# Monte Carlo simulations for the J-PET scanner


Wojciech Krzemień
On behalf of the J-PET collaboration

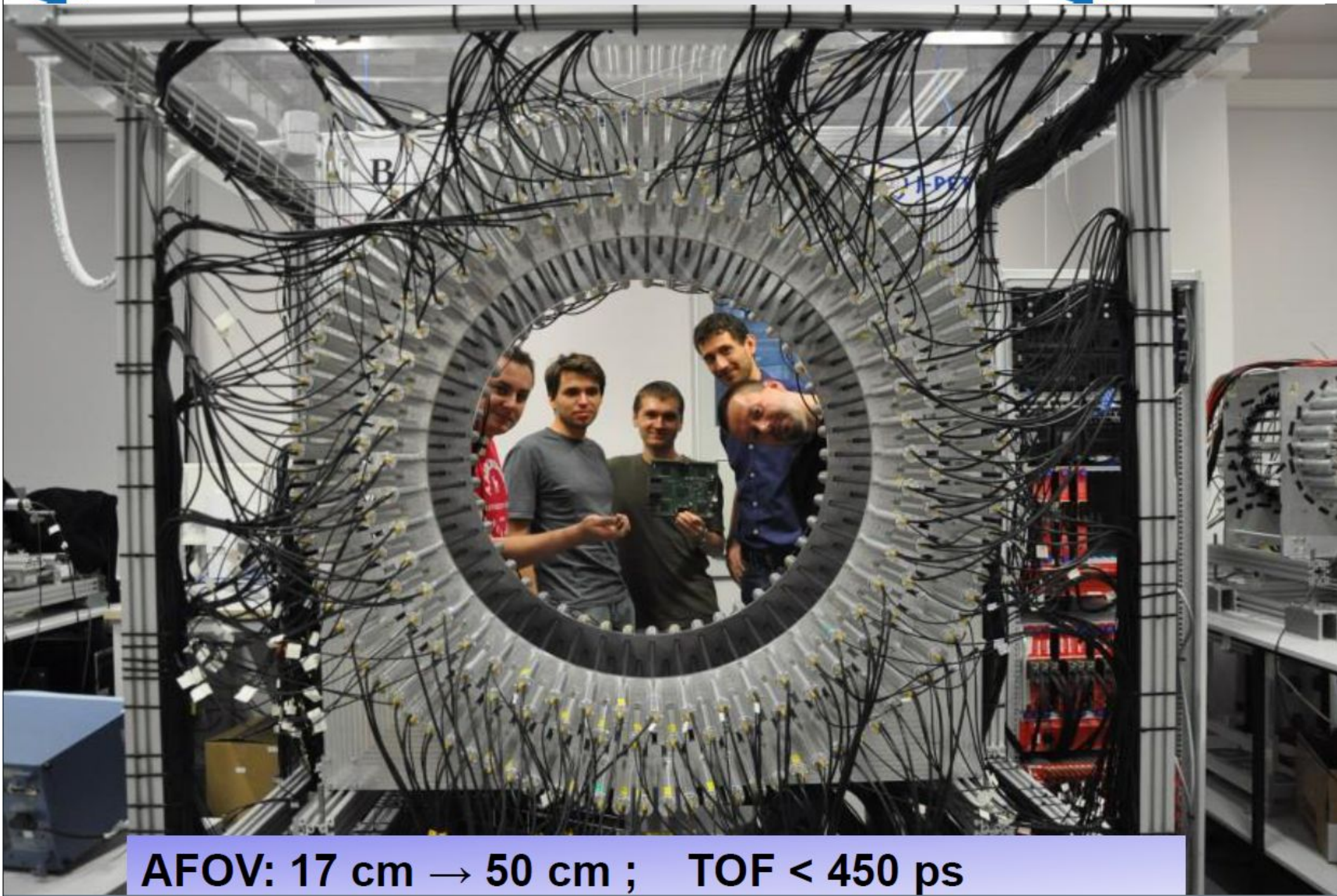
Gate Technical Meeting
Lyon, 04.07. 2019

NATIONAL CENTRE
FOR NUCLEAR RESEARCH
ŚWIERK

# Outline

- J-PET project
- **Monte Carlo applications and extensions:**
  - **Scanner performance studies according to NEMA norms**
  - **Positronium imaging**
  - Quantum entanglement/polarization studies
  - Discrete symmetries studies
  - Proton therapy monitoring

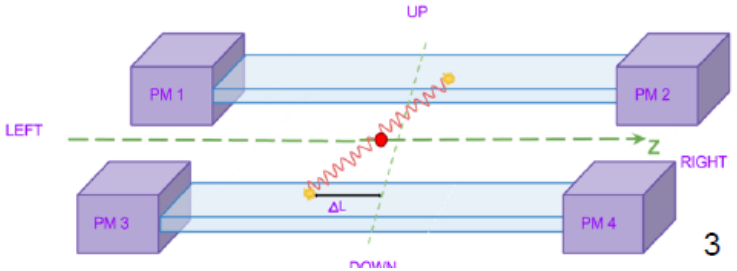
# Jagiellonian PET



AFOV: 17 cm → 50 cm ;  TOF < 450 ps

# Cost-effective total body scanner

$$\Delta l = \frac{(t_2 - t_1)\cdot v}{2} \cong \frac{(t_2 - t_1)\cdot c}{4}$$



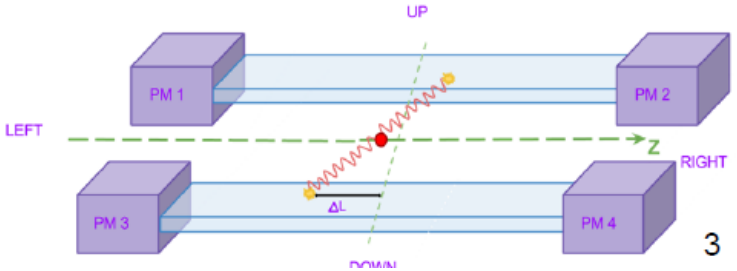

$$\Delta x = \frac{(t_l - t_r)\cdot c}{2} \Longrightarrow \Delta x = \frac{\Delta t}{2}\cdot c$$

P. Moskal, P 388 555 [WIPO ST 10/C PL388555] (2009), PCT/PL2010/00062 (2010), WO2011008119, US2012112079, JP2012533734, EP2454612.

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

# Cost-effective total body solution

$$\Delta l = \frac{(t_2 - t_1)\cdot v}{2} \cong \frac{(t_2 - t_1)\cdot c}{4}$$




3

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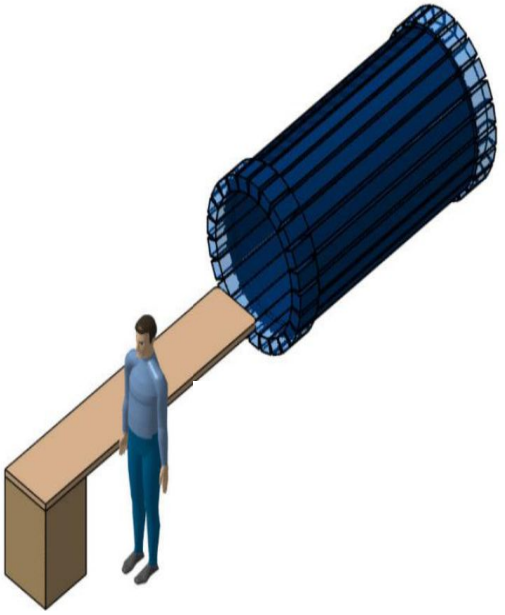


P. Moskal, P 388 555 [WIPO ST 10/C PL388555] (2009), PCT/PL2010/00062 (2010), WO2011008119, US2012112079, JP2012533734, EP2454612.

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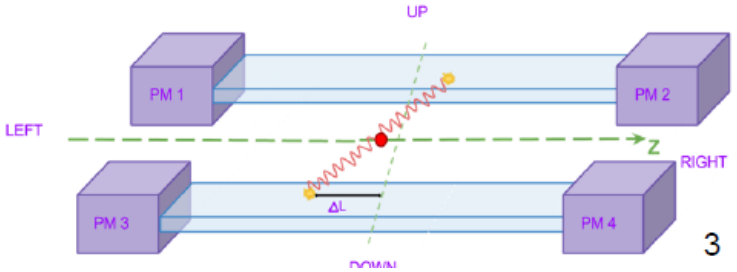


3

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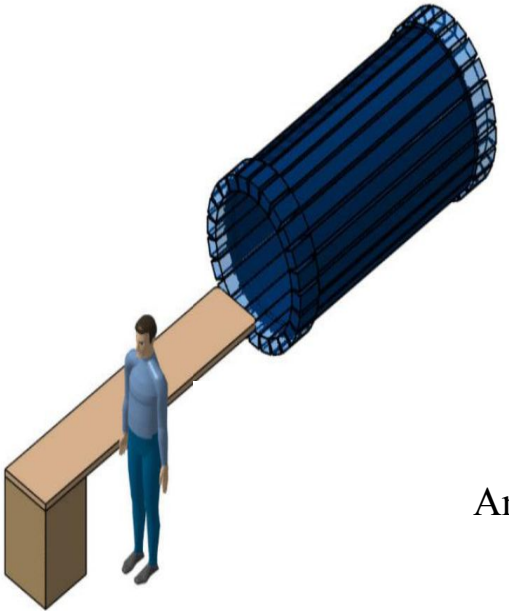


## Change of the paradigm

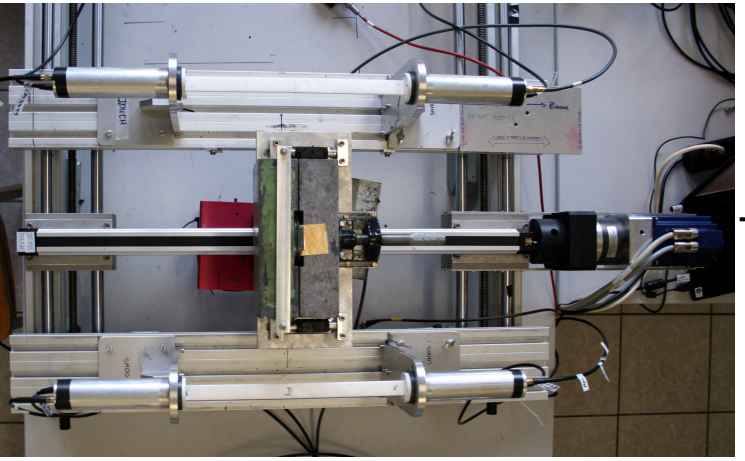
| | | |
|---|---|---|
| **Crystal** | → | **Plastic** |
| Energy | → | Time |
| High efficiency | → | Low efficiency |
| Photoeffect | → | Compton scattering |
| Low acceptance | → | High acceptance |
| Analog electronics | → | Digital electronics |
| Triggering | → | No master trigger |

P. Moskal, P 388 555 [WIPO ST 10/C PL388555] (2009), PCT/PL2010/00062 (2010), WO2011008119, US2012112079, JP2012533734, EP2454612.

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

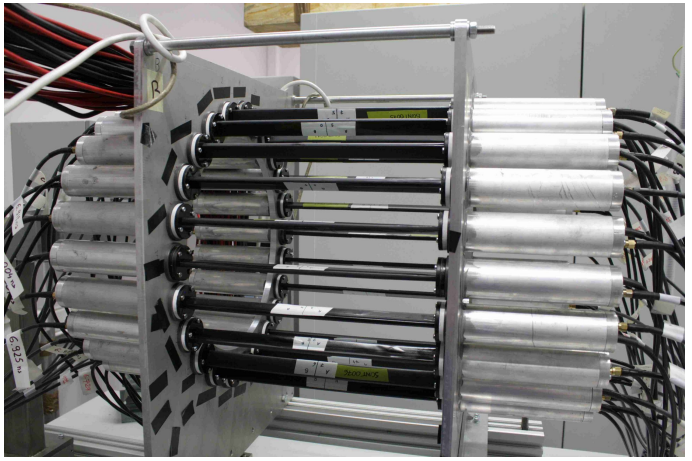
2012

2 strips

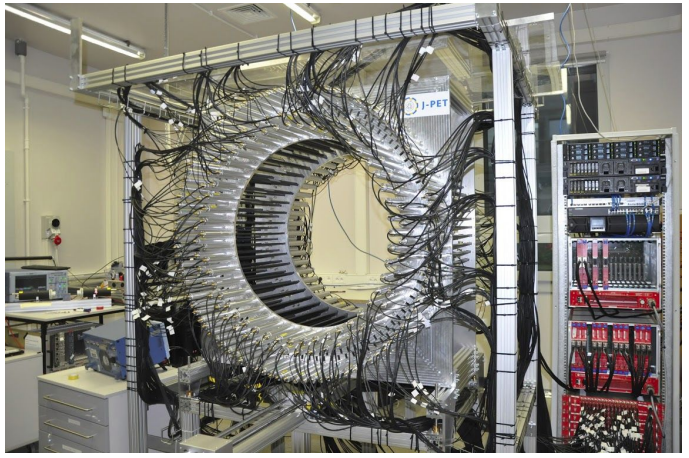


2014

48 plastic strips



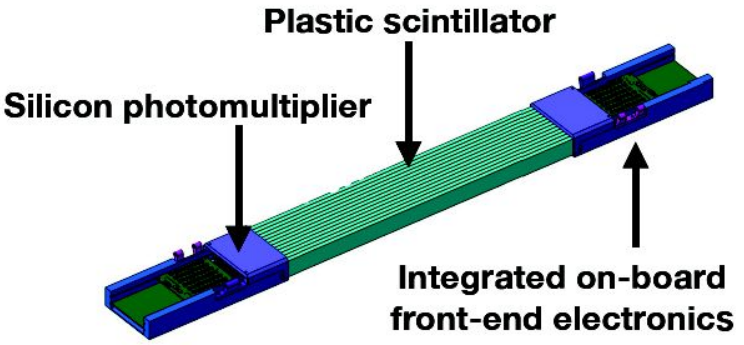
192 plastic strips



24 modules
312 strips

**Modular Prototype**

light weight, portable, reconfigurable



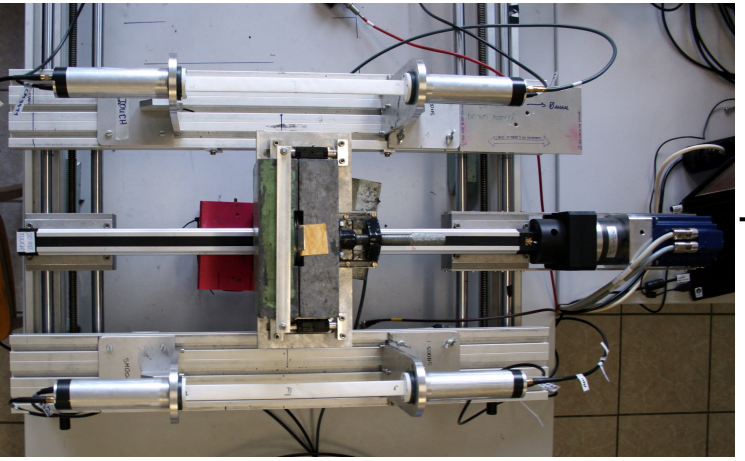

2016

- Three cylindrical layers of EJ-230 plastic scintillator strips (7x19x500 $mm^3$)
- Vacuum tube photomultipliers

2018

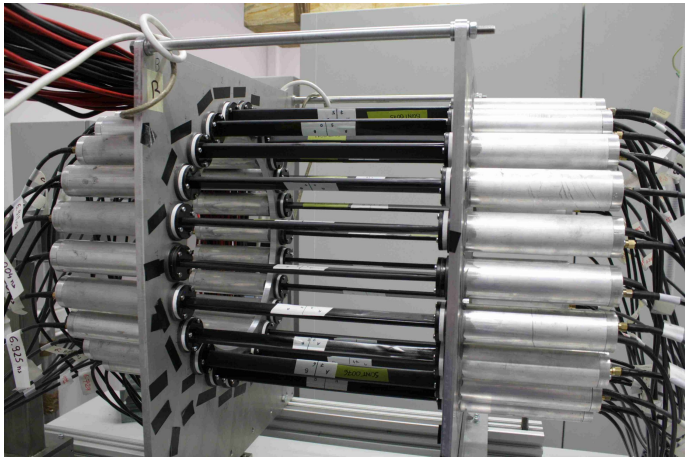
2012

2 strips



2014

48 plastic strips



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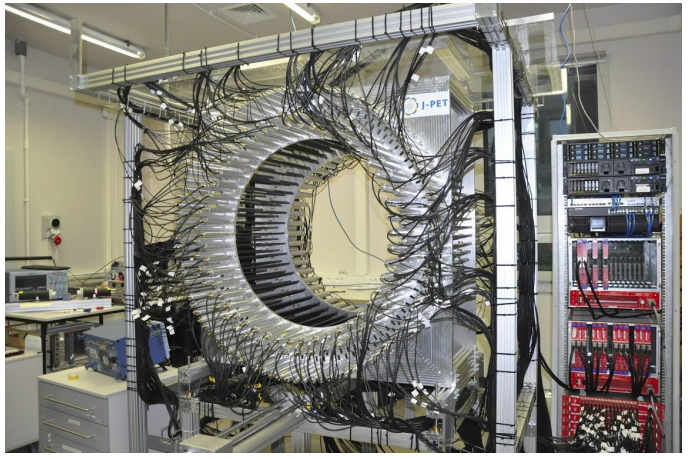

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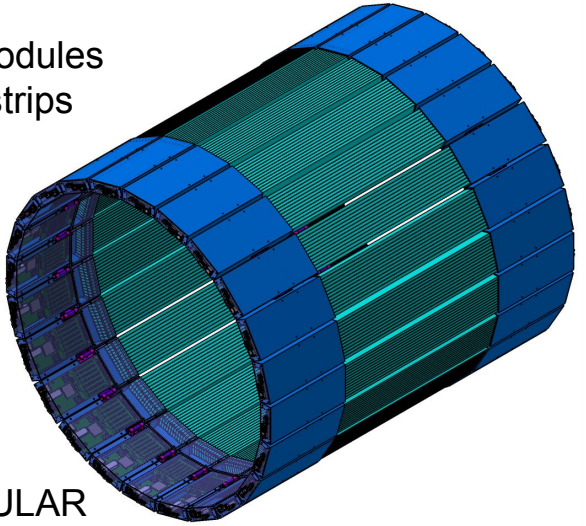


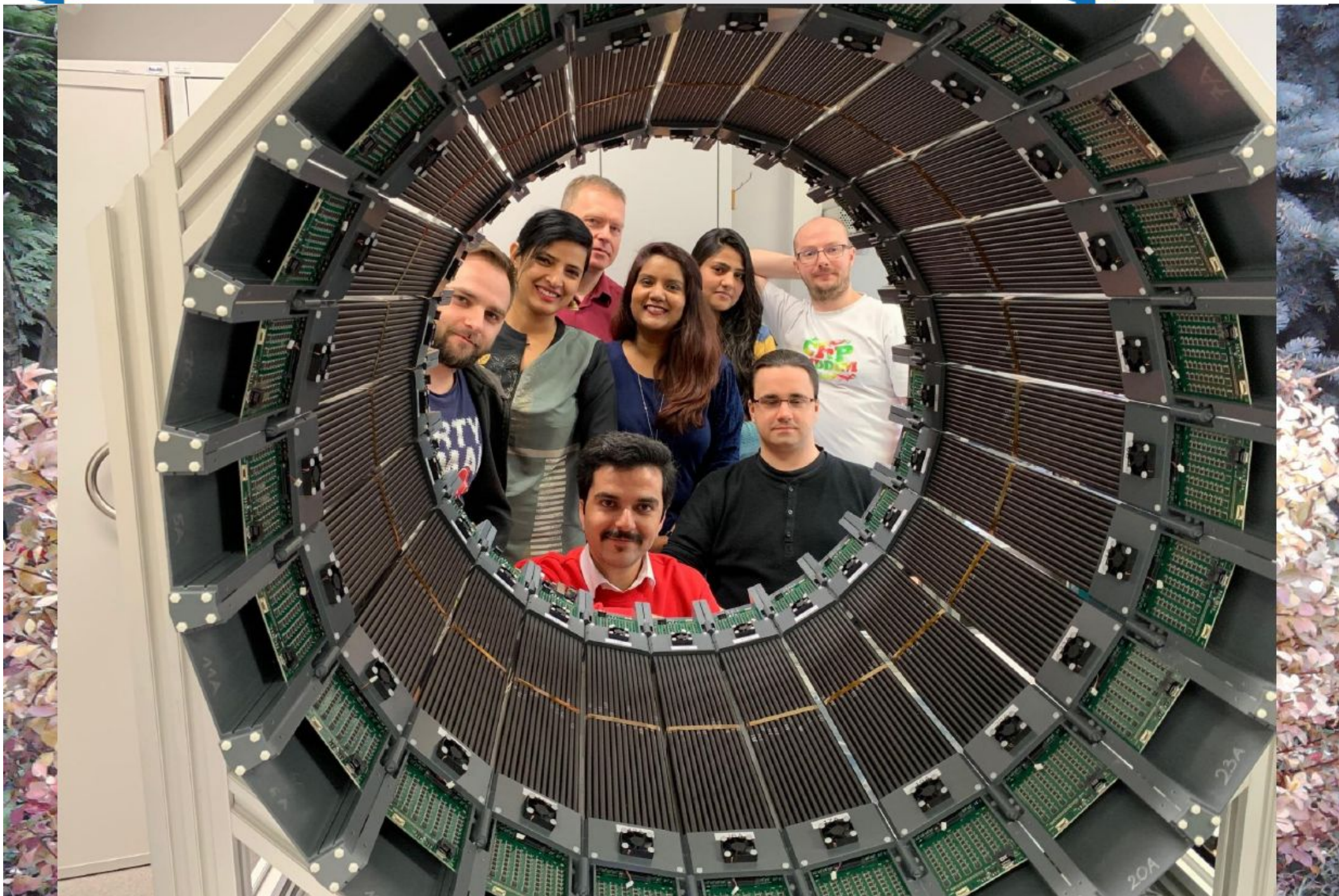
MODULAR

2016

2018

- Three cylindrical layers of EJ-230 plastic scintillator strips (7x19x500 $mm^3$)
- Vacuum tube photomultipliers

# Jagiellonian PET



# J-PET Software@GitHub

https://github.com/JPETTomography

J-PET collaboration

http://koza.if.uj.edu

your organization's avatar

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**21 repositories**

Find a repository… | Type: All | Language: All | Customize pins | New

## J-PET-geant4

Forked from daria137/jpetmc

MC simulations for J-PET using the modified Geant4 package

C++ Apache-2.0 10 0 0 1 Updated 8 hours ago

## -pet-framework-examples

Example analyses based on the J-PET Analysis Framework

C++ Apache-2.0 19 1 0 3 Updated 15 hours ago

## RectangularScintillator

Library for Monte Carlo simulation of photons movement in scintillator of ectangular shape (C++11)

C++ 1 0 0 0 Updated 3 days ago

## Gate

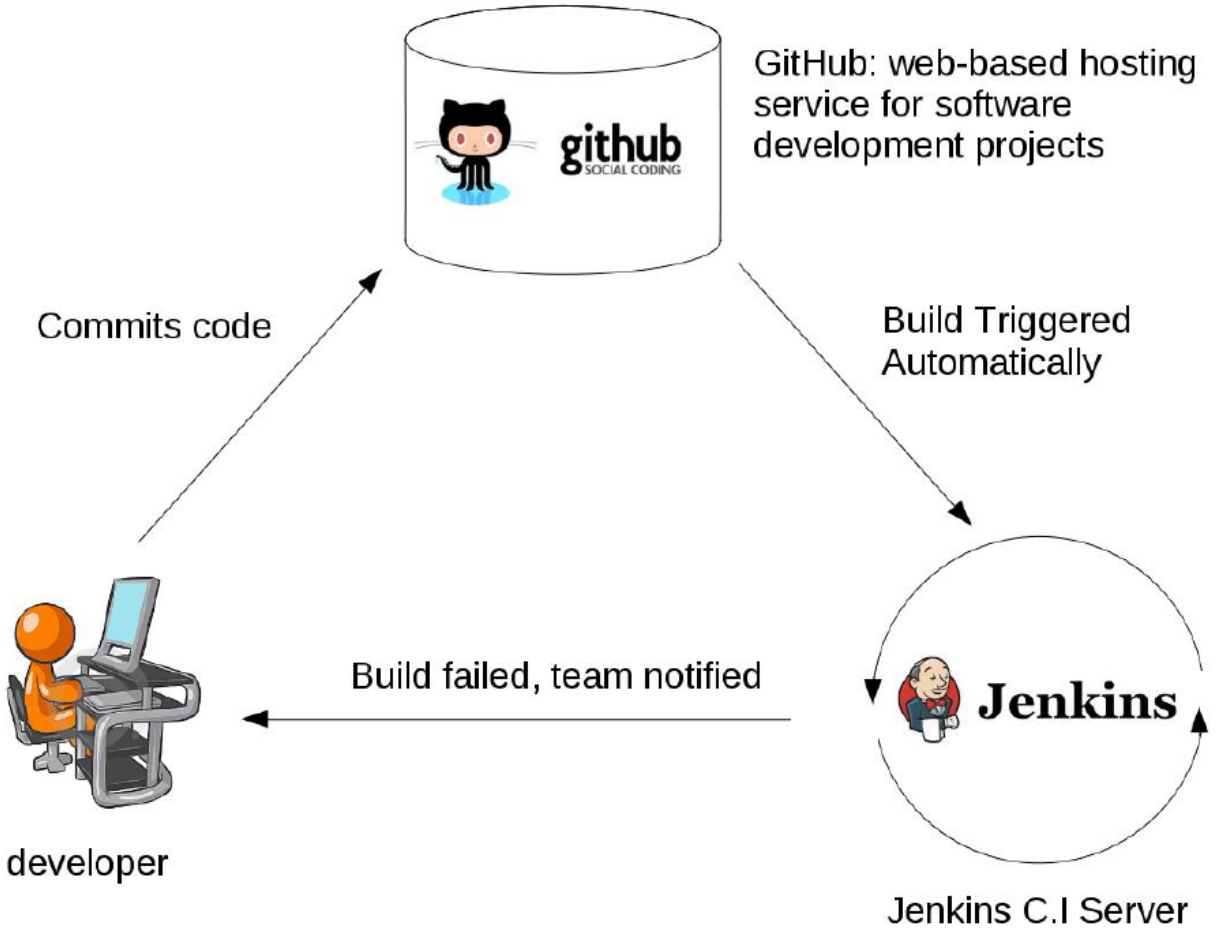
Top languages

C++ Python Haskell R Mathematica

People 23 >


0 seats left — Buy more

# Continous integration and testing




Travis CI

# J-PET software workshops & tutorials

- Gate Output J-PET Analyzer( GOJA) Worshop, 23.24 05. 2019
- STIR FBP 3D Workshop, NCBJ, Warszawa, 22.03.2018
- GATE and Reconstruction Workshop, NCBJ, Warszawa, 22.03.2018
- Second J-PET Framework Workshop, UJ, Kraków, 20-21.03.2017
- J-PET Software Workshop, UJ, Kraków, 07-08. 07.2016
- First J-PET Framework Workshop, NCBJ, Warszawa, 09.04.2015

# Performance studies of the J-PET scanner according to the NEMA norms

IOP Publishing Phys. Med. Biol. 63 (2018) 165008 (17pp) https://doi.org/10.1088/1361-6560/aad29b

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

OPEN ACCESS

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 Curceanu[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]

[1] Department of Complex Systems, National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland
[2] Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, 30-348 Kraków, Poland
[3] INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy
[4] Institute of Physics, Maria Curie-Skłodowska University, 20-031 Lublin, Poland
[5] Faculty of Physics, University of Vienna, 1090 Vienna, Austria
[6] High Energy Physics Division, National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland
[7] Department of Physics, College of Education for Pure Sciences, University of Mosul, Mosul, Iraq

**E-mail:** pawel.kowalski@ncbj.gov.pl

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

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13 April 2018

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25 June 2018

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# Performance studies of the J-PET scanner according to the NEMA norms

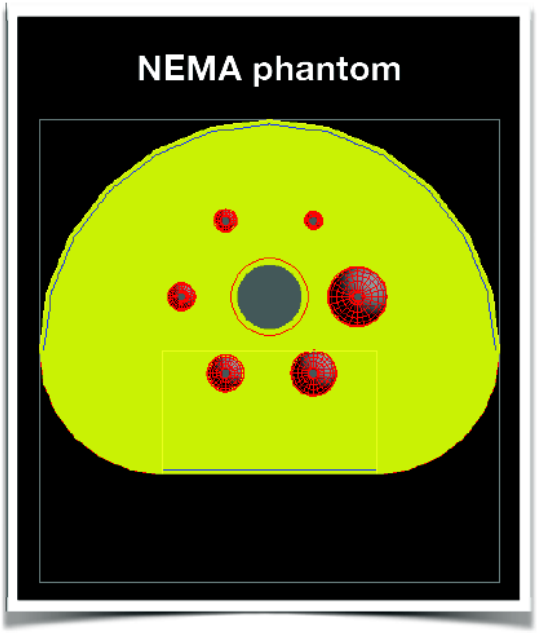
Geometry optimization of the prototype device

- **J-PET detector setup configurations**

  - Plastic length: L (20, 50, 100cm)
  - Diameter: D (75, 85, 95cm)
  - Number of detection layers (1 or 2)
  - Thickness of plastic strips (20x4cm$^2$ or 20x7cm$^2$)
  - Readout: PMT, SiPM and SiPMs combined with wavelength shifters

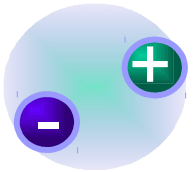
- **National Electrical Manufacturers Association norm (NEMA)**

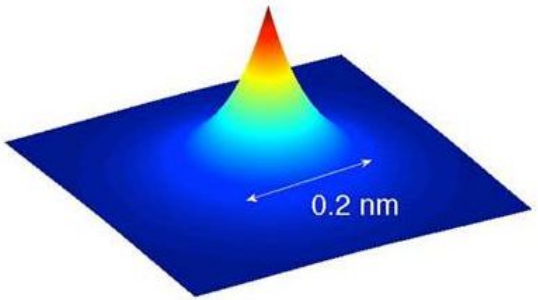
  - spatial resolution (100cm): **3mm (radial, tangential) and 20mm (axial)**
  - sensitivity (2-layer, 100cm): **14.9 cps/kBq$^{-1}$**
  - scatter fraction (sin. method): **35%**
  - noise equivalent count rate (NECR): **110 kcps @63 kBq cc$^{-1}$** (2 layers)




The above studies confirmed that the PET scanner based on plastic scintillator strips may achieve NEMA characteristics comparable to those obtained for commercially used PET scanners. We believe that the presented results may be improved.

# Implementation of ortho-positronium decays






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

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

Positronium tomography

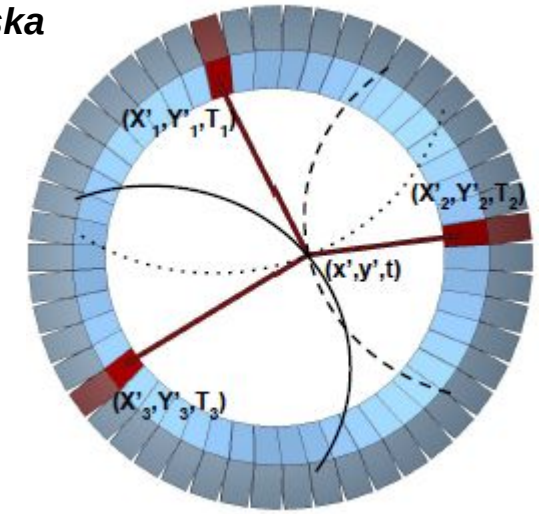
Fundamental physics studies (symmetries)

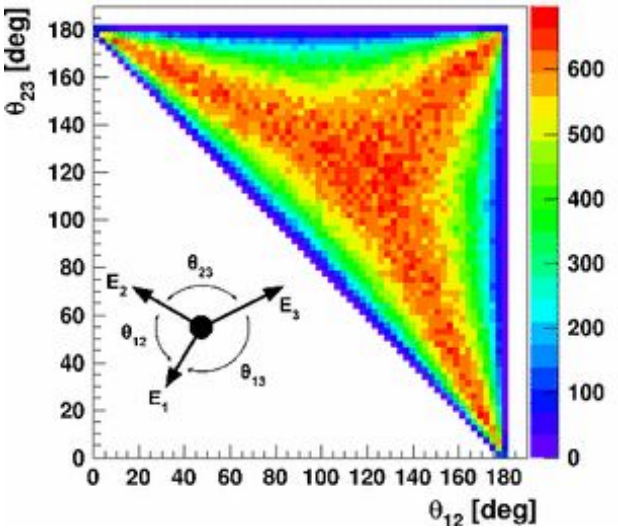
Quantum entanglement tomography

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

# Implementation of ortho-positronium decays

***Daria Kisielewska***




Implementation of QED-complient description of orto-positronium decay

Positronium tomography

Fundamental physics studies (symmetries)

Quantum entanglement tomography

1) P. Moskal et al., Phys. Med. Biol. 64 (2019) 055017
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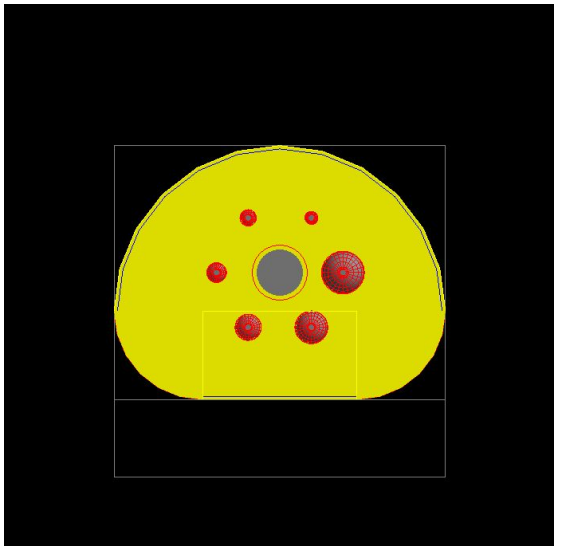
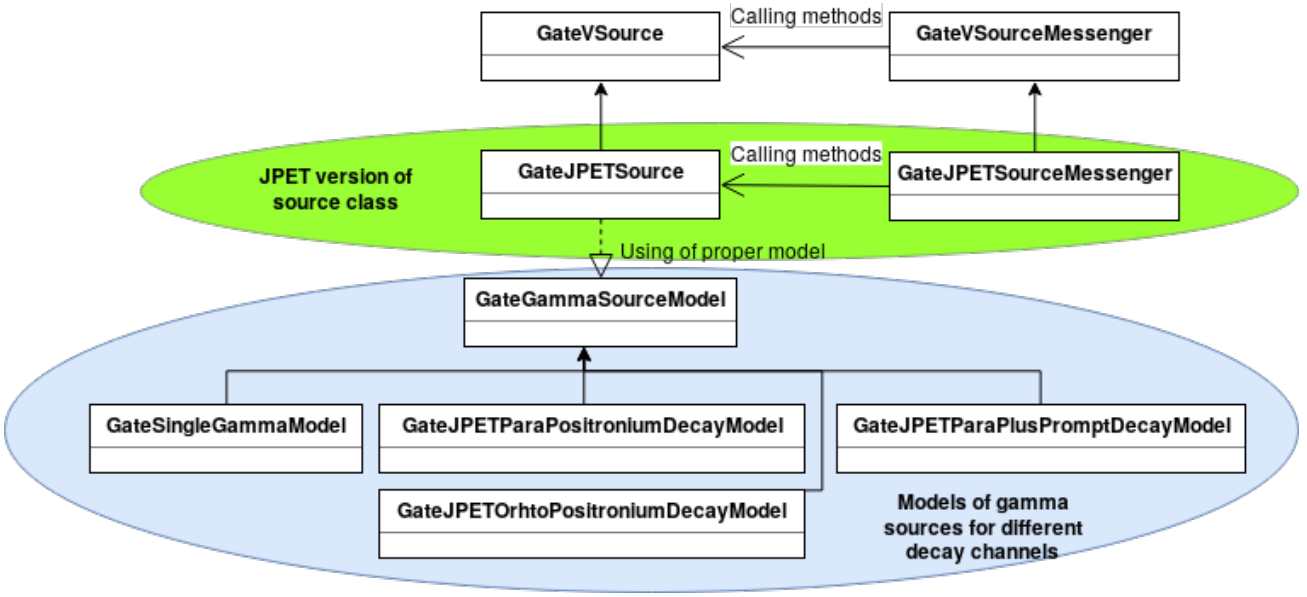
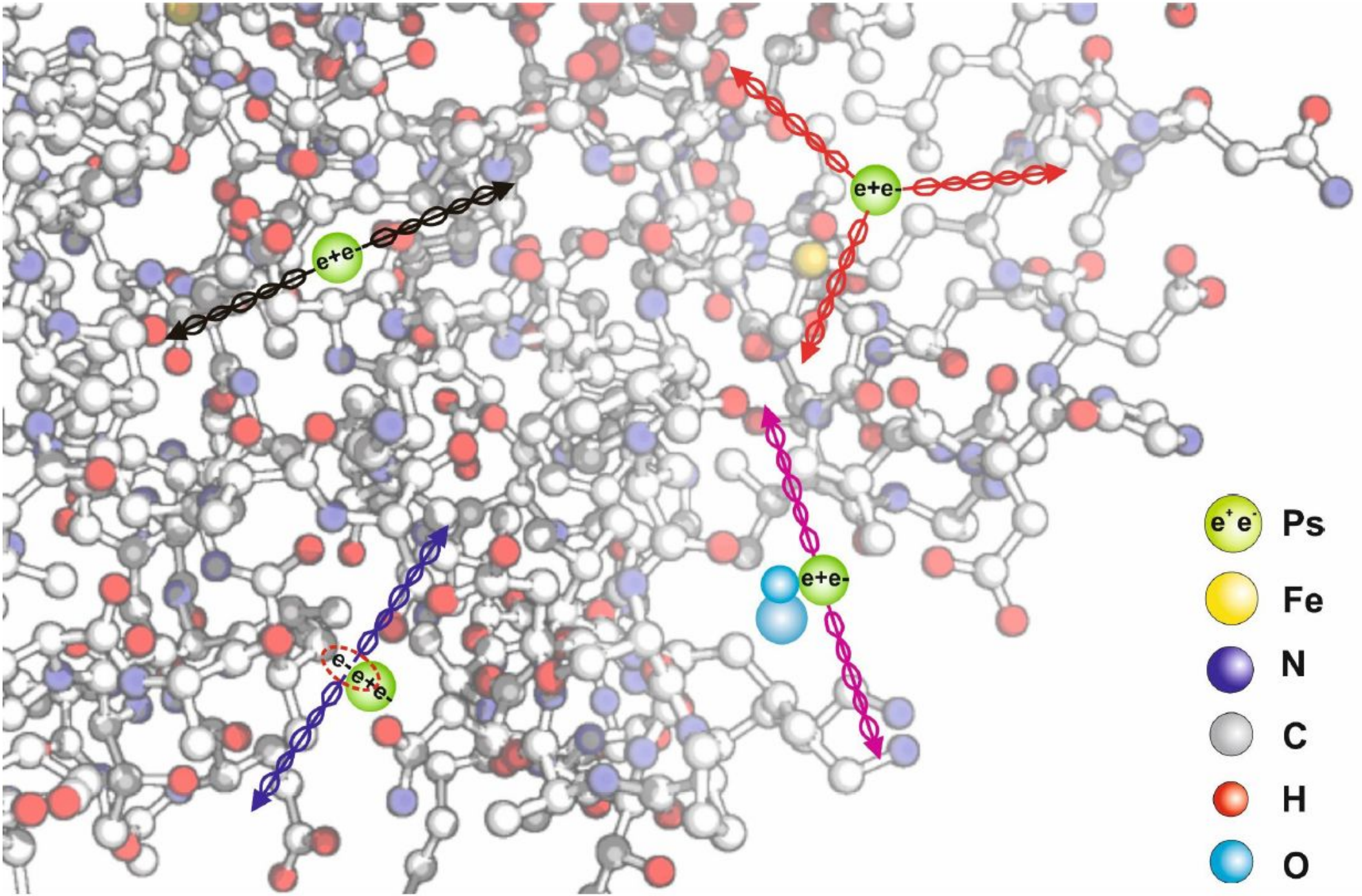
# Extension to new sources and decays

- Ortho-positronium
- Para-positronium
- Non-pure emitters
  (e.g. scandium sources)
- Polarization degrees of freedom

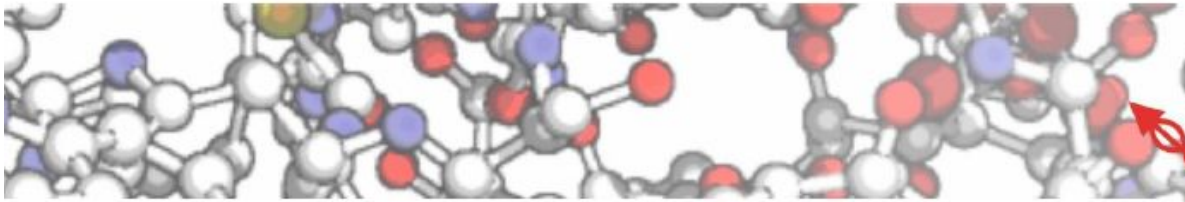




# Model of the hemoglobin molecule



# Model of the hemoglobin molecule



https://www.nature.com/articles/s42254-019-0078-7

Nature Reviews Physics

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 research is needed to take full advantage of what positronium decays reveal.

**Positronium Physics**

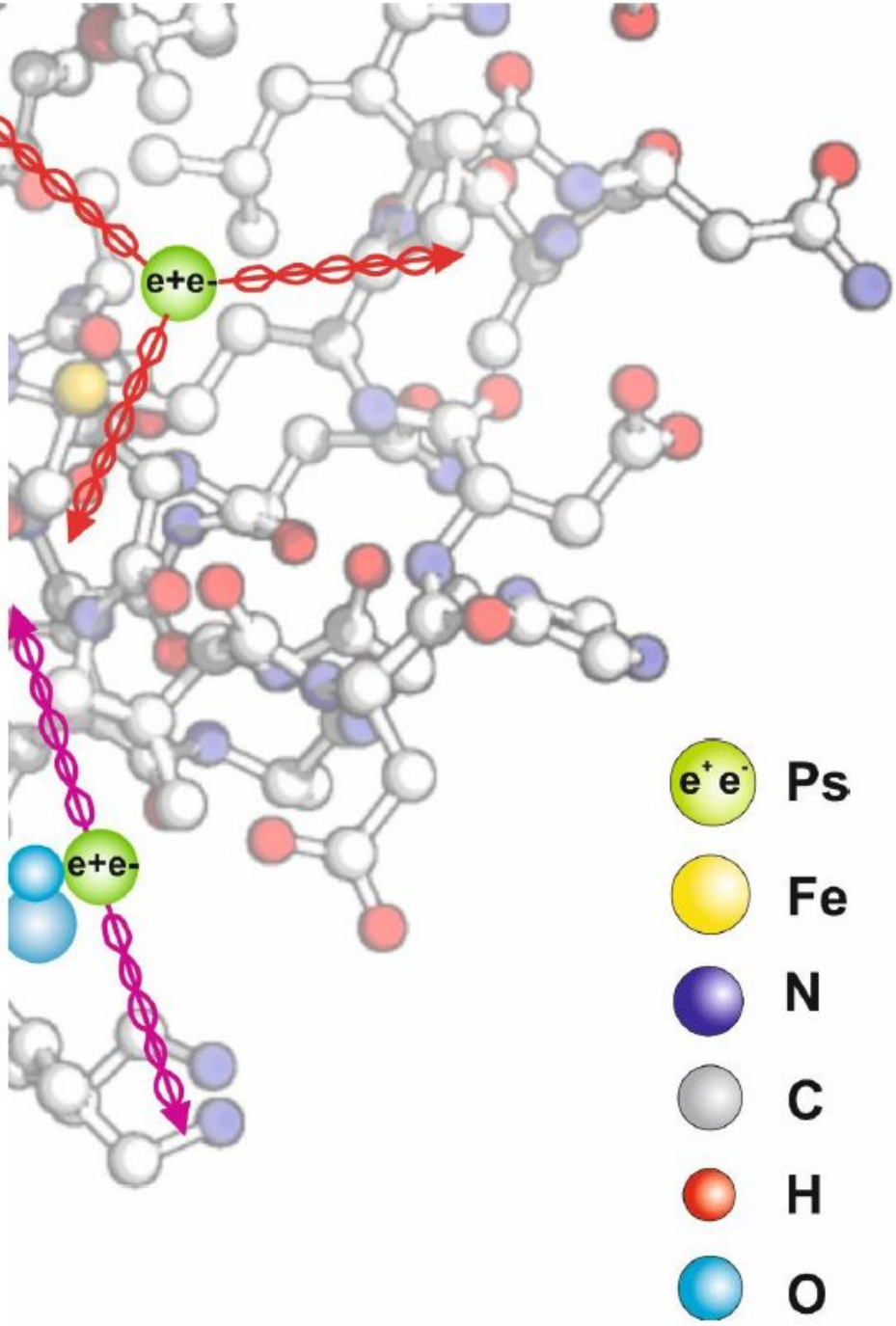
Positronium atoms are bound states of an electron and its antiparticle, the positron. Positronium has two ground states, which are distinguished by their decay processes and their lifetimes, which differ by a factor of more than 1,000. Spin-zero para-positronium is even under charge conjugation symmetry — 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.

**Positronium decays in biological material**

However, inside biological materials, the picture is more complicated. In that setting, positronium mean lifetime and formation probability depend on the healthiness of the material, its nanostructure and concentration of bioactive molecules; these factors are indicative of the stage of development of metabolic disorders of human tissues. Thus, positronium decay studies can provide new input typically of similar strength, with the details dependent on the size of intermolecular voids and the concentration of bio-active molecules. Key observables are the positronium lifetime in the medium, the ratio of two-photon to three-photon decay rates and the probability of positronium production in the biomaterial.

**Measuring positronium lifetimes**

The fate of the positronium atom is investigated by positron annihilation lifetime spectroscopy (PALS). The advantage of using PALS to investigate the structural transformations and micro-environmental changes of a biological sample is that PALS is nondestructive and preserves the structural characteristics of the sample. In particular, PALS can test for structural changes in biological polymeric systems such as chitosan, bilayer interphases (emulsions, liposomes and micellar systems) or self-assembled biomimetic systems as bio-membranes. In terms of specific membrane diffusion and permeability properties, PALS is sensitive to the nanostructural changes caused by the formation of bioactive nano-



IOP Publishing Phys. Med. Biol. 64 (2019) 055017 (14pp) https://doi.org/10.1088/1361-6560/aafe20

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

OPEN ACCESS

PAPER

# Feasibility study of the positronium imaging with the J-PET tomograph

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21 December 2018

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

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6 High Energy Physics Division, National Centre for Nuclear Research, 05-400 Otwock-Świerk, Poland
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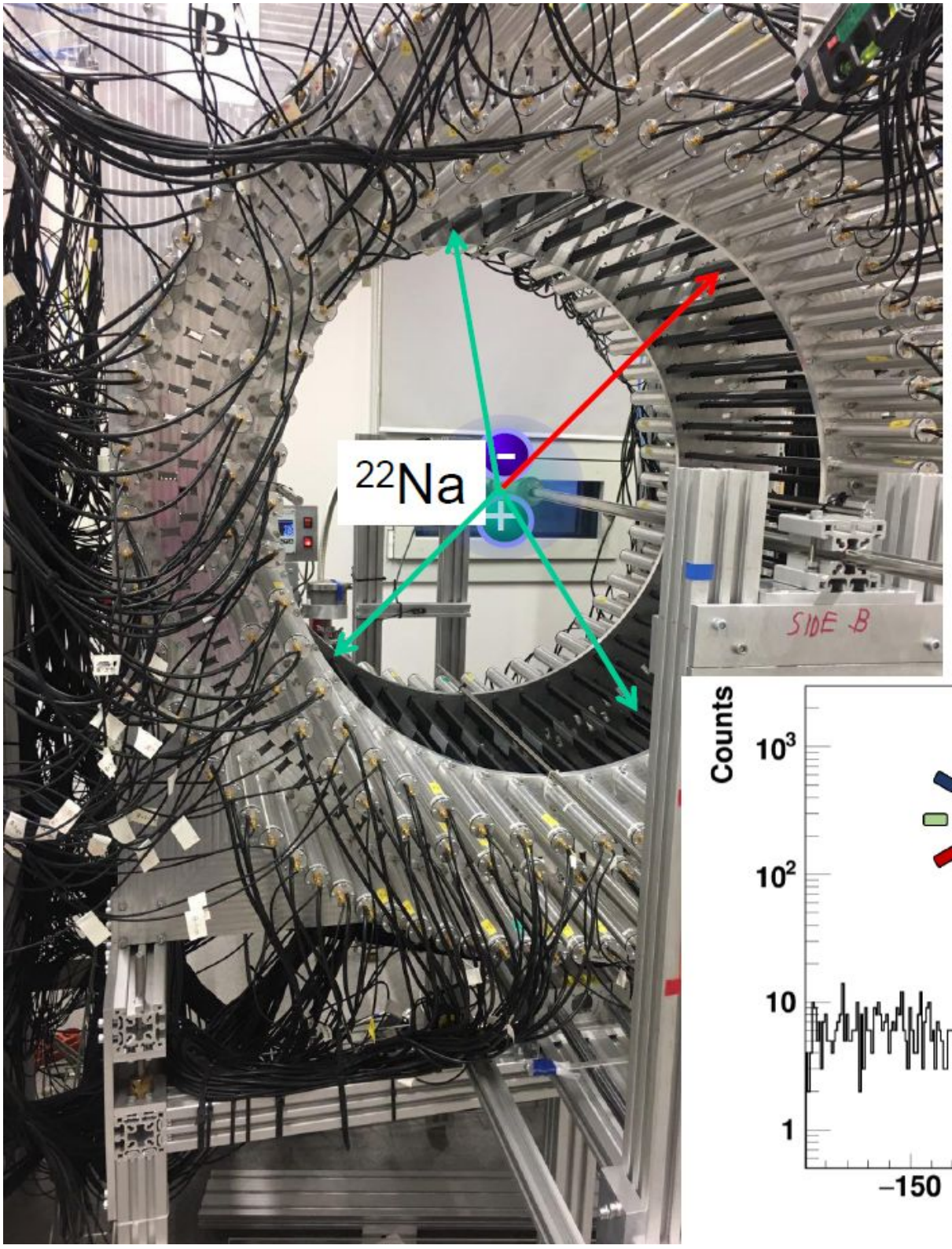
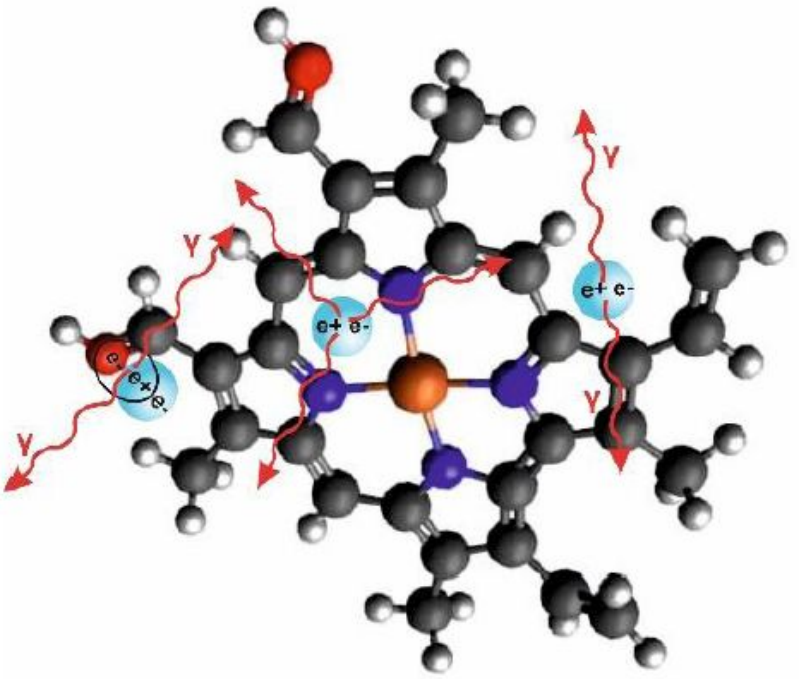
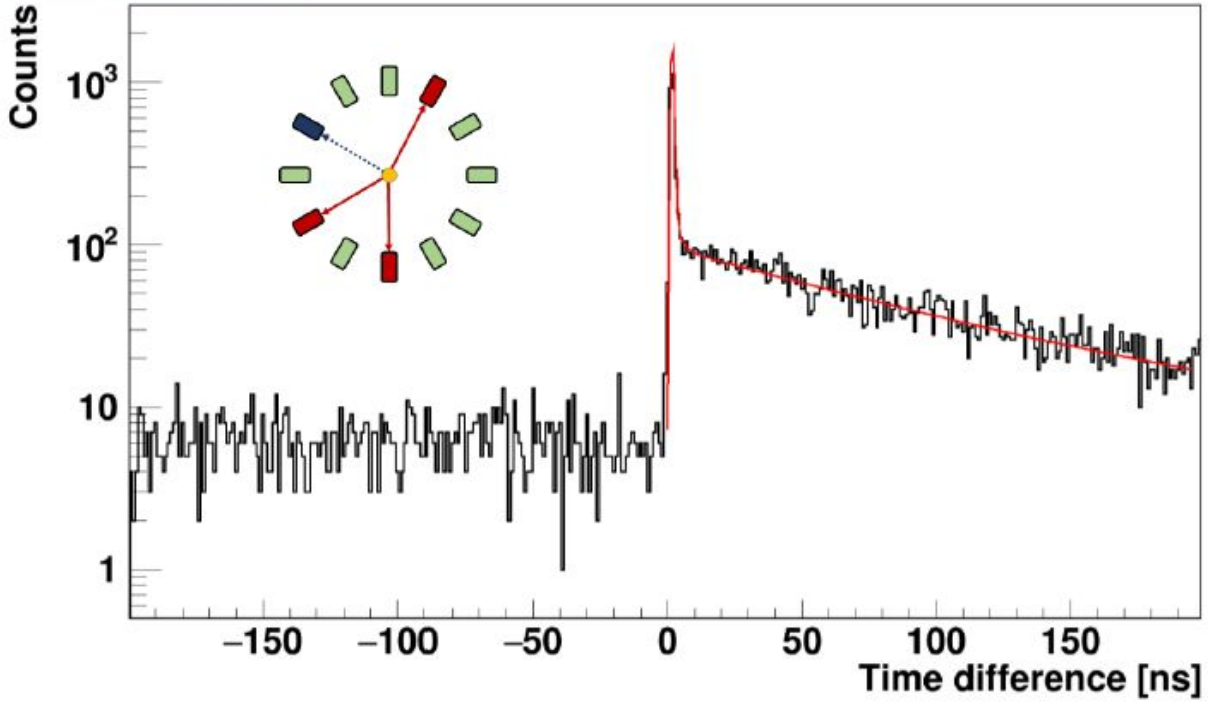
**Keywords:** positron emission tomography, positronium atom, J-PET

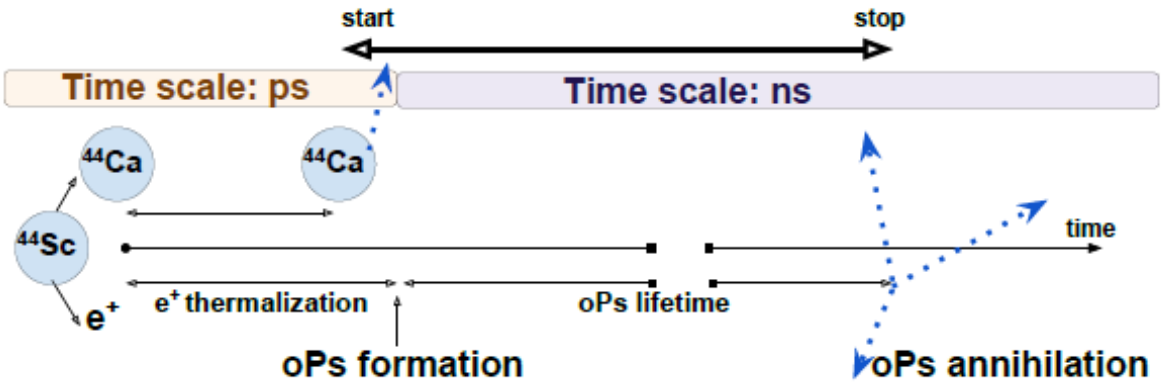
## Abstract

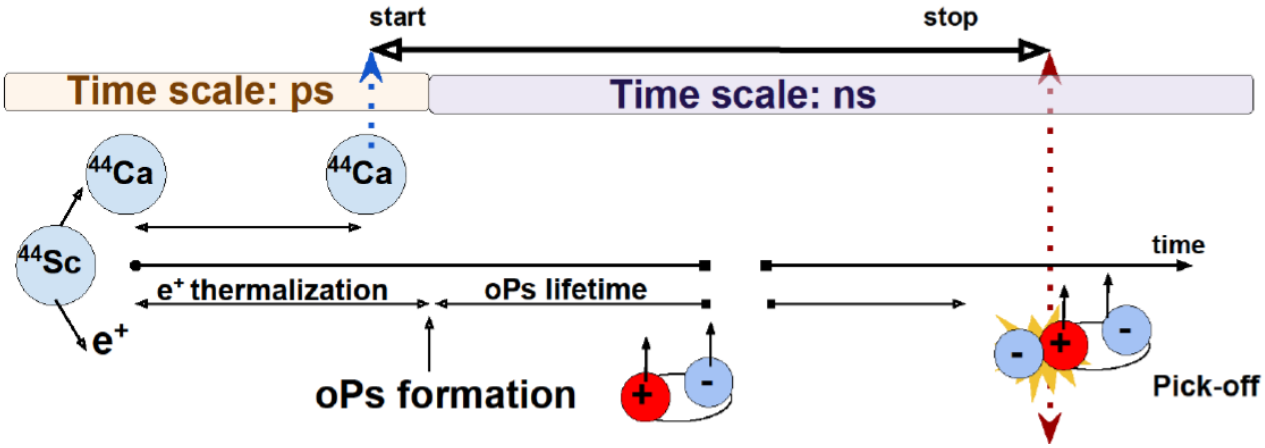
A detection system of the conventional PET tomograph is set-up to record data from $e^+e^-$ annihilation into two photons with energy of 511 keV, and it gives information on the density distribution of a radiopharmaceutical in the body of the object. In this paper we explore the possibility of performing the three gamma photons imaging based on ortho-positronium

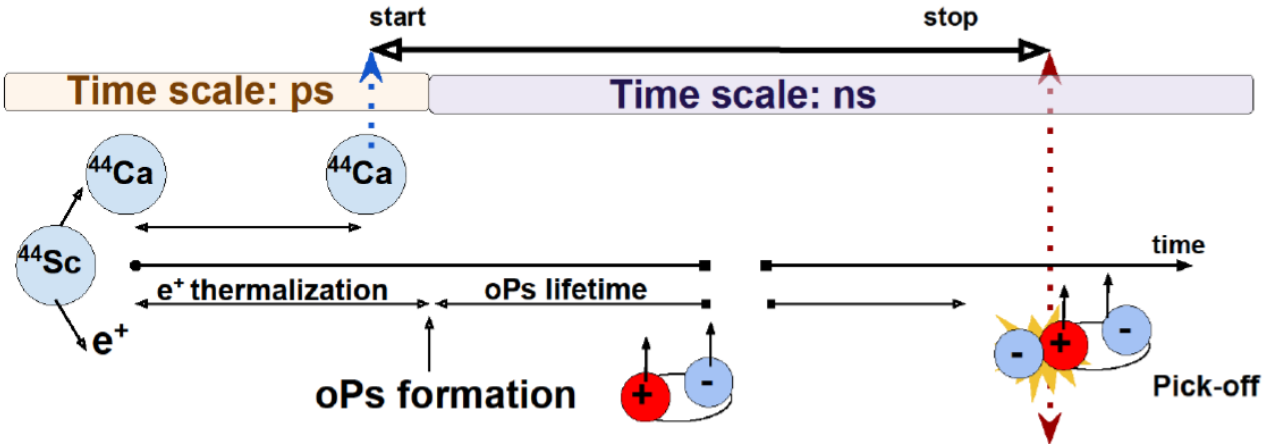

$^{22}$Na
SIDE B

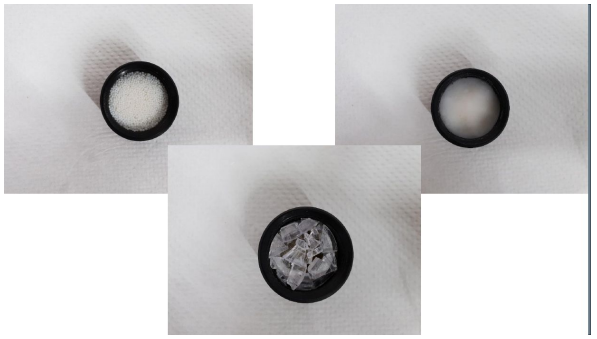

γ
γ
γ
γ
e+ e-
e+ e-
e+ e-


Counts
$10^3$
$10^2$
10
1
−150
−100
−50
0
50
100
150
Time difference [ns]


start
stop
Time scale: ps
Time scale: ns
$^{44}$Ca
$^{44}$Ca
$^{44}$Sc
$e^+$
time
$e^+$ thermalization
oPs lifetime
oPs formation
oPs annihilation


start
stop
Time scale: ps
Time scale: ns
$^{44}$Ca
$^{44}$Ca
$^{44}$Sc
$e^+$
$e^+$ thermalization
oPs lifetime
oPs formation
time
Pick-off


start
stop
Time scale: ps
Time scale: ns
$^{44}$Ca
$^{44}$Ca
$^{44}$Sc
e$^+$
e$^+$ thermalization
oPs lifetime
oPs formation
time
Pick-off

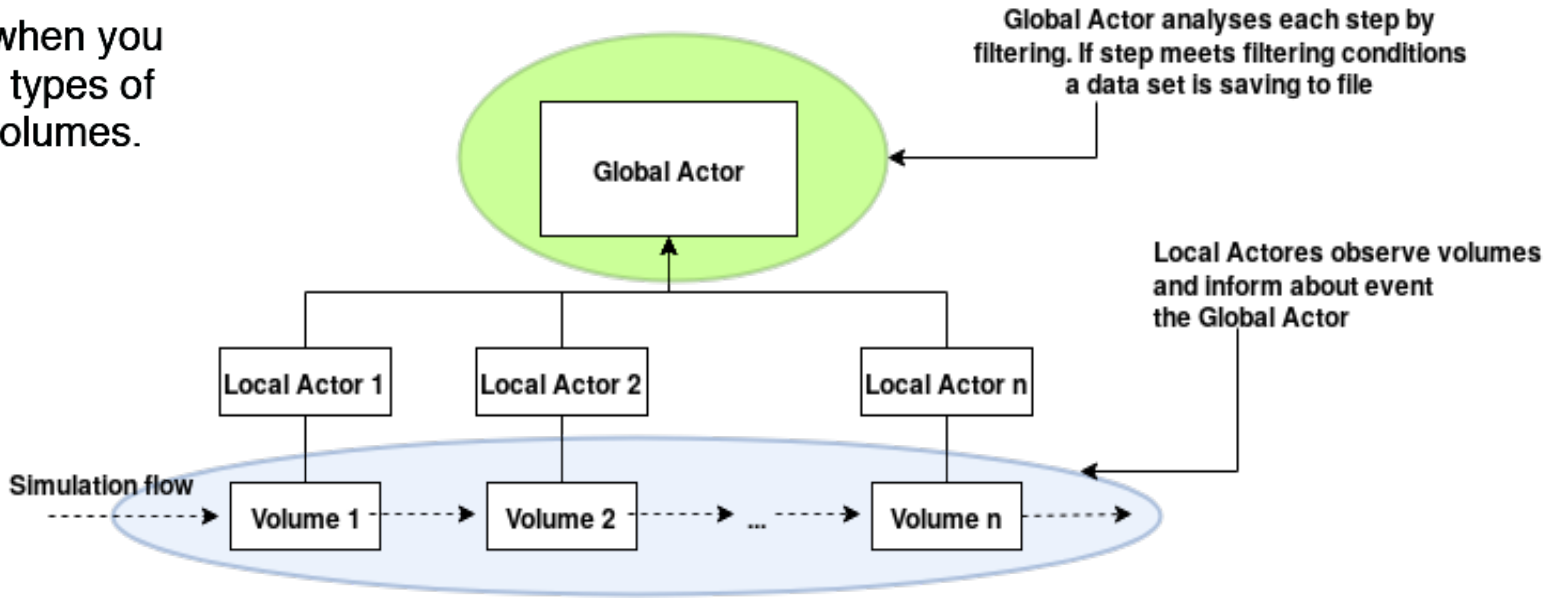


*Mateusz Bała*

# Extension of Actor concept

- **Local Actor (LA)**: a standard actor attached to a volume
- **Global Actor (GA)** can collect data from many volumes
- GA with LA attached, can collect chronologically data from any number of volumes to single ROOT file
- Use GA and LA always when you want to collect the same types of information from many volumes.

- Optional adder included
- Two kind of output formats:
  - standard Ttree
  - grouped in events



# Gate Output J-PET Analyzer (GOJA)

*Paweł Kowalski*

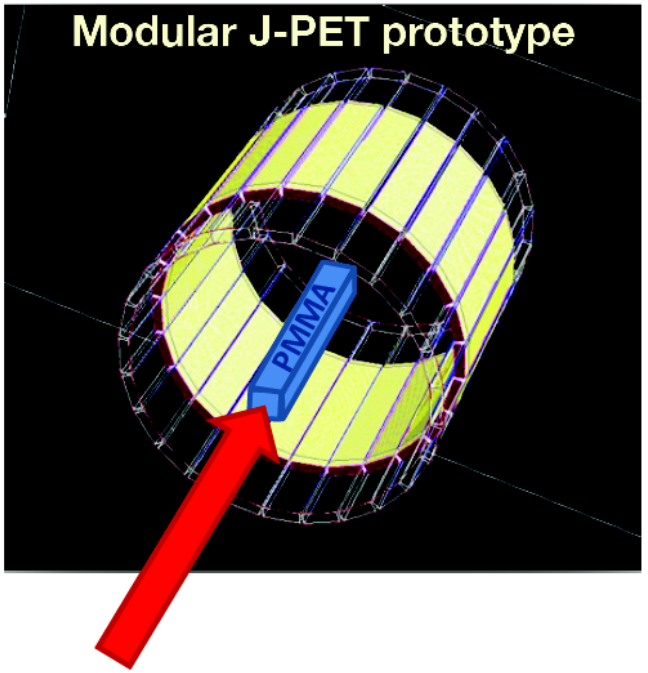
**Python**

Several extra tools such e.g job splitter and coincidence maker :

https://github.com/JPETTomography/j-pet-gate-tools

# Proton therapy application

## Simulation setup




**Settings:**

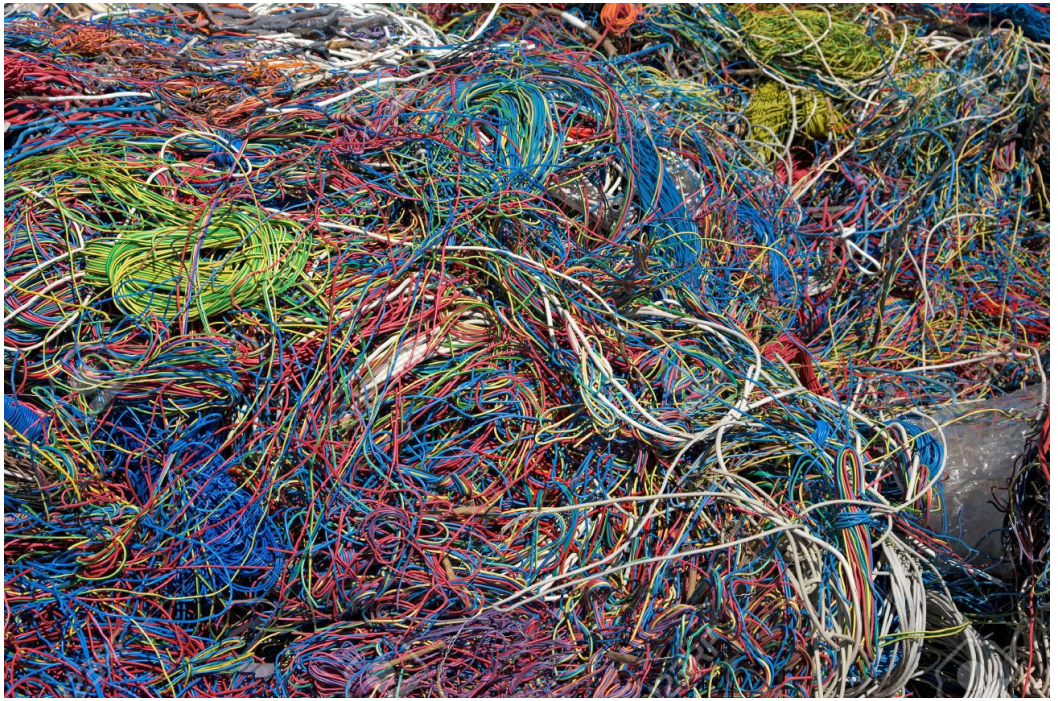
- GATE/Geant4
- Physics list: QGSP_BIC_HP_EMY
- Full simulation
- in-room design
  (in-beam in the future)
- PMMA phantom 10x10x40cm$^3$
- Protons at 150 MeV
- $10^7$ primary protons
- Clinical proton beam model
  used in Krakow for patient treatment

**Scoring:**

- # of annihilations in the PMMA
- # of detected singles
- # of detected coincidences

*Antoni Ruciński's group*

# Thank you for attention



More materials available at:

**http://koza.if.uj.edu.pl/pet/**