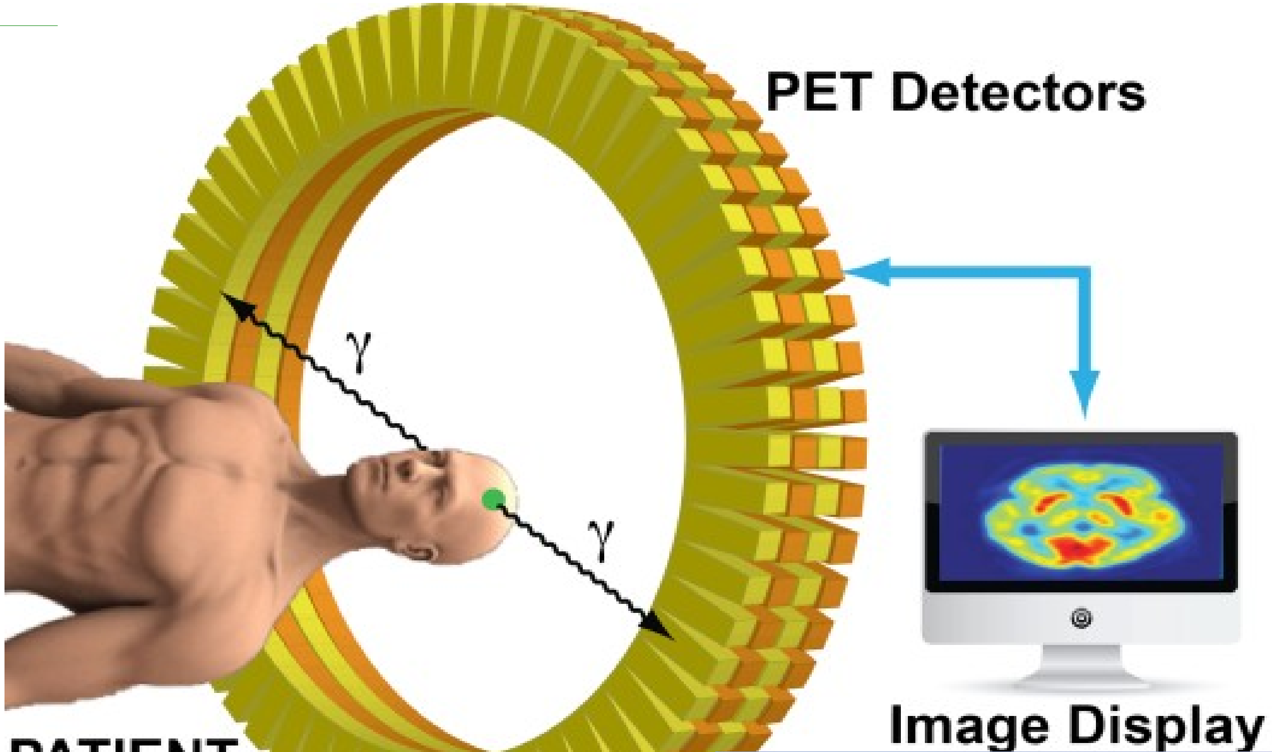
Podać radiofarmaceutyk pacjentowi (lekarz)

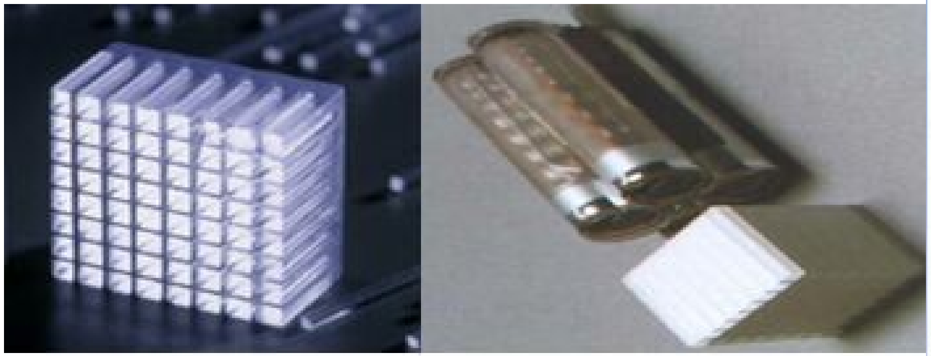
Wykonać pomiar rozkładu promieniowania anihilacyjnego wokół pacjenta (fizyk)

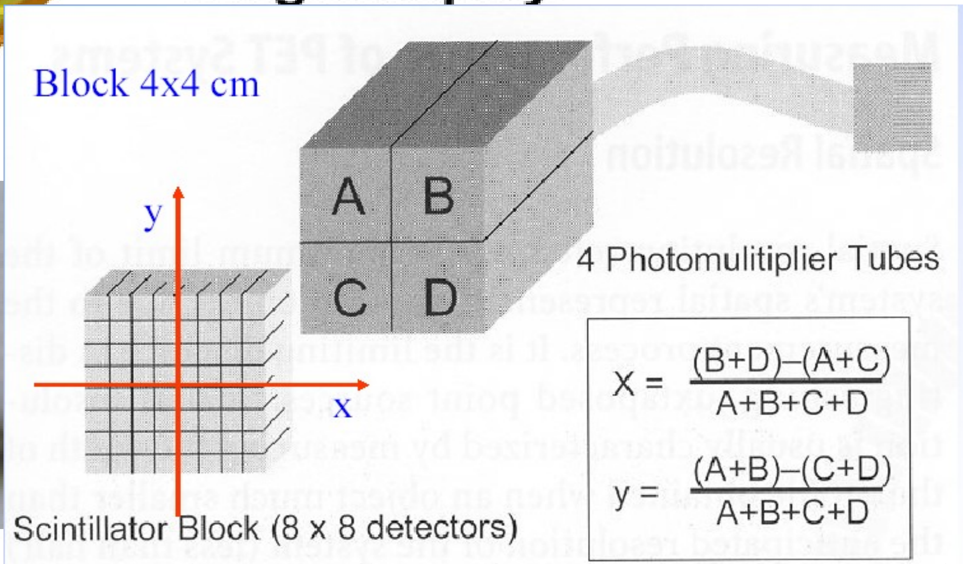
Zrekonstruować rozkład gęstości farmaceutyku w pacjencie (matematyk)

Zinterpretować otrzymany obraz (lekarz)

Zasada działania





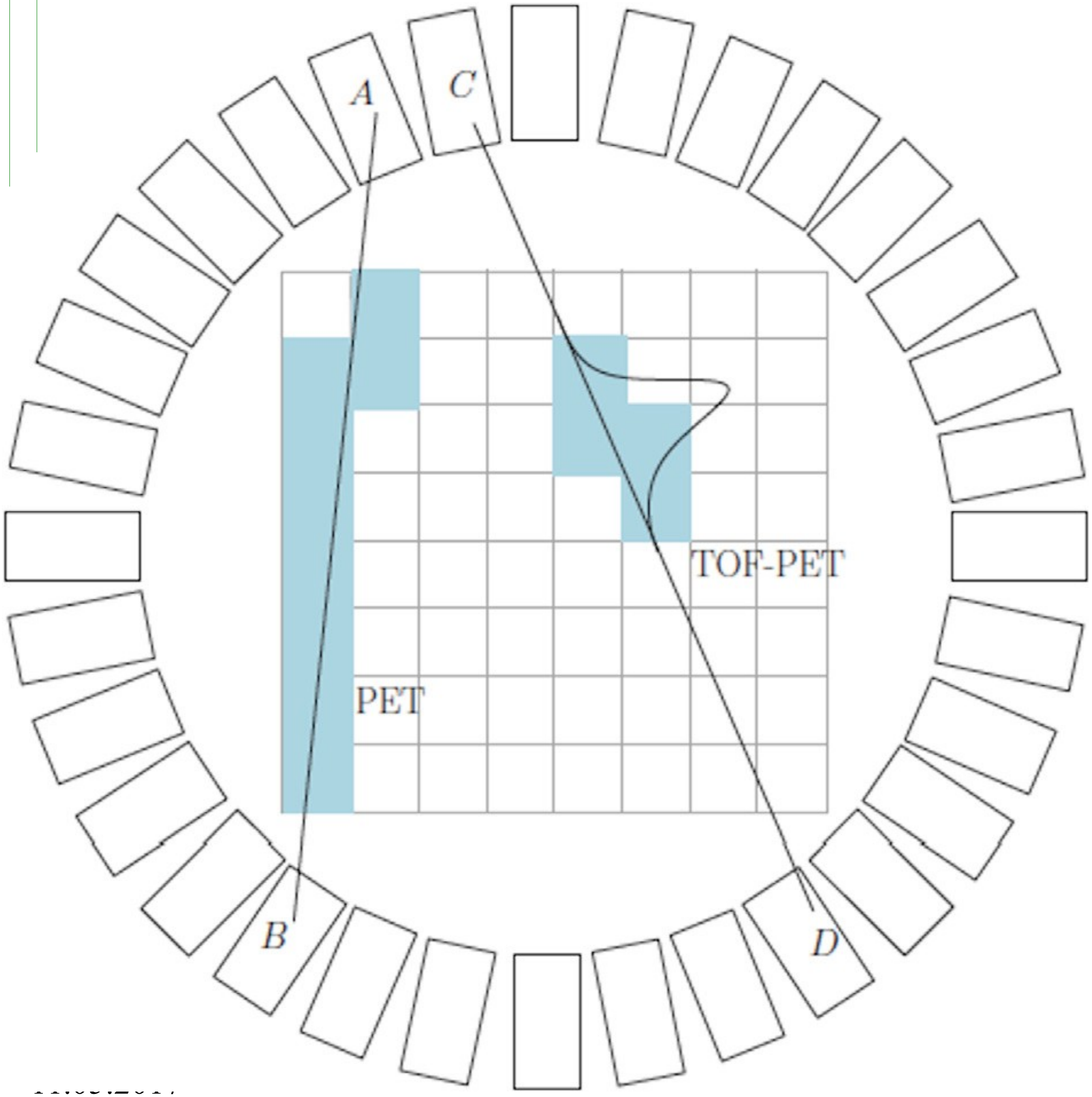


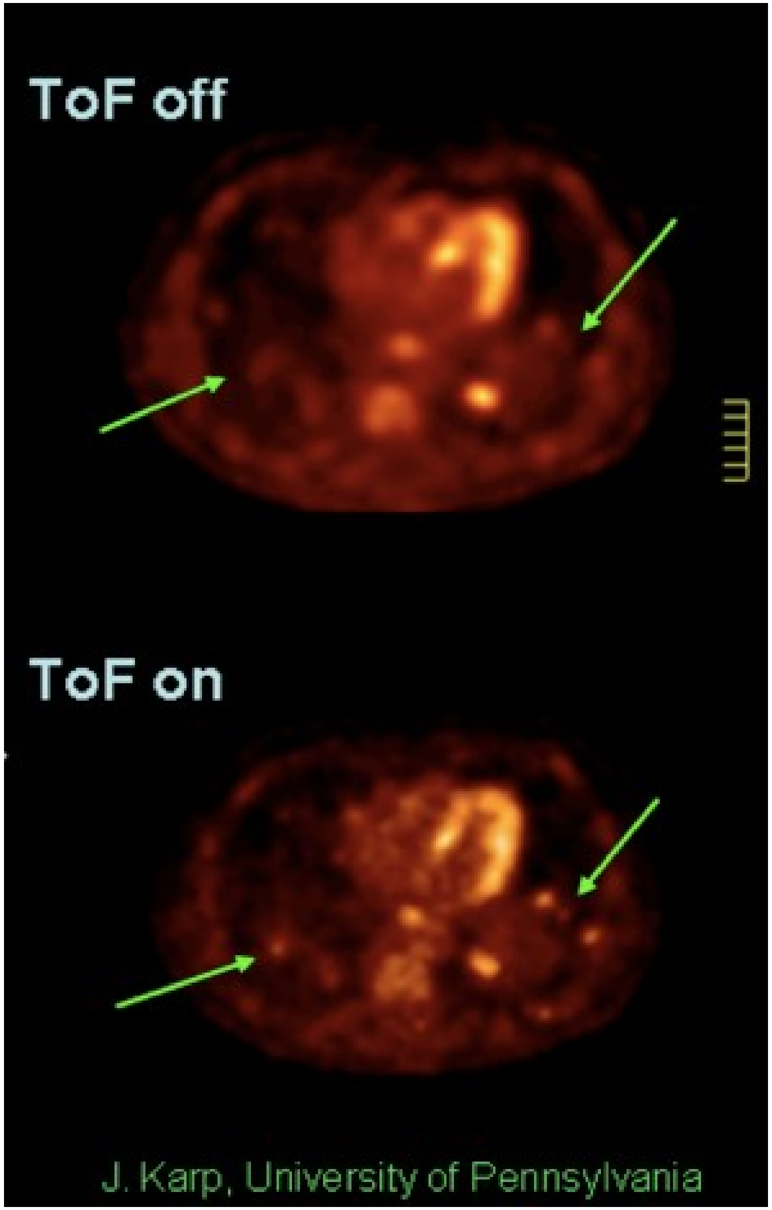
$$X = \frac{(B+D)-(A+C)}{A+B+C+D}$$

$$y = \frac{(A+B)-(C+D)}{A+B+C+D}$$

www.fuw.edu.pl/festiwal/2005/Szeflinski/PET-05.pdf

TOF-PET

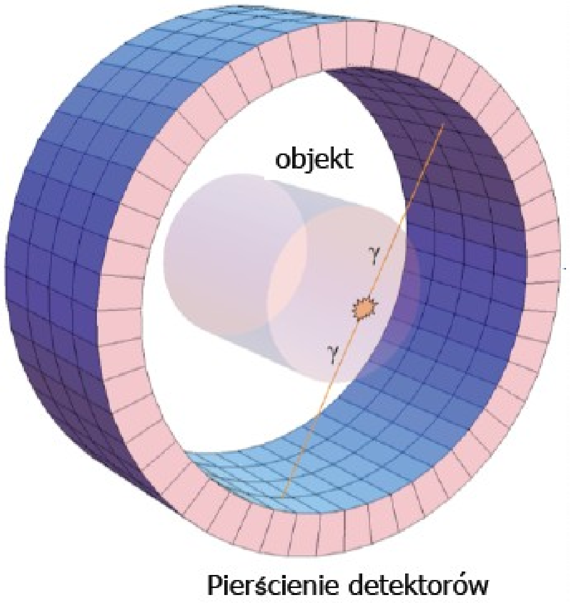


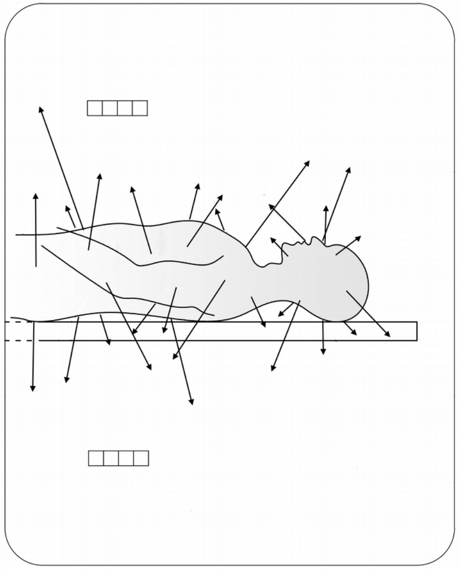


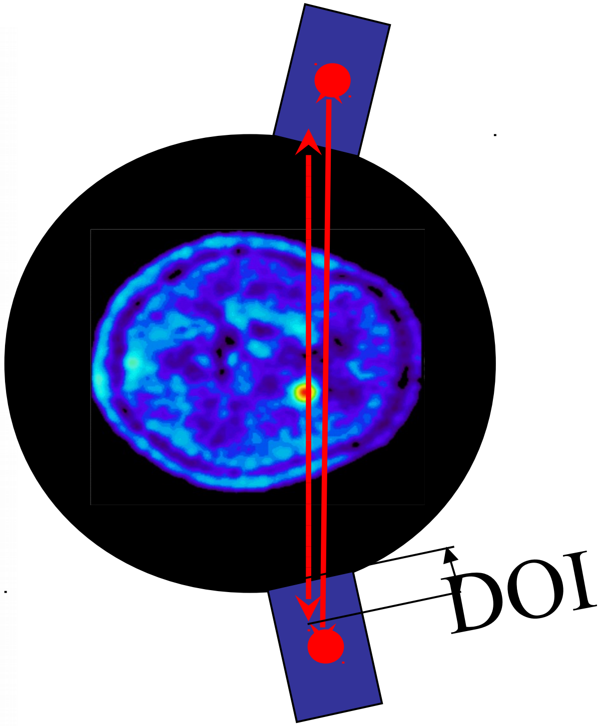
J. Karp, University of Pennsylvania

P. J. Slomka et al., Semin. Nucl. Med. 46 (2016) 5-19

Problemy







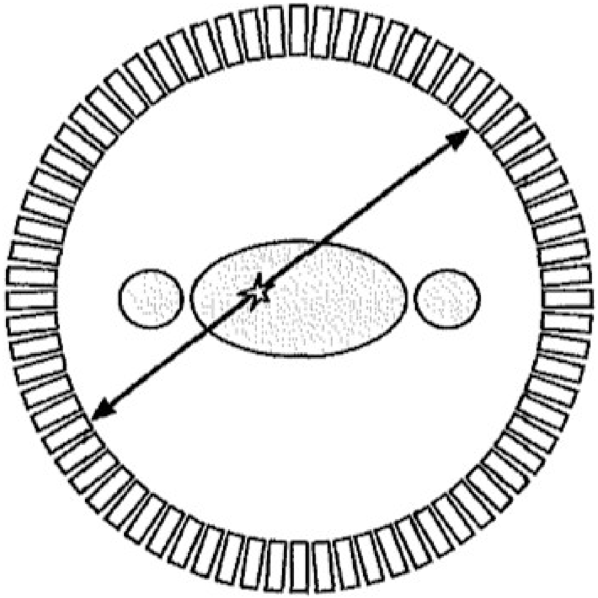
(Depth of Interaction)

- koszt ~15mln zł
- szerokość 18cm

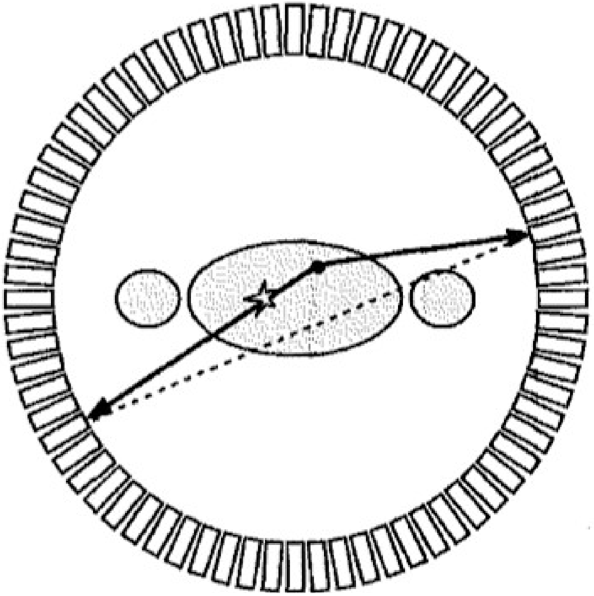
  → 18 pomiarów na całe ciało w krokach po 9 cm

Kryształy vs plastik

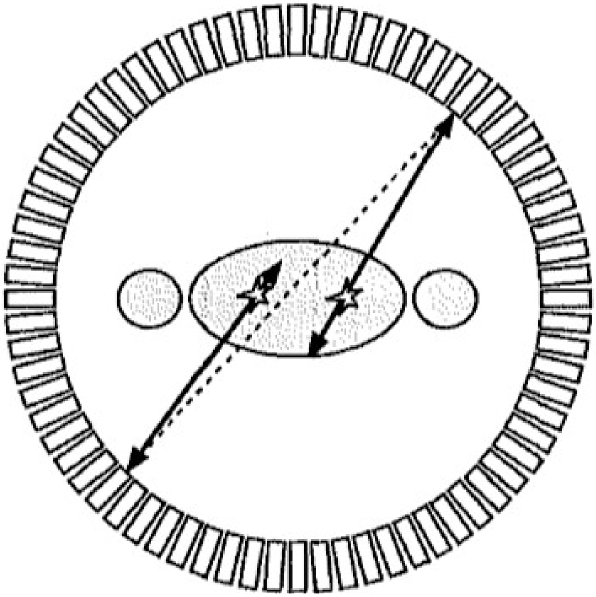
dobre zdarzenie



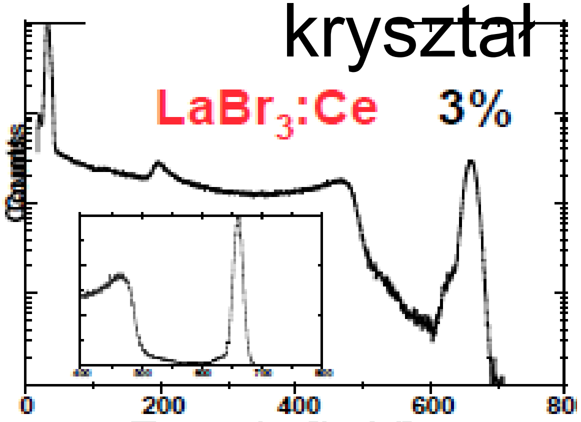
rozproszenie



zdarzenie przypadkowe

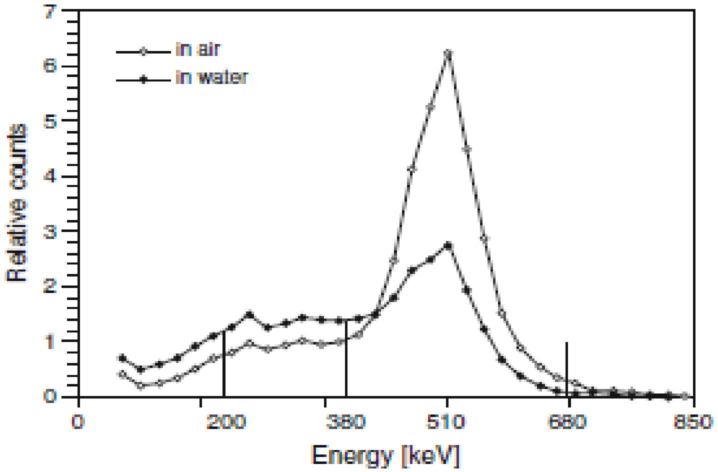


kryształ



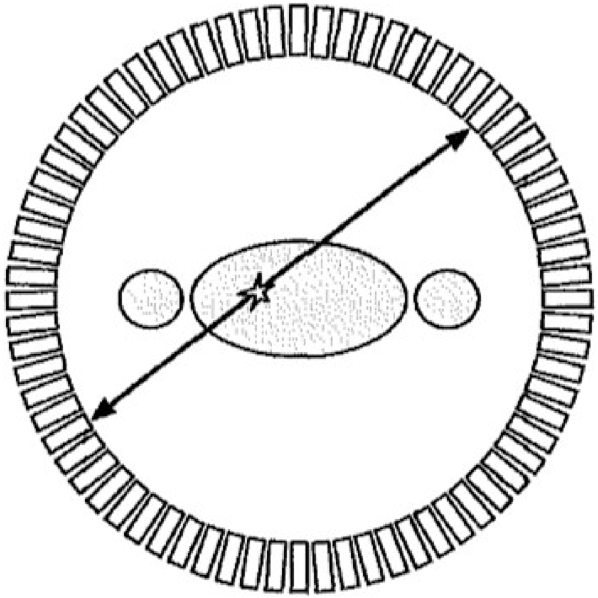
Względna intensywność

Energia [keV]

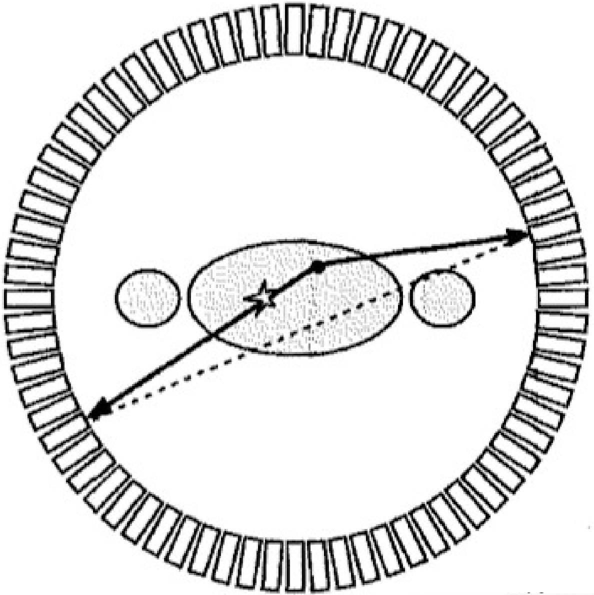


Kryształy vs plastik

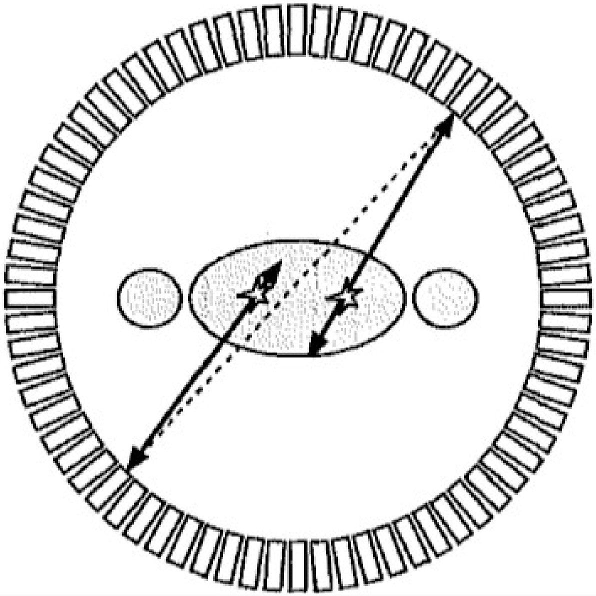
dobre zdarzenie

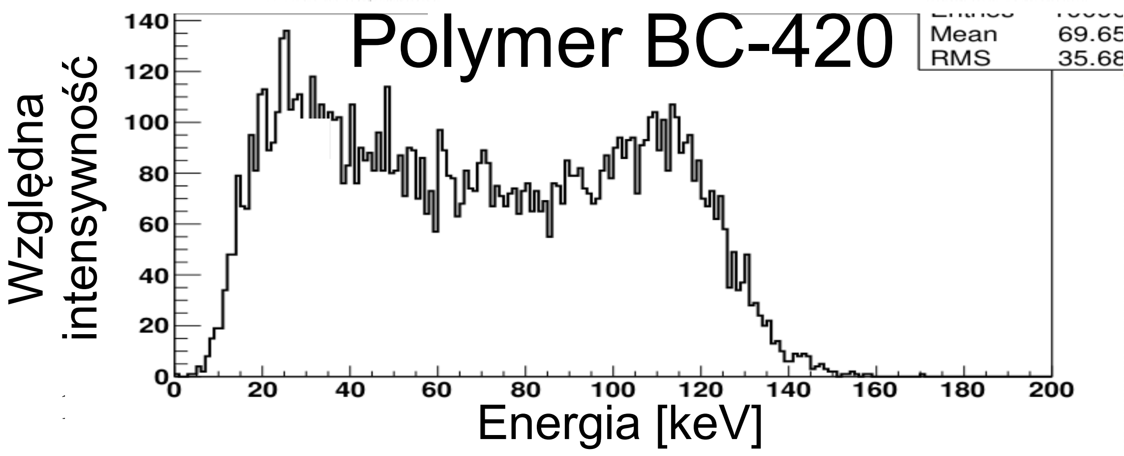


rozproszenie

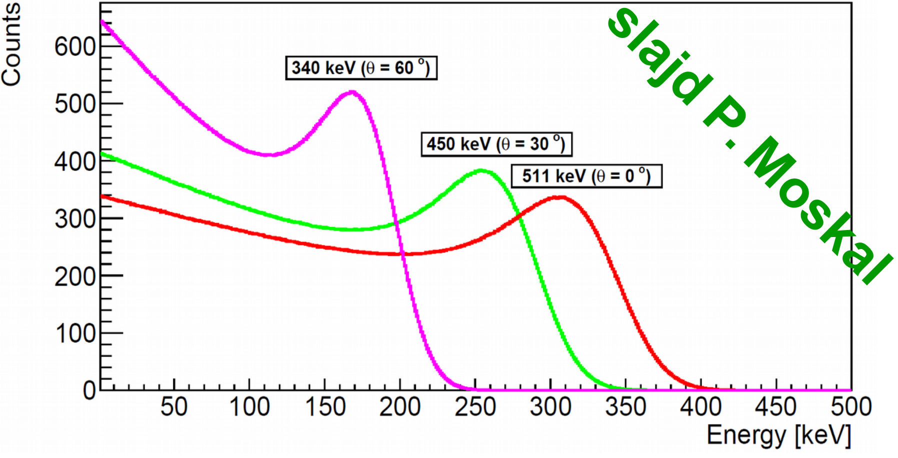


zdarzenie przypadkowe





Polymer BC-420



slajd P. Moskal

Kryształy vs plastik

|- - - kryształy - - - -|= = = = plastik = = = = |

Typ: LSO / LYSO / BGO / scyntylator polimerowy
Cena za cm^3: 86 / 86 / 35 / 1

PHILIPS → LYSO
SIMENS → LSO
GE Healthcare → BGO

Scyntylatory polimerowe mogą być łatwo produkowane w dużych rozmiarach i w różnych kształtach.

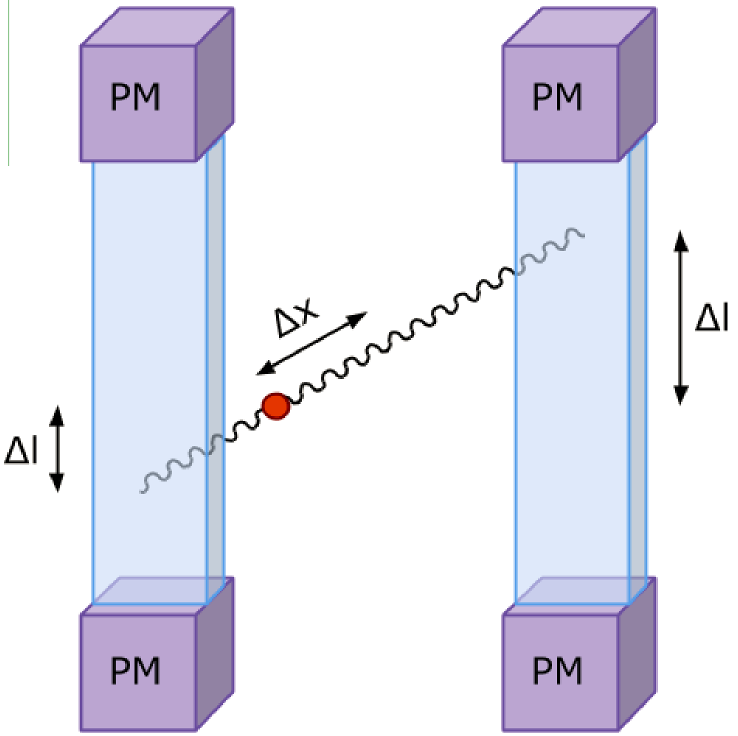
Kryształy vs plastik

Dla warstwy 2.5 cm wydajność na rejestrację zdarzeń użytych do rekonstrukcji obrazu dla scyntylatora polimerowego jest około 20 razy mniejsza niż w przypadku kryształów BGO oraz około 40 razy mniejsza w stosunku do kryształów LSO.

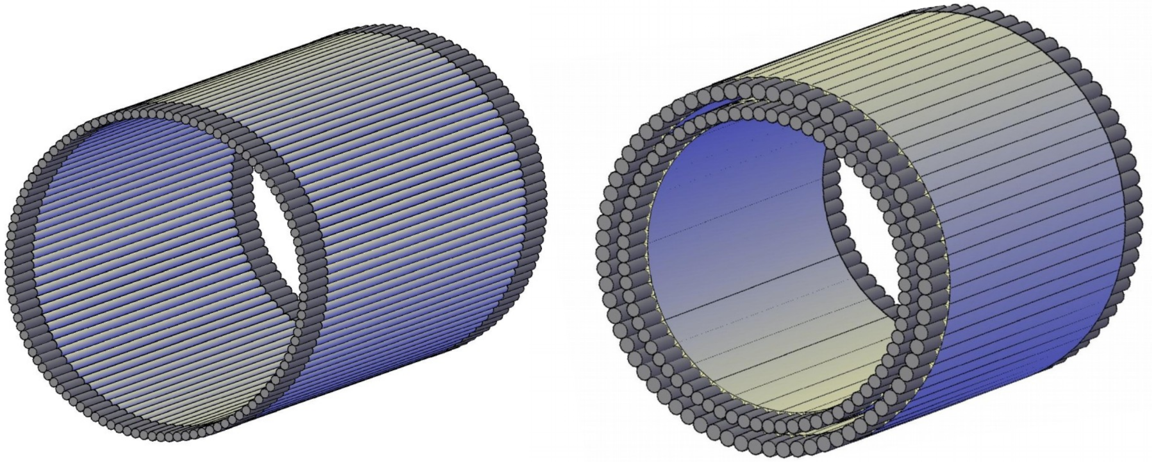
Sygnały świetlne ze scyntylatorów polimerowych są znacznie szybsze.

name	type	density [g/cm3]	decay time [ns]	photons/ MeV	mean free path [cm]
BGO	crystal	7.13	300	6000	1.04
GSO	crystal	6.71	50	10000	1.49
LSO	crystal	7.40	40	29000	1.15
NE102A	polymer	1.032	2.4	10000	10.2
BC404	polymer	1.032	1.8	10000	10.2
RP422	polymer	1.032	1.6	10000	10.2

J-PET (Jagiellonian PET)



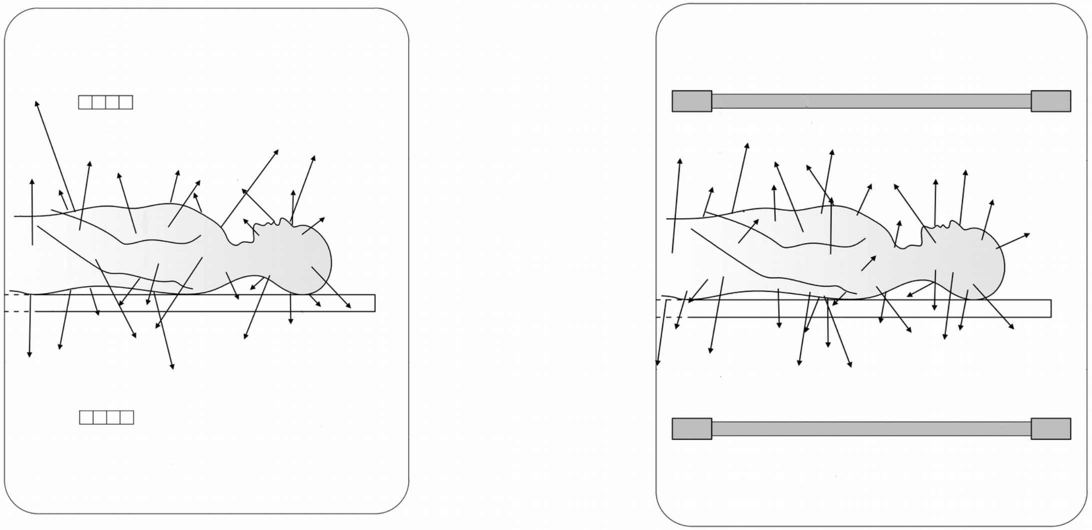
$$\Delta x = (t_l - t_r)\, c / 2$$
$$\Delta l = (t_2 - t_1)\, v / 2$$



P. Moskal, Strip device and the method for the determination of the place and response time of the gamma quanta and the application of the device for the Positron Emission Thomography P 388 555 [WIPO ST 10/C PL388555] (2009), PCT/PL2010/00062 (2010), WO2011008119, US2012112079, JP2012533734, EP2454612.

P. Moskal et al., Nucl. Inst. and Meth. A 764 (2014) 317-321
P. Moskal et al., Nucl. Inst. and Meth. A 775 (2015) 54-62
P. Moskal et al., Phys. Med. Biol. 61 (2016) 2025-2047

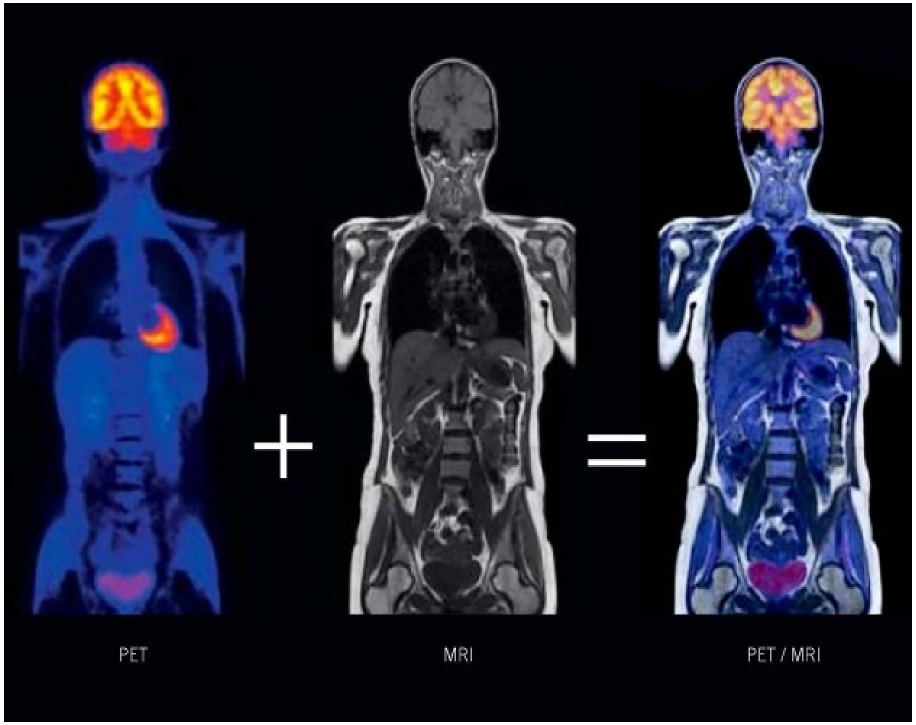
Standardowy PET a J-PET

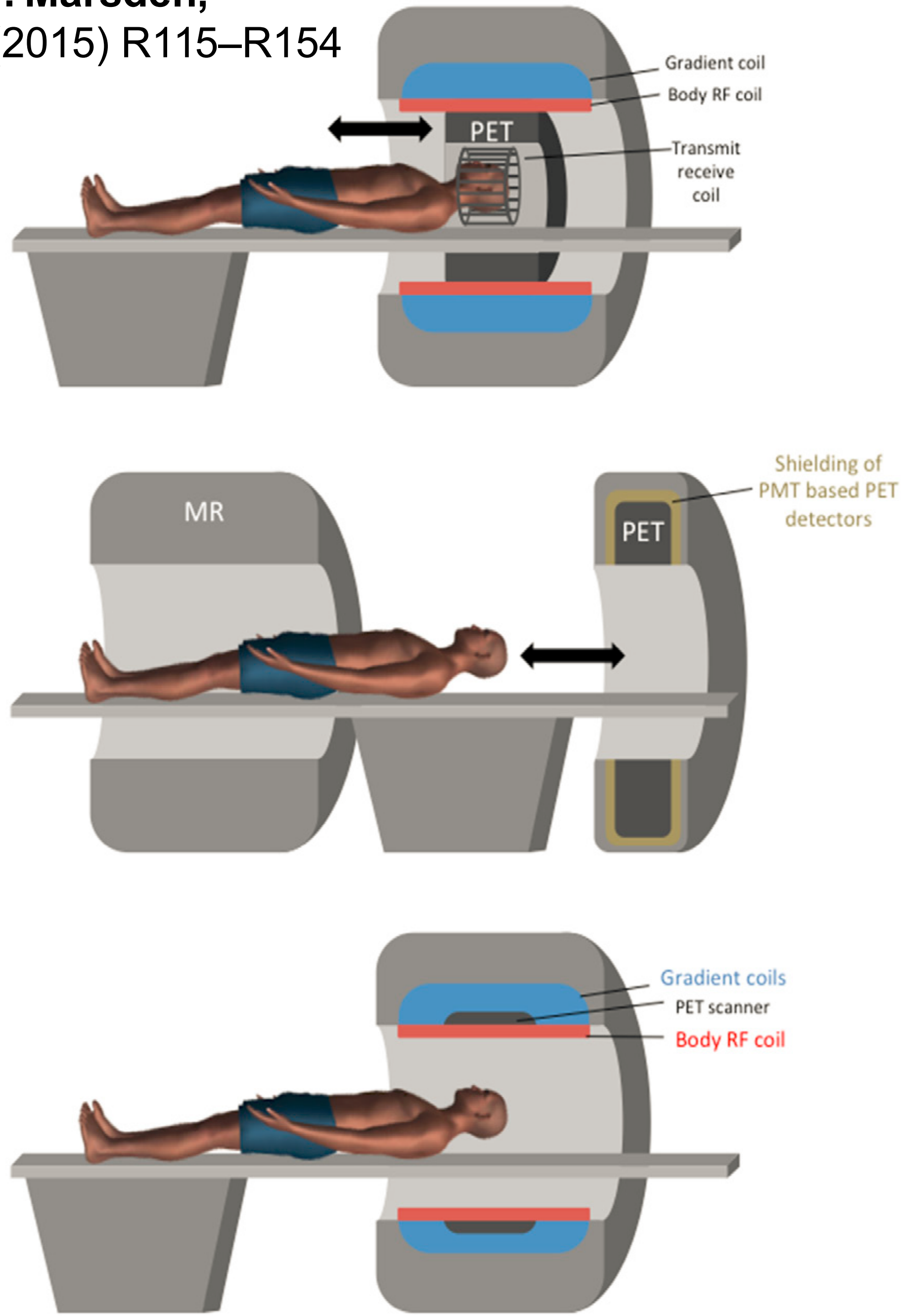


kryształy → polimery
energia → czas
wysoka granulacja → duże bloki
wysoka wydajność → niska wydajność
efekt fotoelektryczny → efekt Comptona
niska akceptancja → wysoka akceptancja
elektronika analogowa → elektronika cyfrowa
→ możliwość jednoczesnego PET i MRI
→ możliwość jednoczesnego PET i CT
→ tańszy

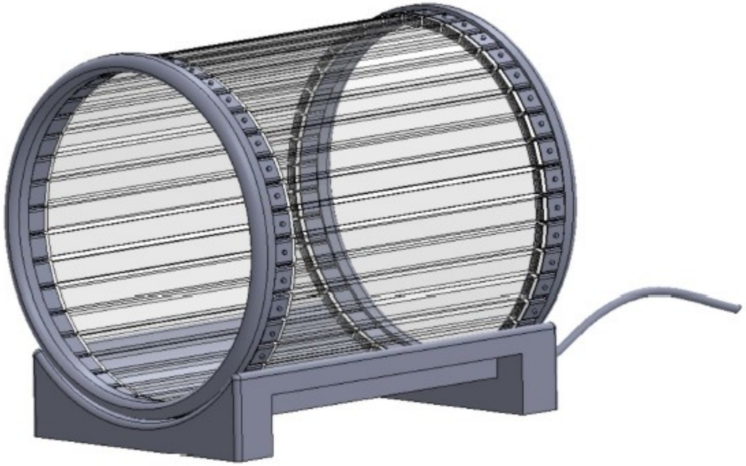
PET/MRI

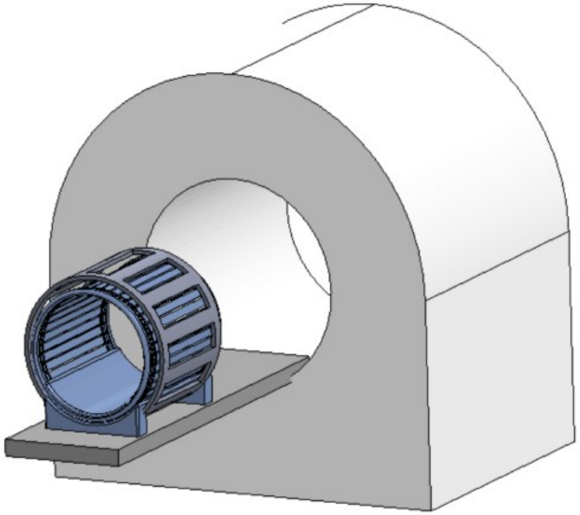
S. Vandenberghe, **P. Marsden,**
Phys. Med. Biol. **60** (2015) R115–R154

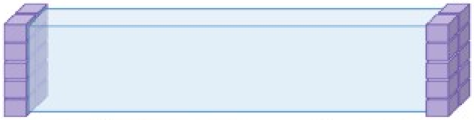


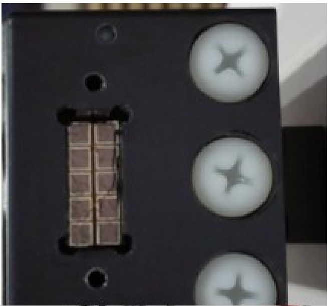


J-PET dalsze możliwości



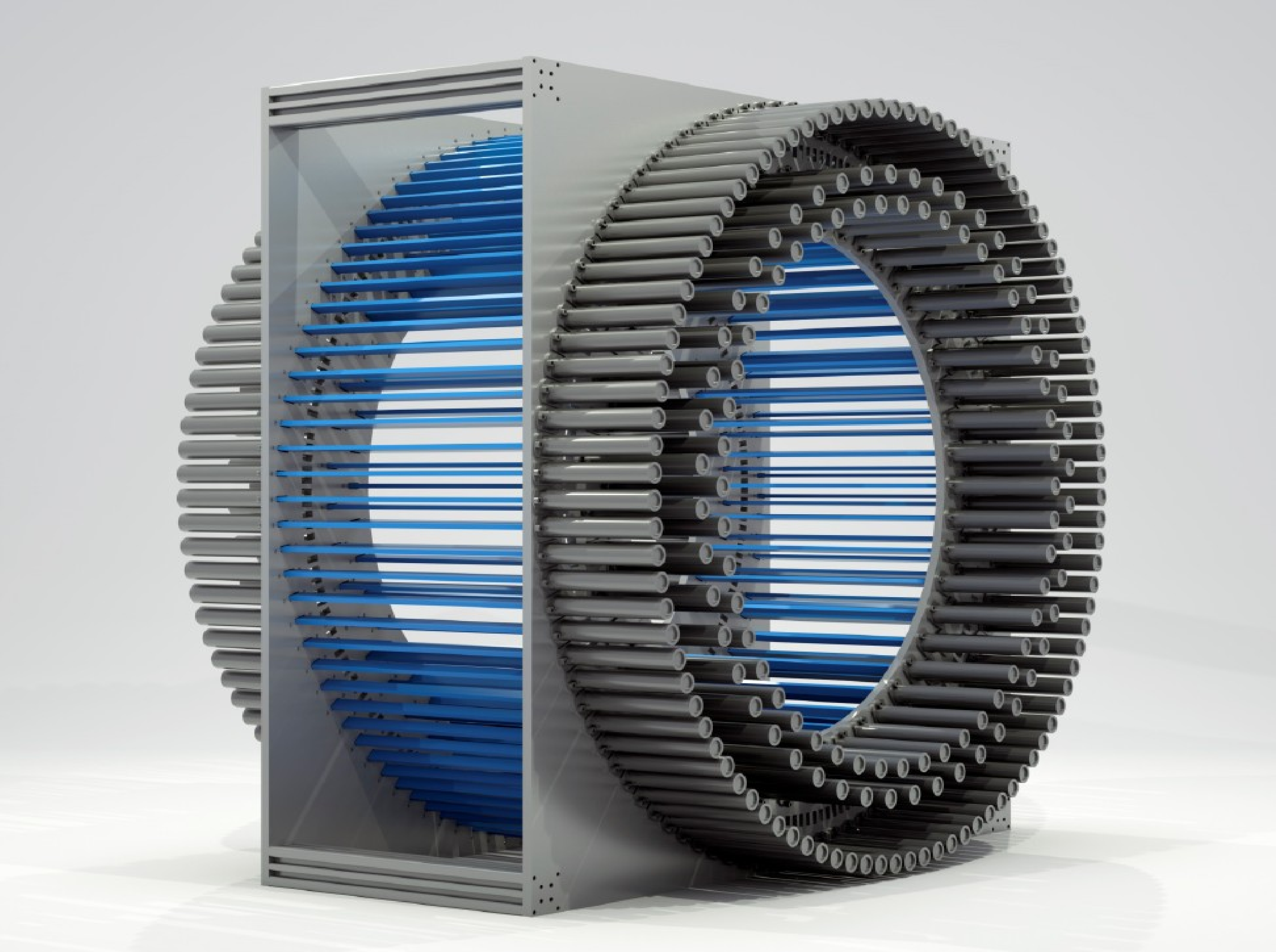




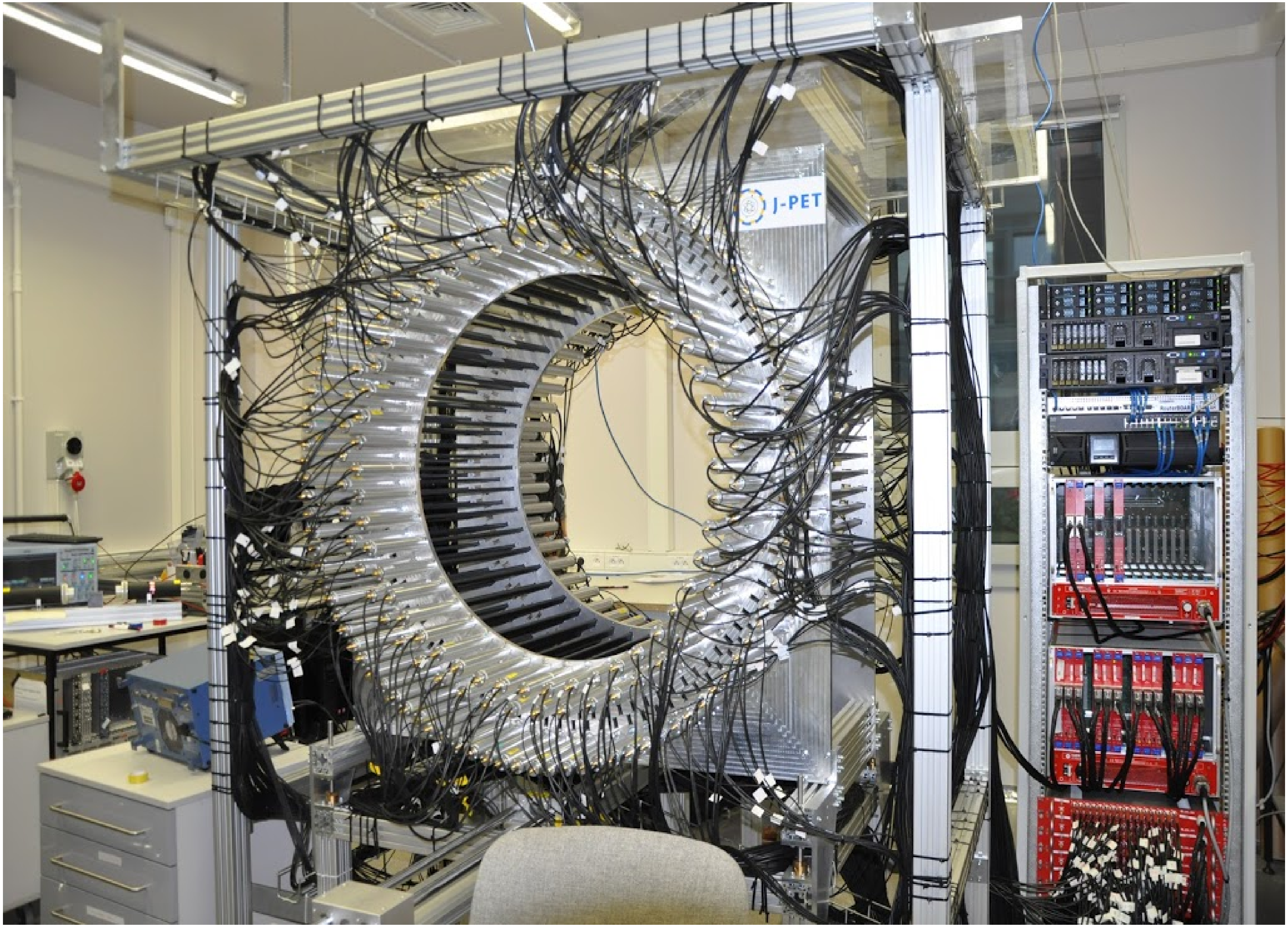


J-PET/CT:	P. Moskal, PCT/EP2014/068363 (2013)
J-PET/MRI:	P. Moskal, PCT/EP2014/068373 (2013)
J-PET/MRI insert:	B. Głowacz, P. Moskal, M. Zieliński, P 413150 (2015)

J-PET wizualizacja



Nowa siedziba WFAIS UJ



AFOV: 50cm TOF < 500ps (FWHM) t_hit: 100ps (sigma)

Projekt J-PET

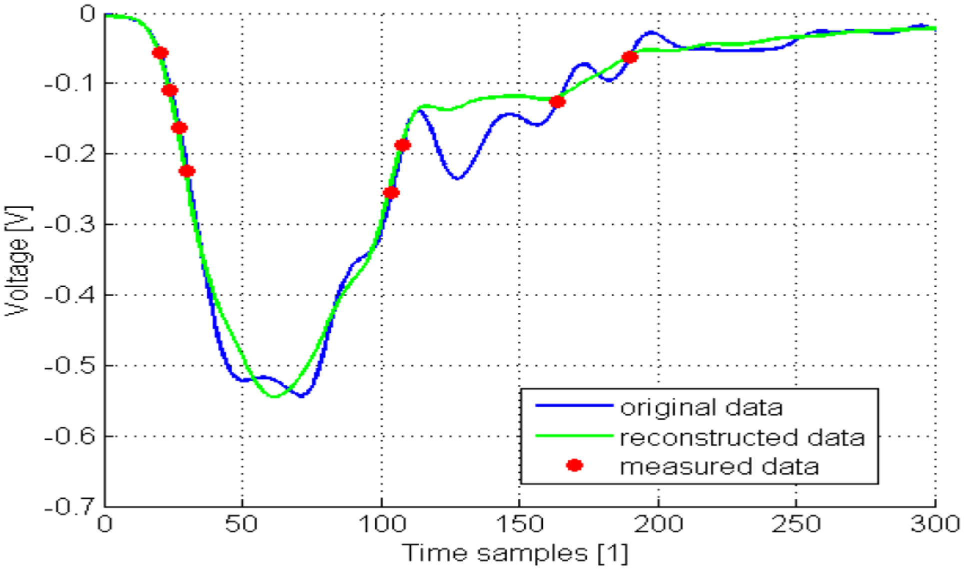
Elektronika odczytu
↓
Akwizycja danych
↓
Rekonstrukcja czasu i miejsca uderzenia
↓
Rekonstrukcja obrazu
↓
Wizualizacja obrazu

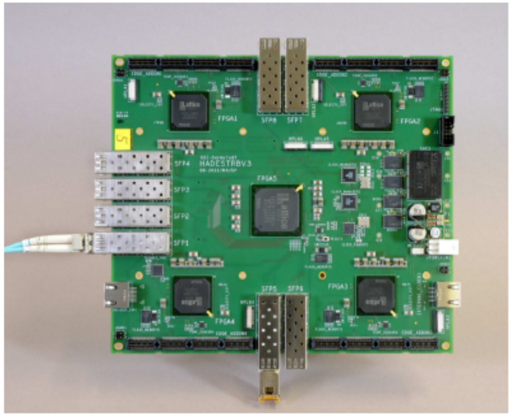
Symulacje komputerowe

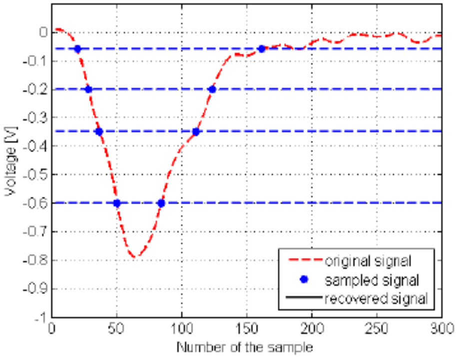
Kalibracja detektora

J-PET

Trigger Readout board



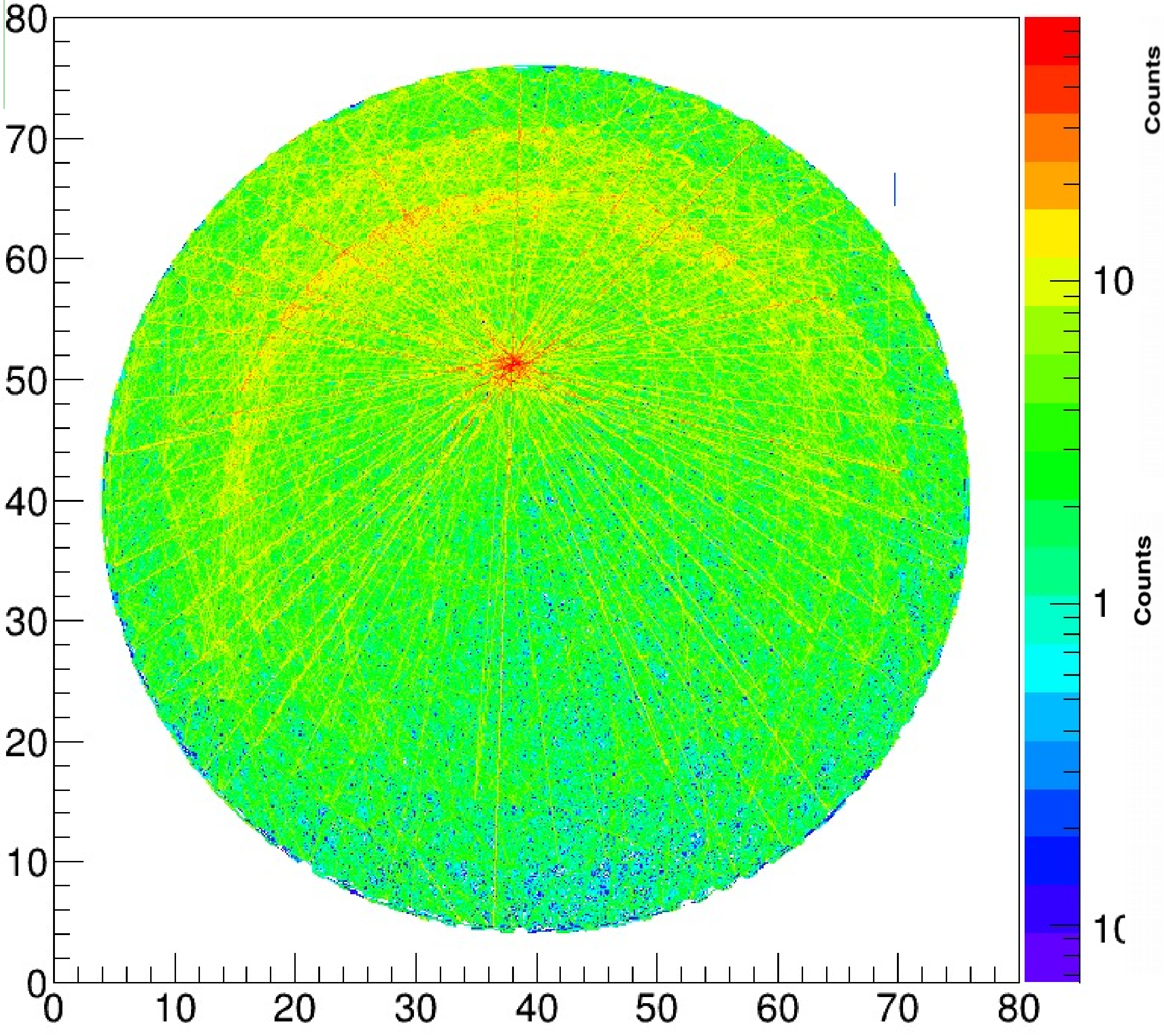


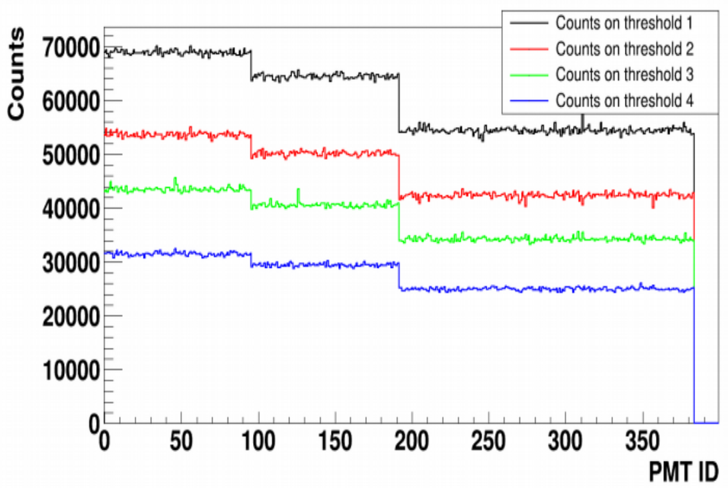


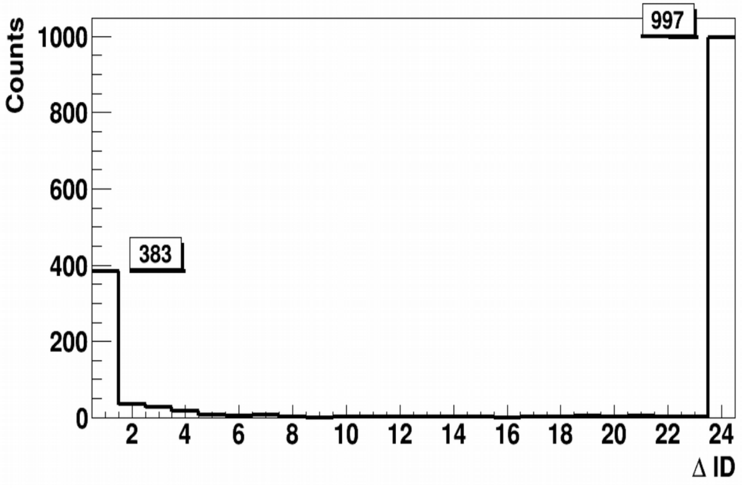
- Electronic board with 4 x configurable FPGA chips
  - FPGA - Silicon chip that can be used to implement any digital design
  - Can be used to probe fast signals (raising time of 1 ns)
  - Multi-threshold signal sampling designs
  - Excellent time measurement parameters (resolution $\sigma \sim$20ps)
- Central FPGA
  - data collector
  - Gigabit ethernet Gateway
- Trigger less mode

M. Pałka, P. Moskal, PCT/EP2014/068367
G. Korcyl, P. Moskal, M. Kajetanowicz, M. Pałka, PCT/EP2014/068352
G. Korcyl et al., Acta Phys. Polon. B 47, 492 (2016)
M. Pałka et al., JNST, wysłane
L. Raczyński et al., Nucl. Inst. and Meth. A764 (2014) 186
L. Raczyński et al. Nucl. Inst. and Meth. A786 (2015) 105
L. Raczyński et al., Phys. Med. Biol. (2017) w druku

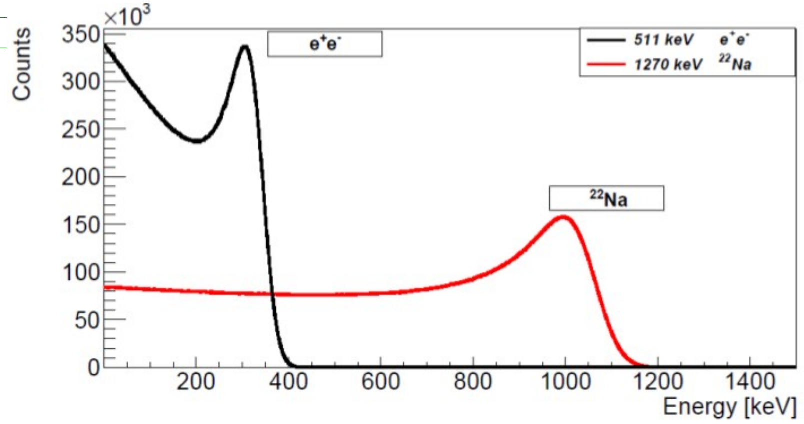
J-PET w działaniu

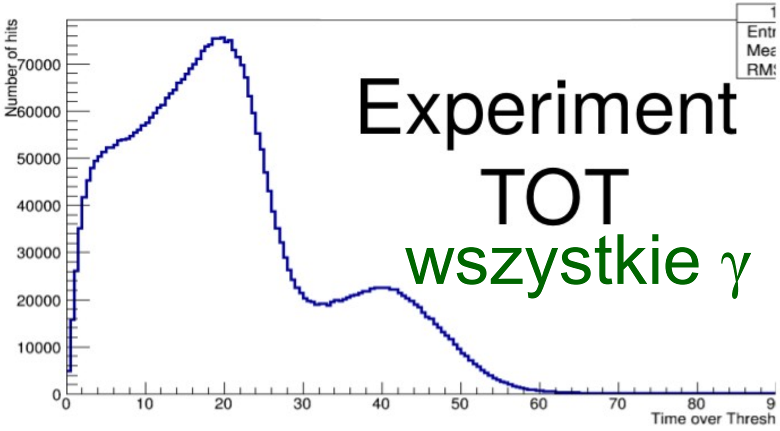




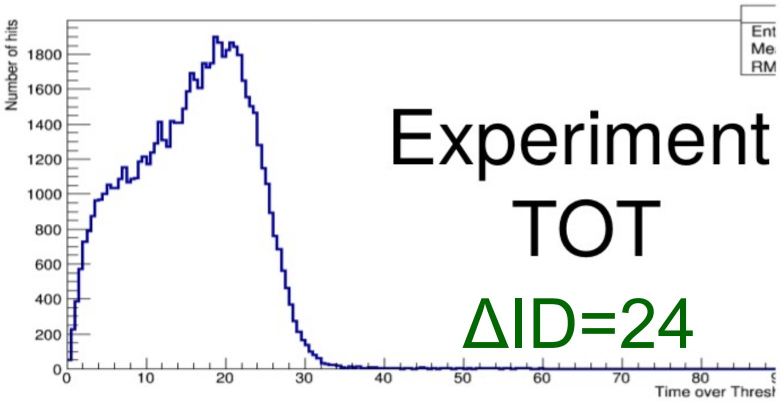


J-PET w działaniu

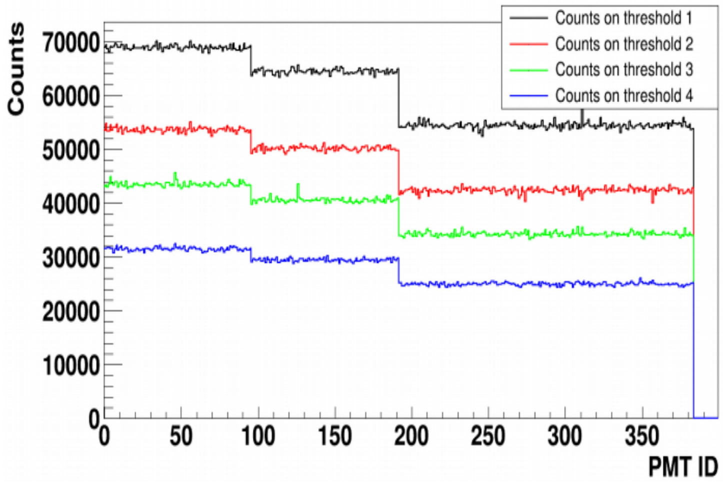


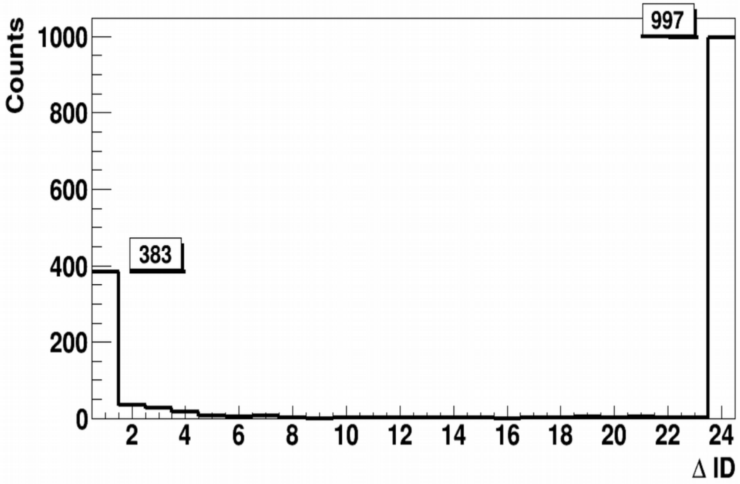


Experiment
TOT
wszystkie γ



Experiment
TOT
ΔID=24

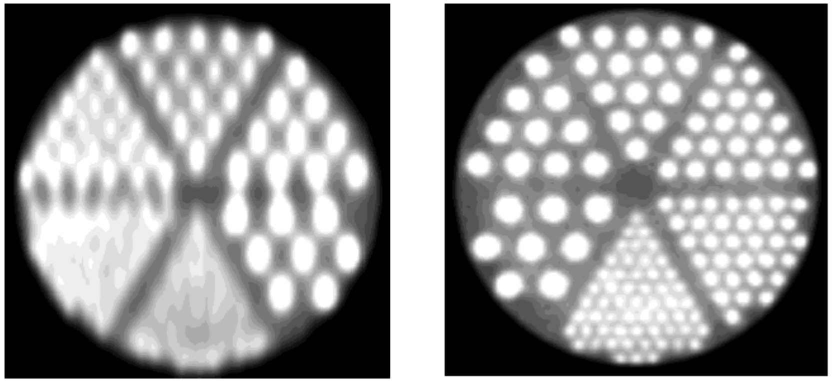




Rekonstrukcja obrazu

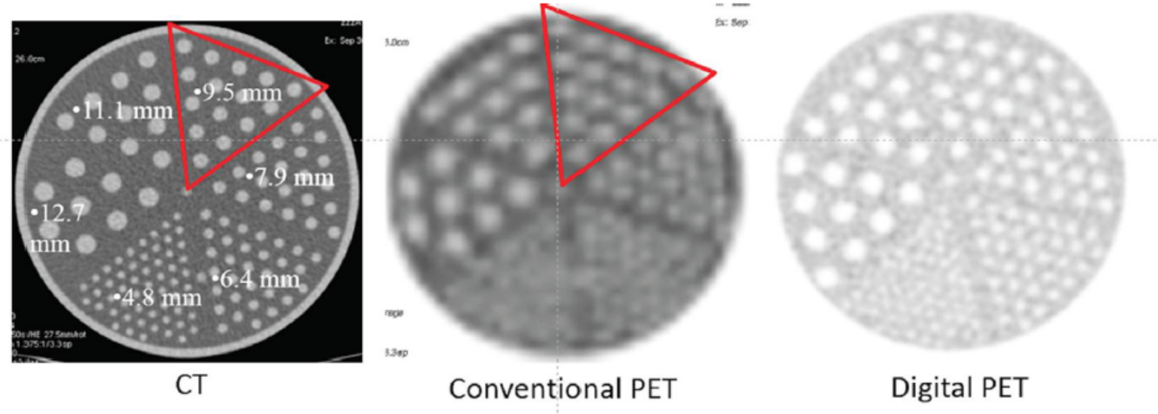
J-PET: P. Bialas, J. Kowal, A. Strzelecki et al. Acta Phys. Pol. A127 (2015) 1500
Adam Strzelecki, PhD thesis, 2016

384 strips, diameter 85 cm, 50 cm AFOV, 10^8 events, 50 iterations,



J-PET: image reconstracted from simulated data

rotated (coronal) axially arranged



CT

Conventional PET

Digital PET

Figure from P. Slomka, T. Pan, G. Germano, Semin. Nucl. Med. 46 (2016) 46

Digital PET, courtesy of Jun Zhang (PhD), Michael V. Knopp (MD, PhD), The Ohio State University

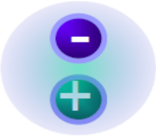
Pozytonium (Ps)

1. Stan związany e+e-
2. Stan własny Hamiltonianu i operatorów P, C, CP
3. Najlżejszy znany atom i anty-atom, który ulega anihilacji
4. Elektrony i pozytrony są najlżejszymi leptonami
   - brak możliwości rozpadu na lżejsze cząstki przez oddziaływanie słabe
5. Brak cząstek naładowanych w stanie końcowym
   - małe poprawki radiacyjne $2*10^{-10}$
6. Do tej pory brak obserwacji łamania symetrii dyskretnych
   w układach leptonowych

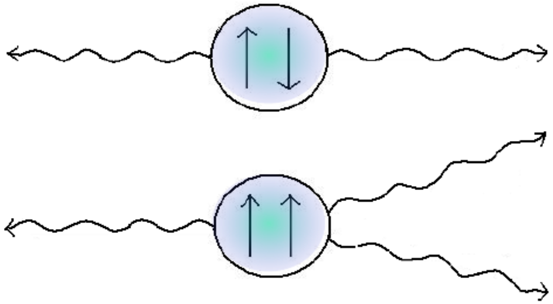
Model Standardowy 10^{-9} - górne ograniczenia $3*10^{-3}$ dla T, CP, CPT

Pozytonium (Ps)

slajd P. Moskal

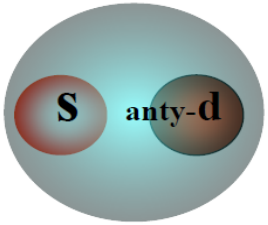


POSITRONIUM

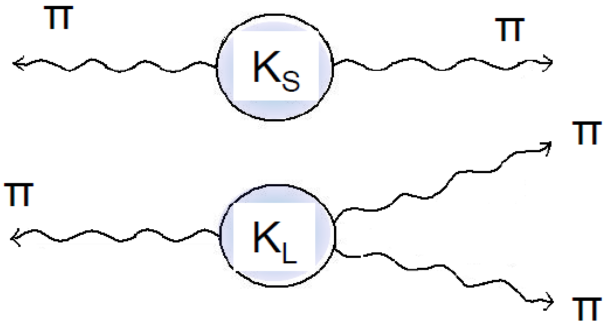


CP = + Para-positronium   tau(p-Ps) ≈ 125 ps

CP = - Ortho-positronium tau(o-Ps) ≈ 142 ns



MESON K

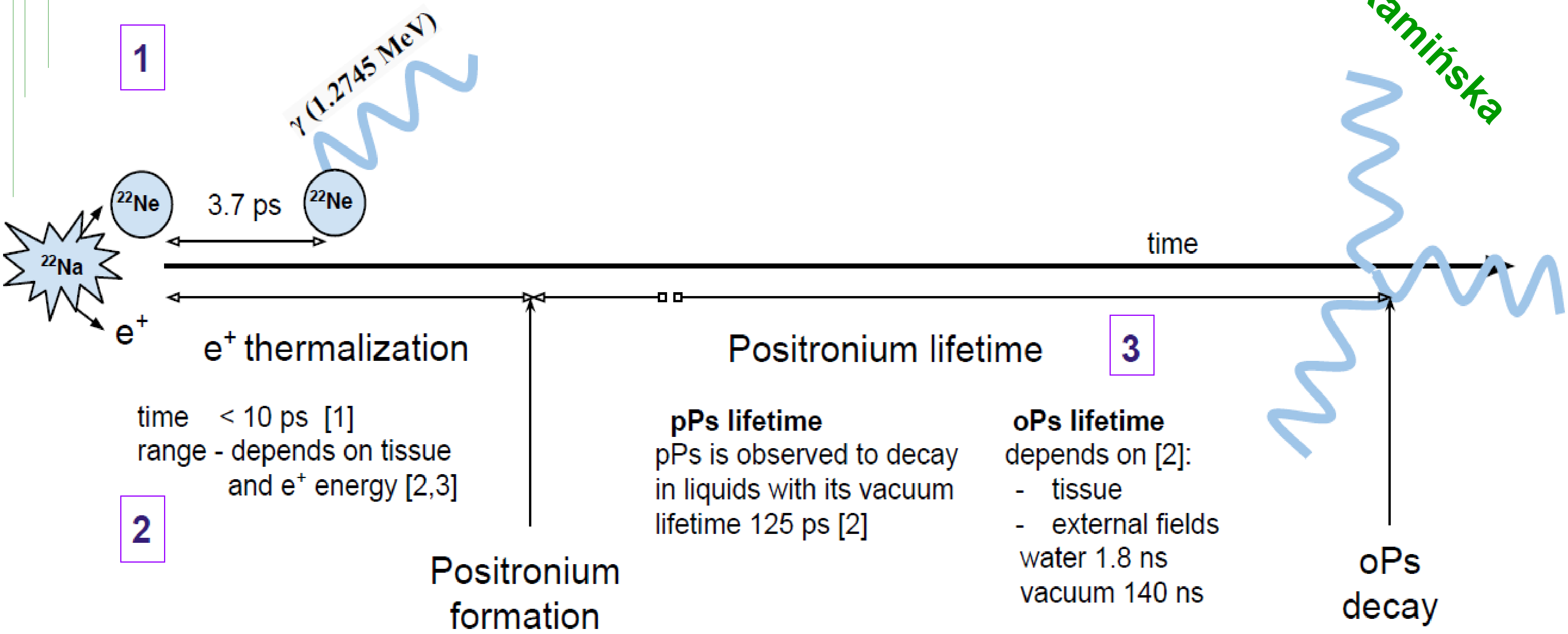


CP ~= +   tau(K_S) ≈ 90 ps

CP ~= -   tau(K_L) ≈ 52 ns

Pozytonium (Ps)

slajd D. Kamińska



time < 10 ps [1]
range - depends on tissue
and e^{+} energy [2,3]

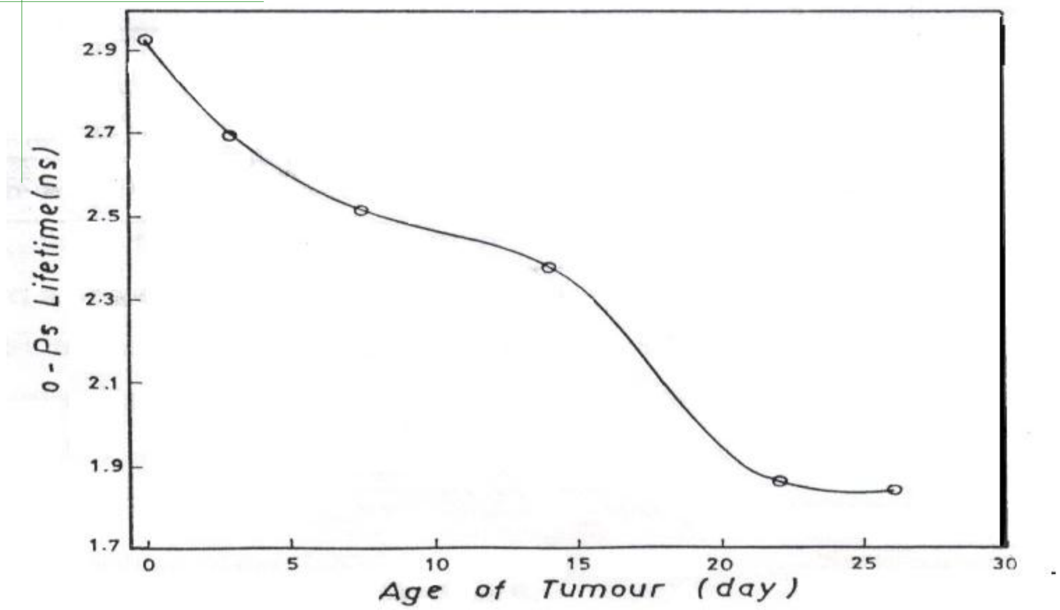
pPs lifetime
pPs is observed to decay in liquids with its vacuum lifetime 125 ps [2]

oPs lifetime
depends on [2]:
- tissue
- external fields

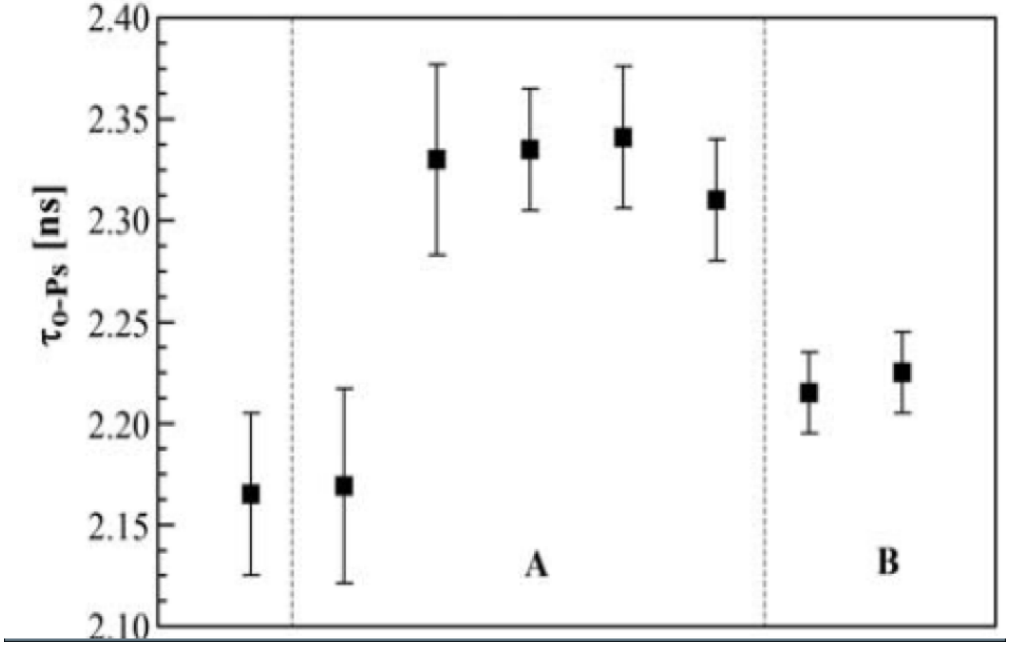
water 1.8 ns
vacuum 140 ns

[1] P. Kubica and A. T. Stewart, Phys. Rev. Lett. 34 (1975) 852
[2] M. Harpen Med.Phys. 31 (2004) 57-61
[3] J Cal-Gonzalez et al, Phys. Med. Biol. 58 (2013) 5127–5152

Pozytonium w medium

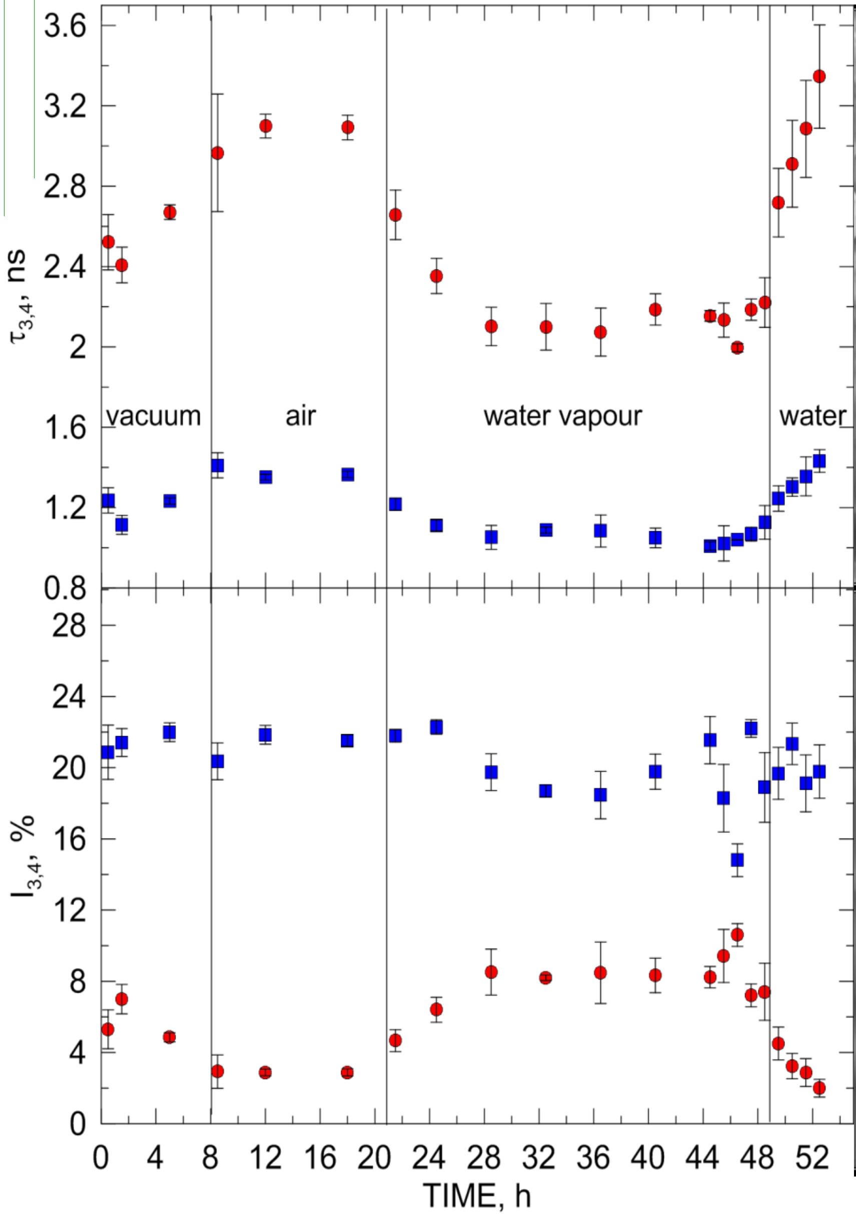


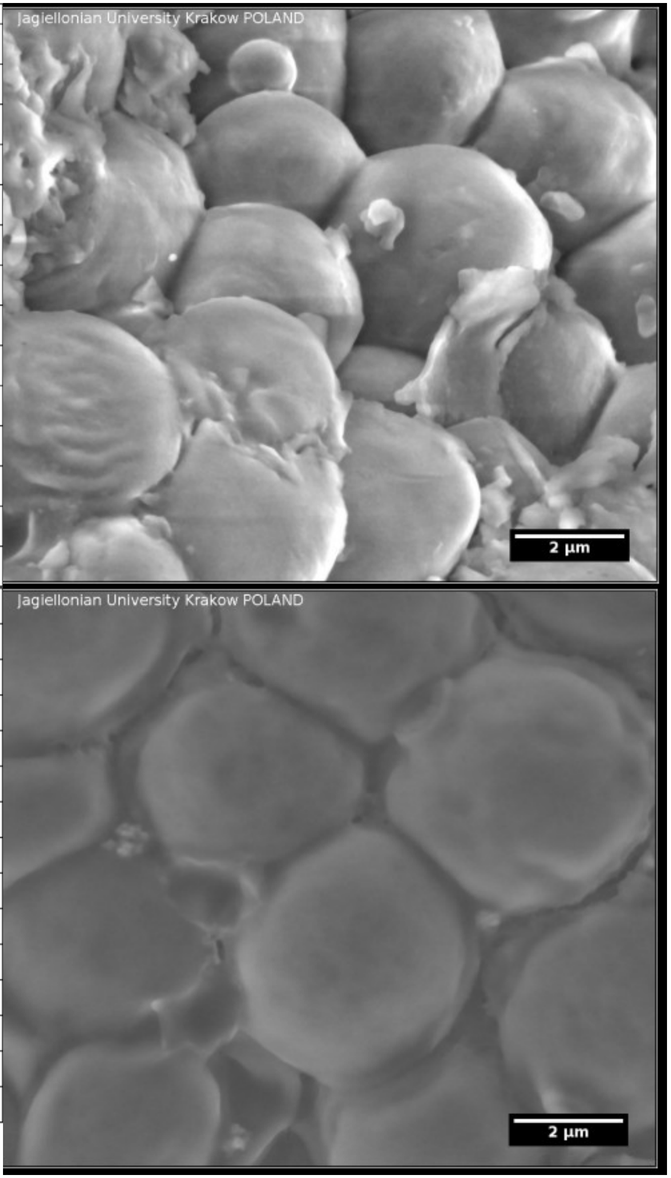
The age of mice’s tumour with o-Ps lifetime
A.H. Al-Mashhadani et al.,
Iraqi J. Sci. 42C, 60 (2001) 3.



R. Pietrzak et al., NUKLEONIKA 58 (2013) 199

J-PET a pozytonium





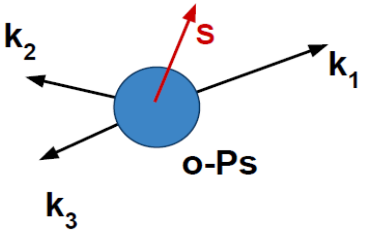
J-PET:
E. Kubicz,
B. Jasińska et al.,
Nukleonika 60 (2015)749
Studies of unicellular micro-organisms Saccharomyces cerevisiae by means of positron annihillation lifetime spectroscopy

Environmental Scanning Electron Microscopy images of lyophilised yeasts (upper) and dried under normal conditions, after addition of water (bottom).

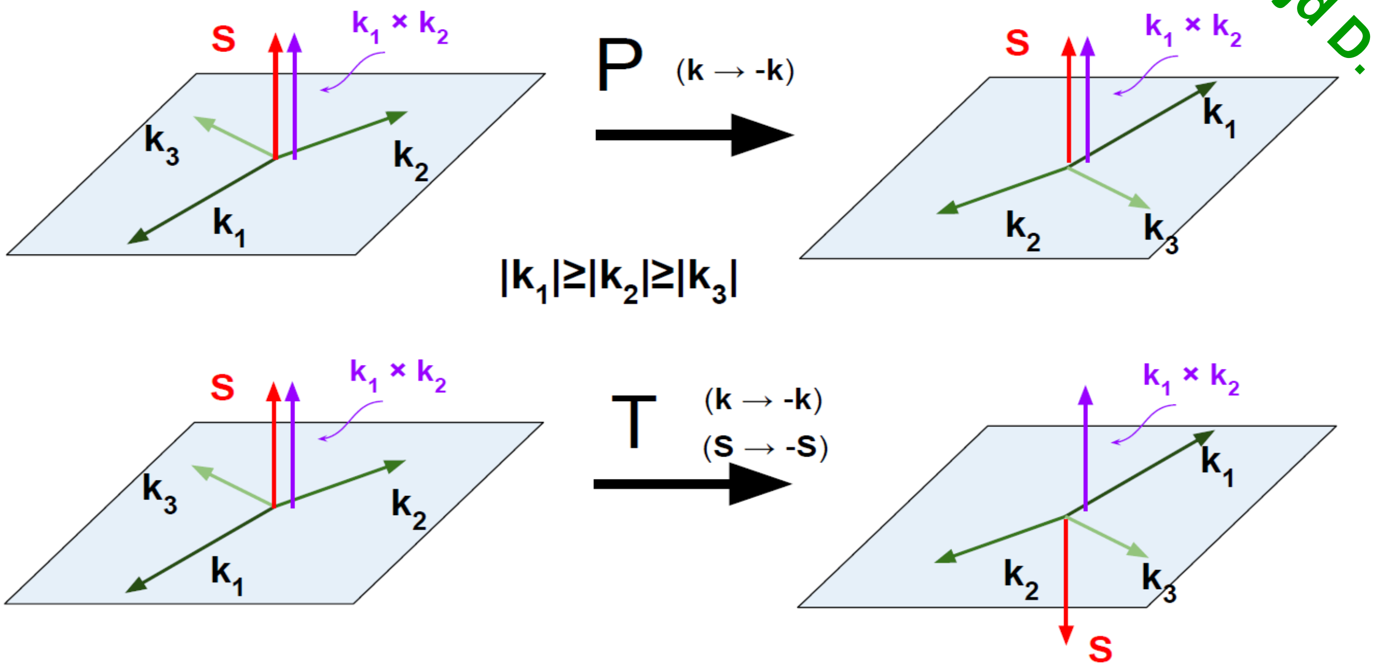
o-Ps

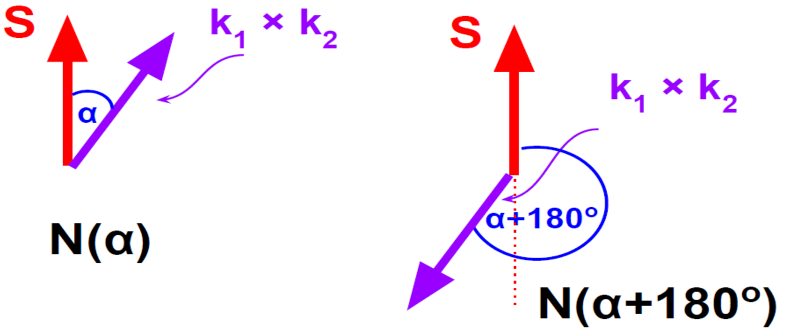
o-Ps operator example: $\vec{S}\cdot\hat{k}_1\times\hat{k}_2$

Operator	C	P	T	CP	CPT
$\vec{S}\cdot\hat{k}_1\times\hat{k}_2$	+	+	−	+	−



slajd D. Kamińska





$N(\alpha) = N(\alpha + 180^\circ)$

CPT symmetry is conserved

$N(\alpha) \neq N(\alpha + 180^\circ)$

CPT symmetry is violated

o-Ps @ J-PET

Operator	C	P	T	CP	CPT
$\vec{S}\cdot\hat{k}_1\times\hat{k}_2$	+	+	−	+	−
$(\hat{S}\cdot\hat{k}_1)(\hat{S}\cdot\hat{k}_1\times\hat{k}_2)$	+	−	−	−	+

$$C_{CP} = 0.0013 \pm 0.0022$$

(T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401)

$$C_{CPT} = 0.0071 \pm 0.0062$$

(P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401)

$$\text{SM: } 10^{-9} - 10^{-10}$$

effects of final state interaction

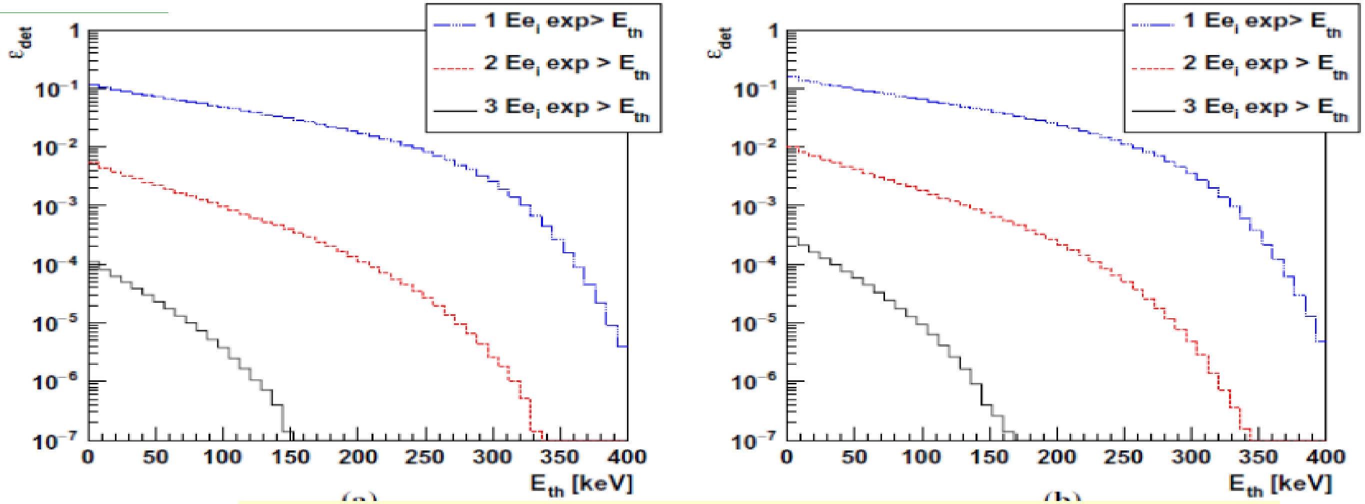
(W. Bernreuther et al., Z. Phys. C 41 (1988) 143)

Operator	**C**	**P**	**T**	**CP**	**CPT**
$\vec{S}\cdot\vec{k}_1$	+	−	+	−	−
$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$	+	+	−	+	−
$(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$	+	−	−	−	+
$\vec{k}_1\cdot\vec{\varepsilon}_2$	+	−	−	−	+
$\vec{S}\cdot\vec{\varepsilon}_1$	+	+	−	+	−
$\vec{S}\cdot(\vec{k}_2\times\vec{\varepsilon}_1)$	+	−	+	−	−

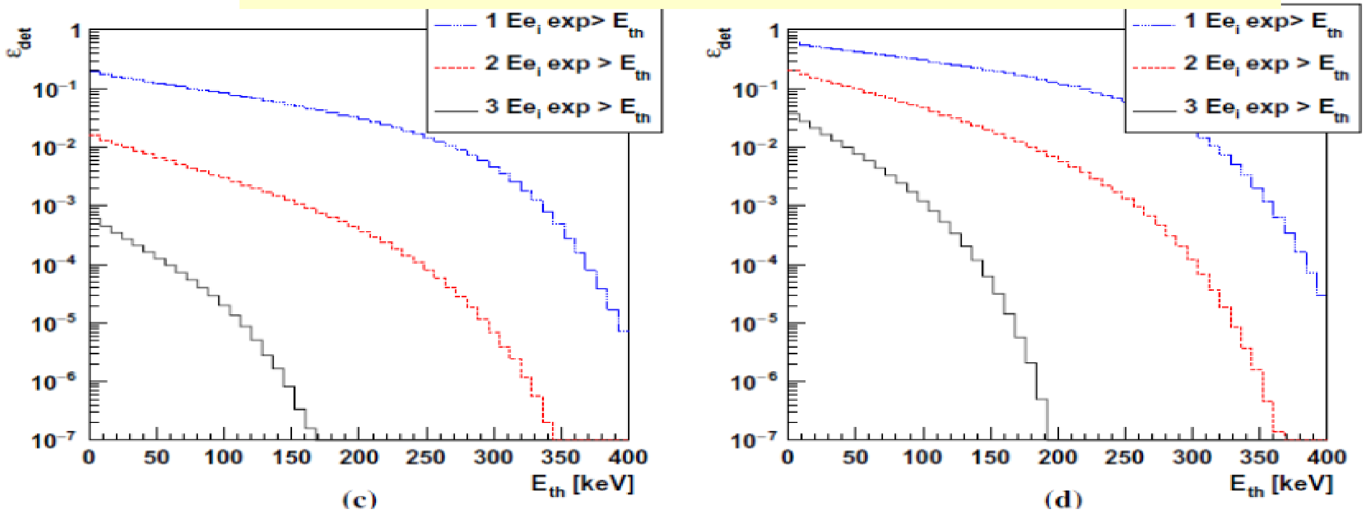
J-PET a inne eksperymenty

	J-PET	**CP-Tokyo**	**Gammasphere**
Detector material	BC-420	LYSO	HPGe and BGO
Time resolution	80 ps	0.9 ns	4.6 ns
Angular resolution (polar/azimuthal)	1.4°/0.5°	3.5°/3.5°	4°/4°
Source activity	10 MBq	0.04 MBq (limited by pile-ups)	1 MBq (limited by pile-ups)
reconstruction efficiency (including registration of deexcitation γ)			
o-Ps $\rightarrow 3\gamma$	$6 \cdot 10^{-6}$	-	$5.7 \cdot 10^{-3}$
o-Ps $\rightarrow \gamma\gamma\gamma_n$[1]	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	-
Registered events (length of measurement in days)			
o-Ps $\rightarrow 3\gamma$	$1.4 \cdot 10^{9}$ (270)	-	$2.65 \cdot 10^{7}$ ($\sim$ 36)
o-Ps $\rightarrow \gamma\gamma\gamma_n$	$6.8 \cdot 10^{10}$ (270)	$\sim 10^{7}$ ($\sim$ 180)	-

Wydajność rejestracji o-Ps



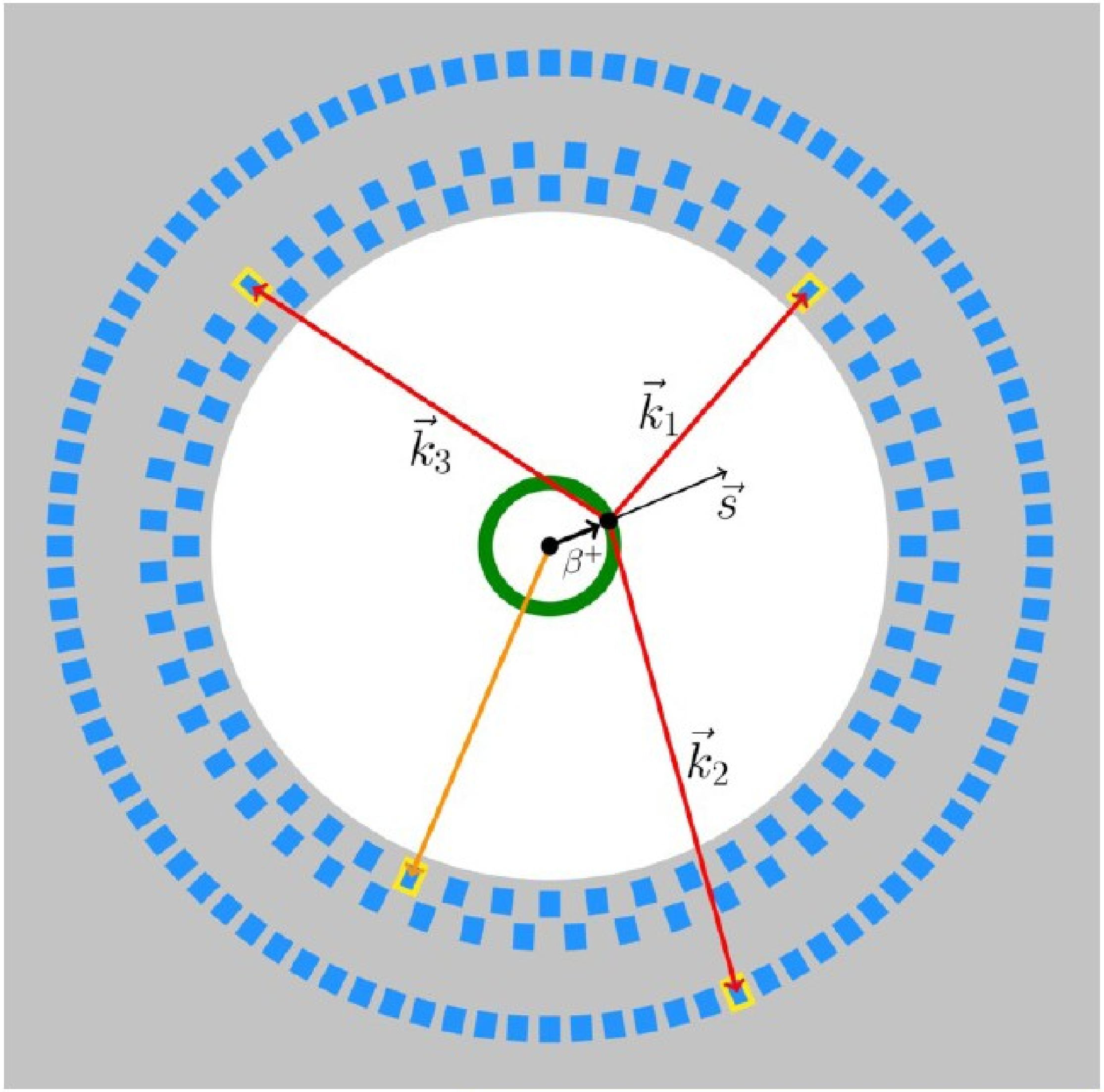
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445

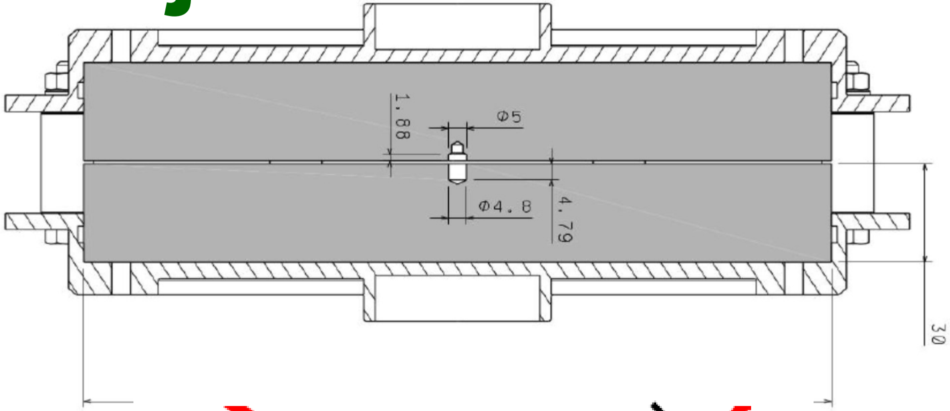


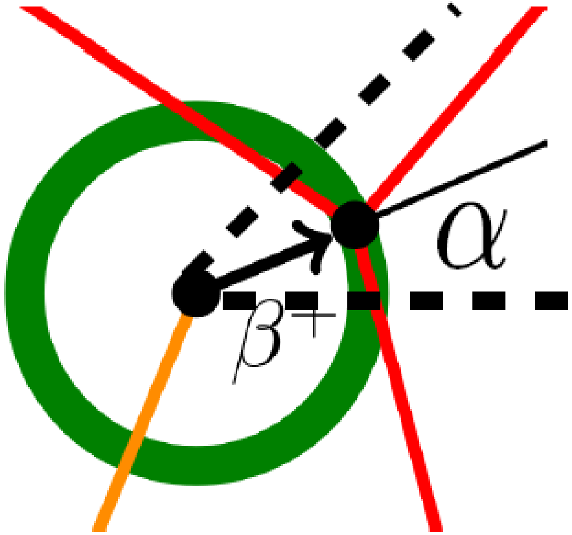
(c) (d)

Target material	Rate of registered o-Ps → 3γ events (s^{-1})			
	J-PET	J-PET+1	J-PET+2	J-PET-full
IC3100	15	70	130	10600
XAD-4	25	115	230	18300

Wyznaczenie polaryzacji e+





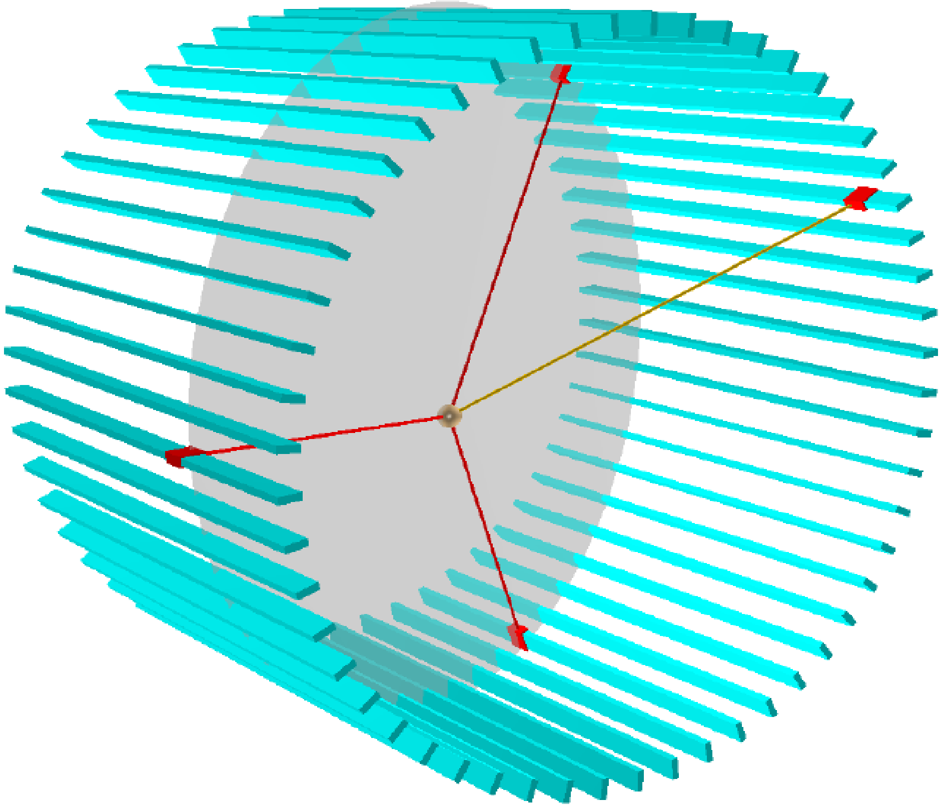


$$P = \frac{v}{c}(1 + \cos\alpha)/2$$

$$\approx 98\%$$

A. Gajos, E Czerwiński et al., Nucl. Inst. and Meth. A819 (2016) 54-59
P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509

GPS @ J-PET

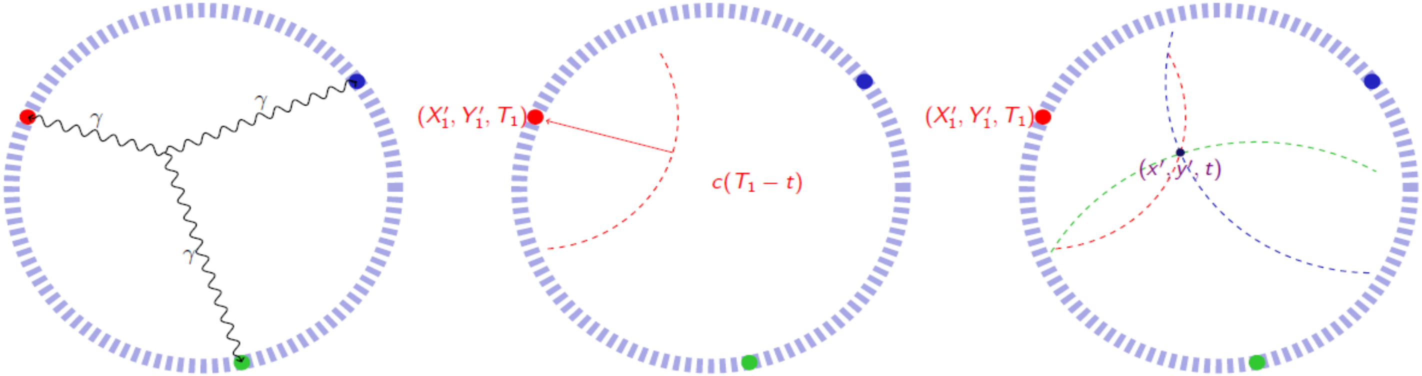


GPS @ J-PET

J-PET

slajd A. Gajos

Principle of o-Ps → 3γ decay reconstruction



(Courtesy of A. Gajos)

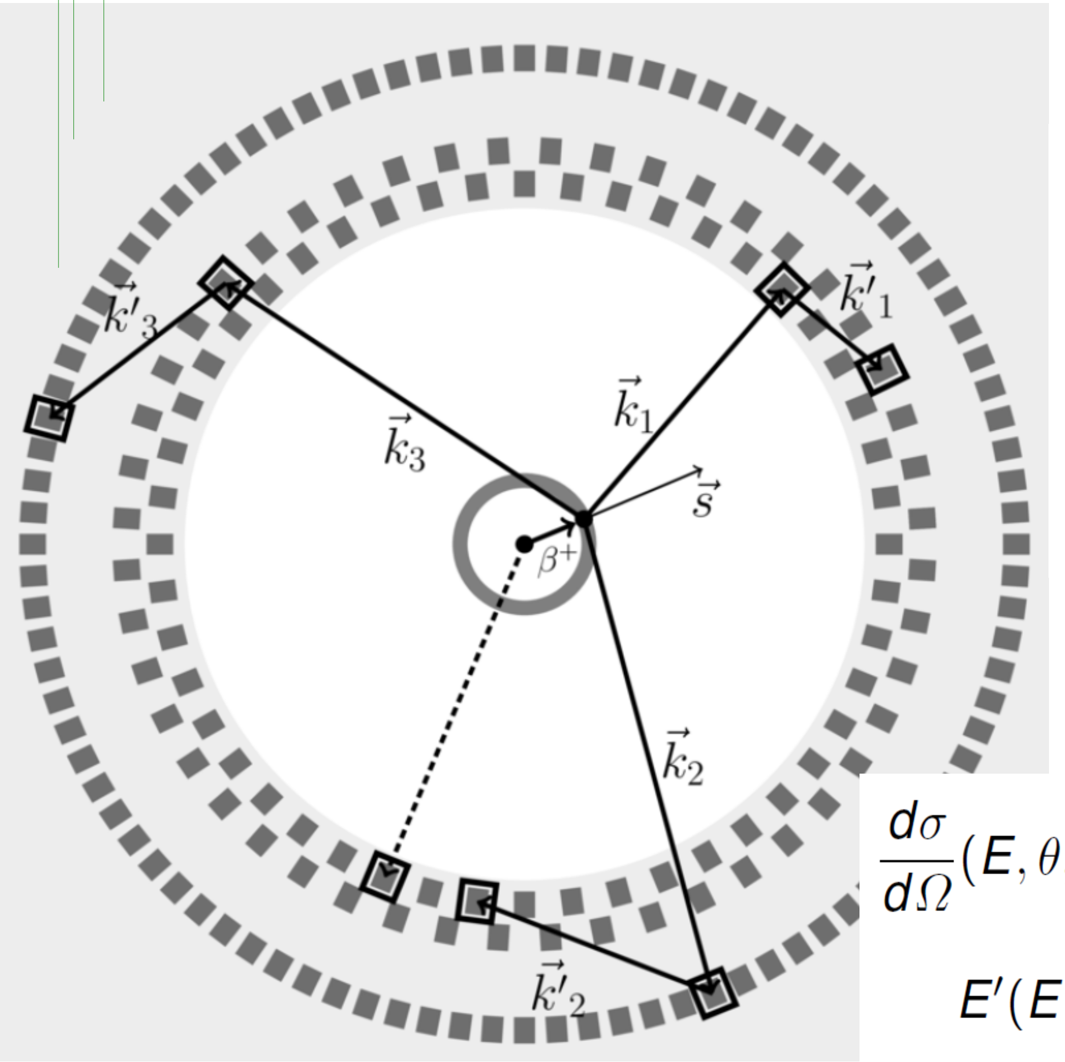
1. Find the decay plane containing the 3 hits in the J-PET barrel
2. Transform the hit coordinates to a 2D coordinate system in the decay plane $(X_i, Y_i, Z_i, T_i) \rightarrow (X_i', Y_i', 0, T_i')$
3. For each of the recorded γ hits define a circle of possible origin points of the incident photon assuming o-Ps decay at time t
4. Find the decay point (x', y') in the decay plane and time t as an intersection of 3 circles by solving the following equation system:

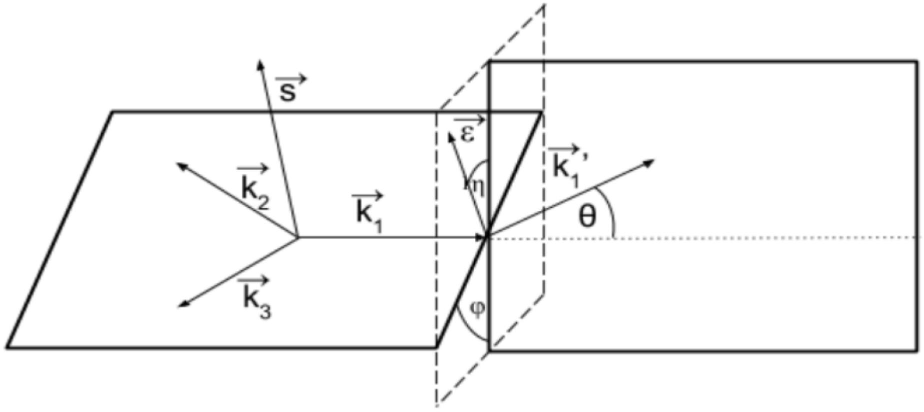
$$(T_i - t)^2 c^2 = (X_i' - x')^2 + (Y_i' - y')^2, \quad i = 1, 2, 3$$

   where: x', y', t - unknowns, T_i - time of i-th hit, X_i', Y_i' - coordinates of the i-th hit in the barrel expressed in the decay plane coordinates
5. Transform (x', y', t) of the decay point back to the detector 3D coordinate system

A. Gajos, E Czerwiński et al., Nucl. Inst. and Meth. A819 (2016) 54-59

Wyznaczenie polaryzacji anihilacyjnych kwantów γ



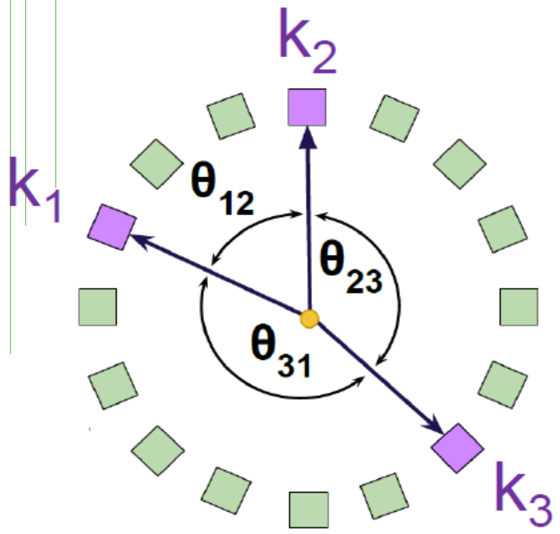


$$\frac{d\sigma}{d\Omega}(E,\theta,\eta) = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'}+\frac{E'}{E}-2\sin^2\theta\cos^2\eta\right)$$

$$E'(E,\theta) = \frac{E}{1+\frac{E}{m_e c^2}(1-\cos\theta)}$$

P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509

Wyznaczenie energii anihilacyjnych kwantów γ



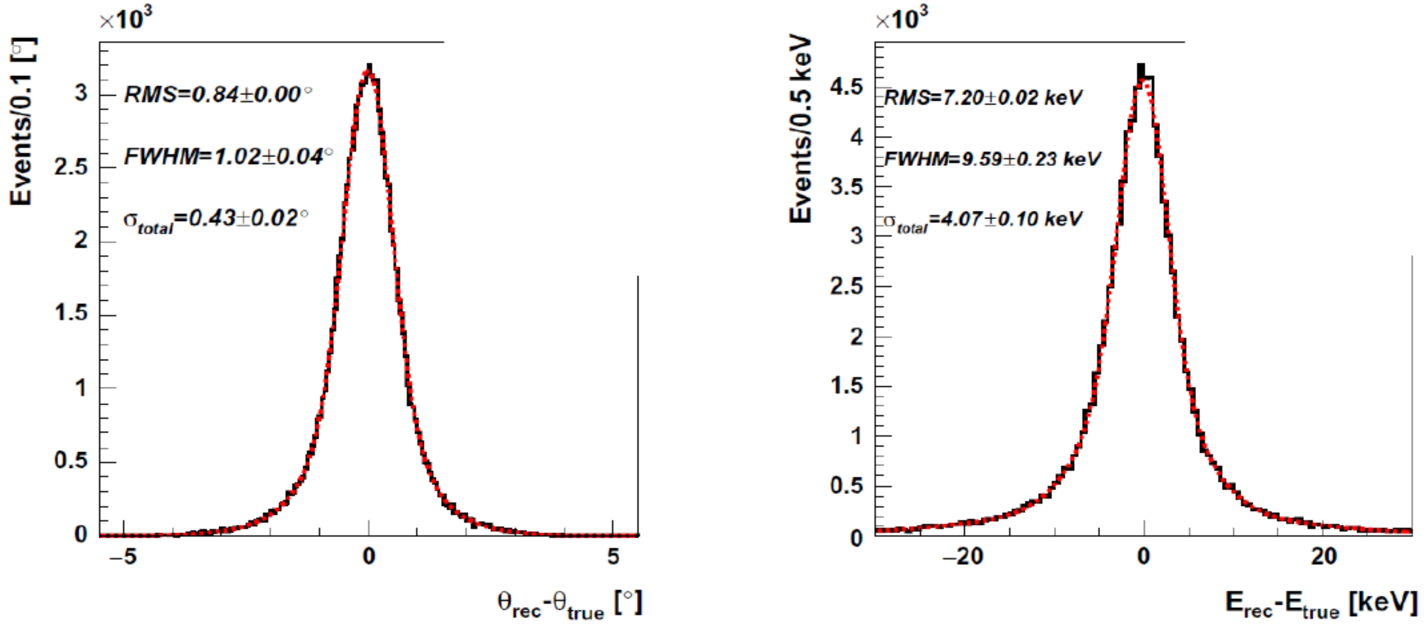
o-Ps → 3γ

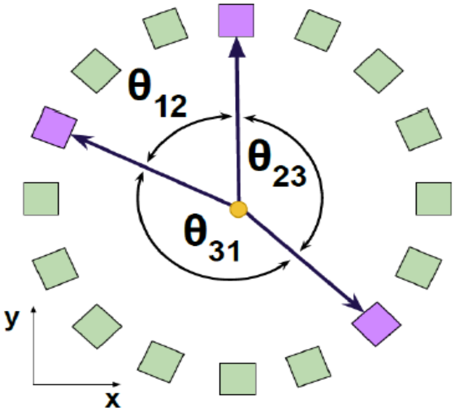
$$E_1 = -2m_e \frac{-\cos\theta_{13} + \cos\theta_{12}\cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

$$E_2 = -2m_e \frac{\cos\theta_{12}\cos\theta_{13} - \cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

$$E_3 = 2m_e \frac{1+\cos\theta_{12}}{1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23}}.$$

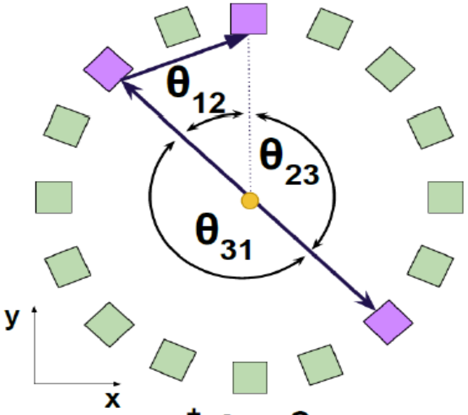
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445





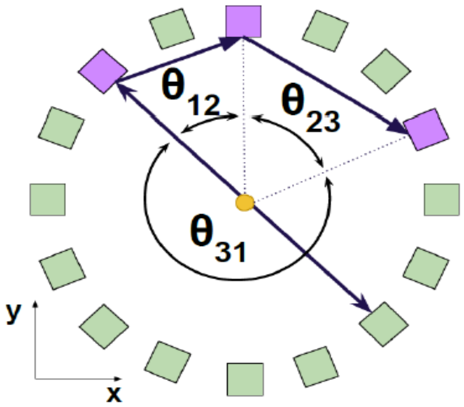
o-Ps → 3γ

$\theta_{23} > 180 - \theta_{12}$



$e^+e^- \rightarrow 2\gamma$
single scattered

$\theta_{23} = 180 - \theta_{12}$

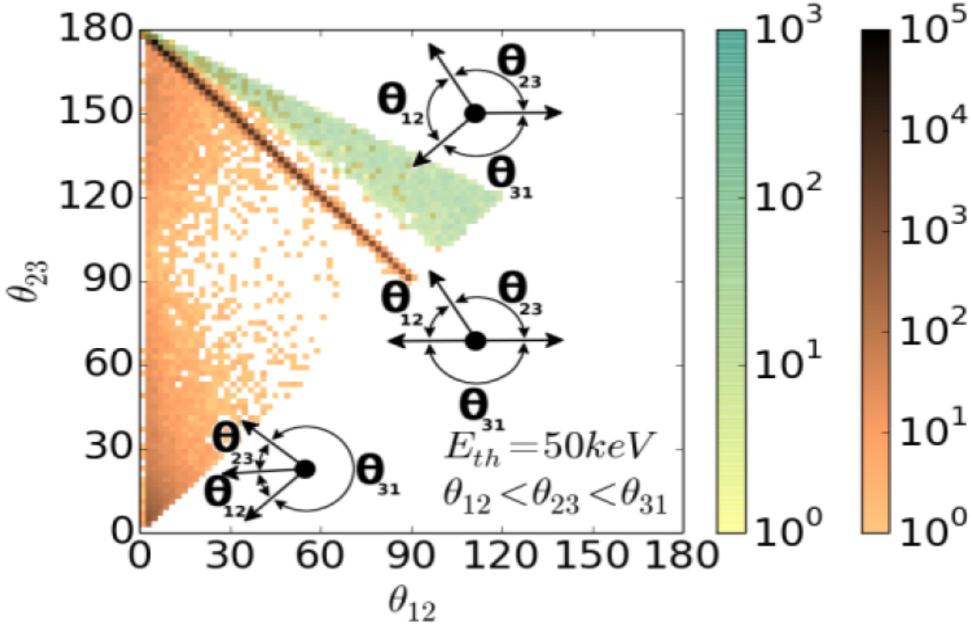


$e^+e^- \rightarrow 2\gamma$
double scattered

$\theta_{23} < 180 - \theta_{12}$

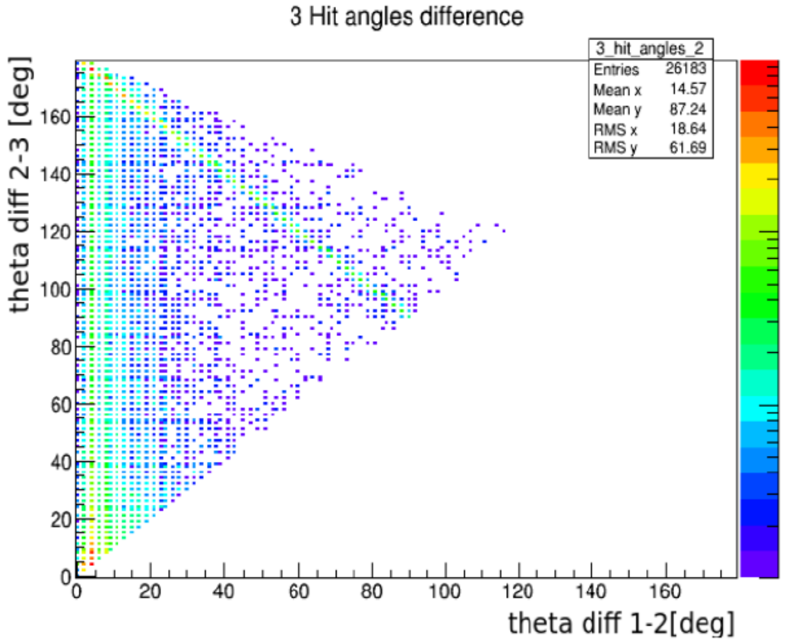
Simulations

Eur. Phys. J. C76 (2016) 445



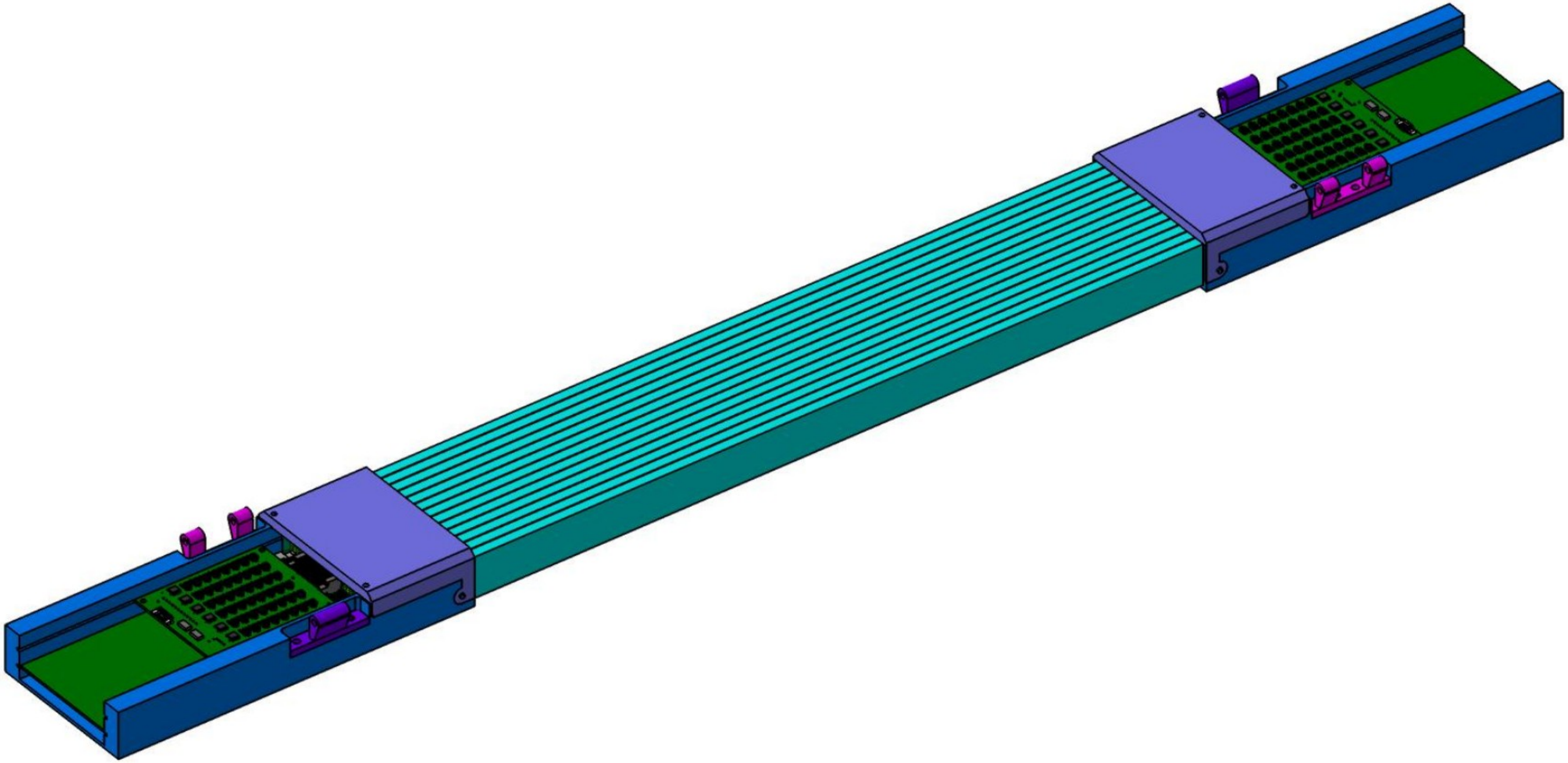
EXPERIMENT Run-1

analysed by K. Kacprzak

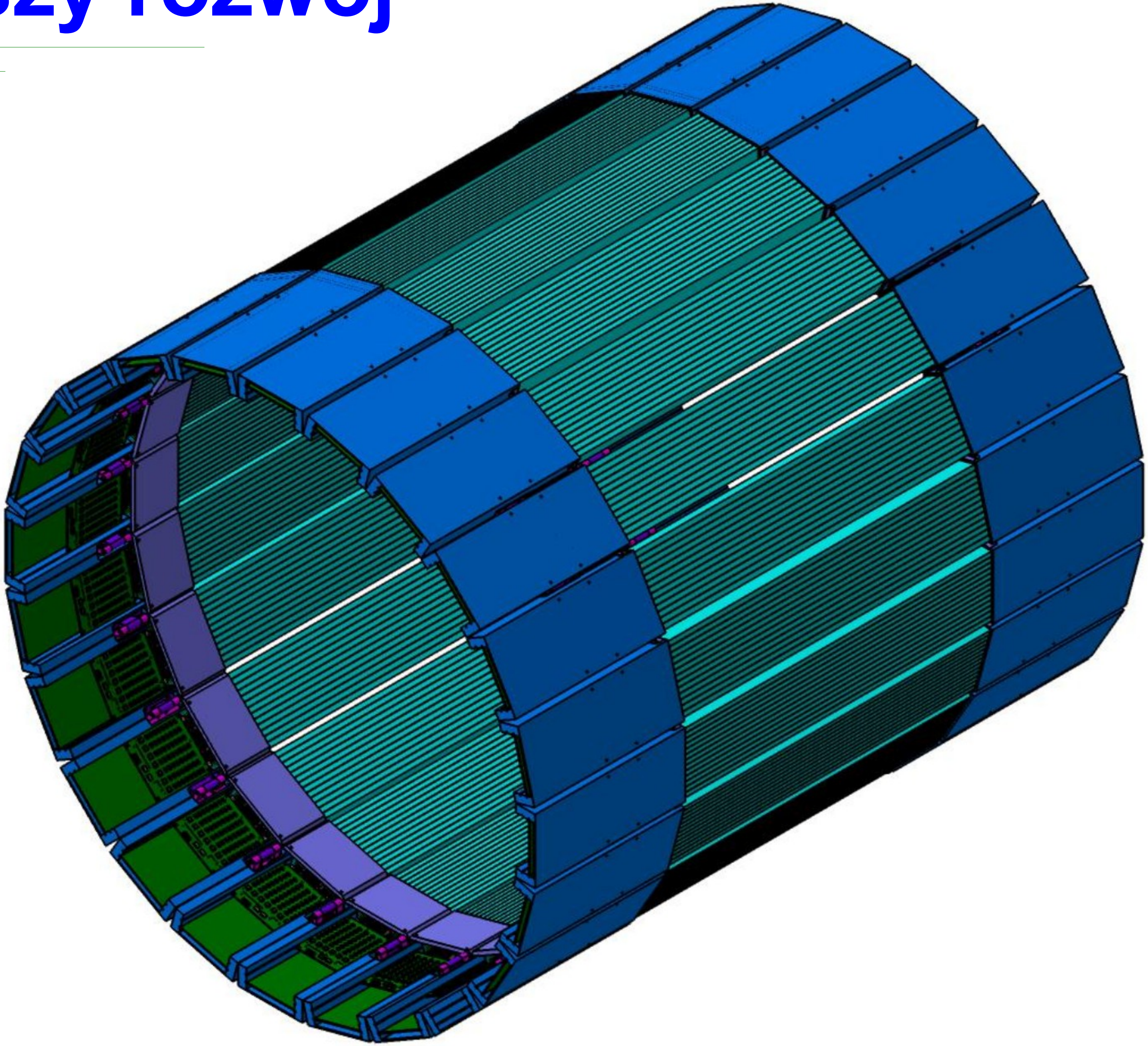


$$\theta_{12} < \theta_{23} < \theta_{31}$$

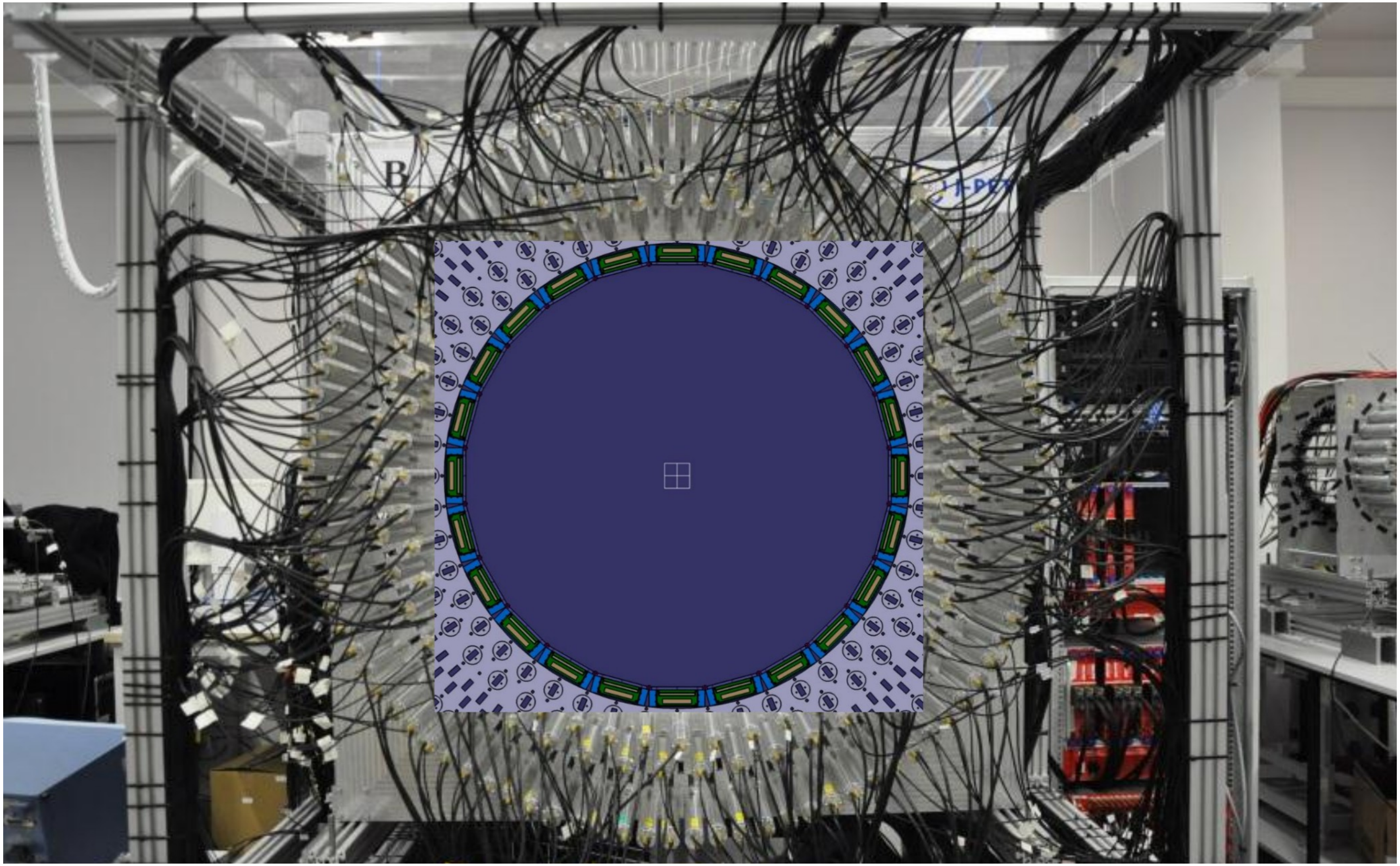
Dalszy rozwój



Dalszy rozwój



Dalszy rozwój



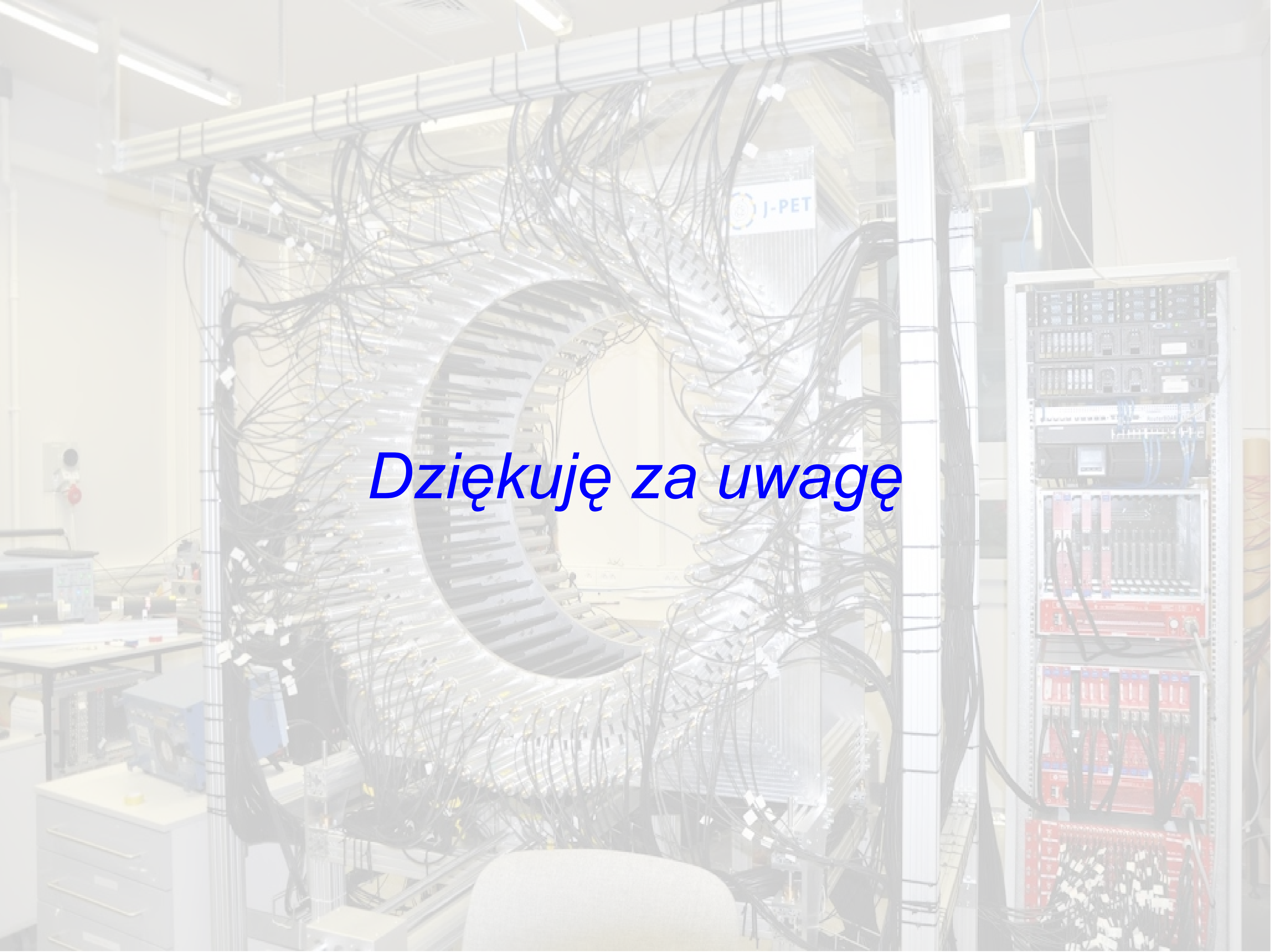
Podsumowanie

1. Pierwszy na świecie tomograf PET
   zbudowany w oparciu o scyntylatory plastikowe zbiera dane

2. Eksperymentalne potwierdzenie symulacji możliwości redukcji tła
   oraz identyfikacji kwantów gamma z bezpośredniej anihilacji

3. Finalizacja synchronizacji czasowej układu i rozpoczęcie analizy *GPS*

4. Dalszy rozwój detektora z wykorzystaniem SiPM



Dziękuję za uwagę