Towards Total-Body J-PET with GATE simulations :-)

Wojciech Krzemień
On behalf of the J-PET collaboration

Gate Scientific Meeting
25.04 2023

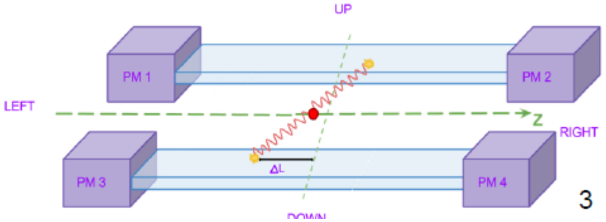
UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE
NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Jagiellonian Positron Emission Tomography

J-PET

Cost-effective total body solution

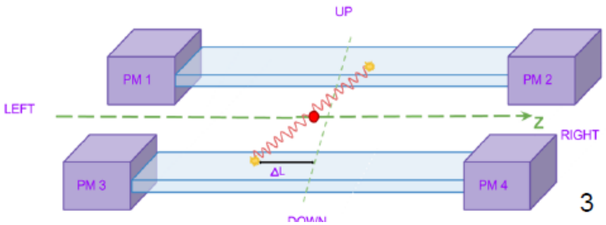
$$\Delta l = \frac{(t_2 - t_1) \cdot v}{2} \cong \frac{(t_2 - t_1) \cdot c}{4}$$



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

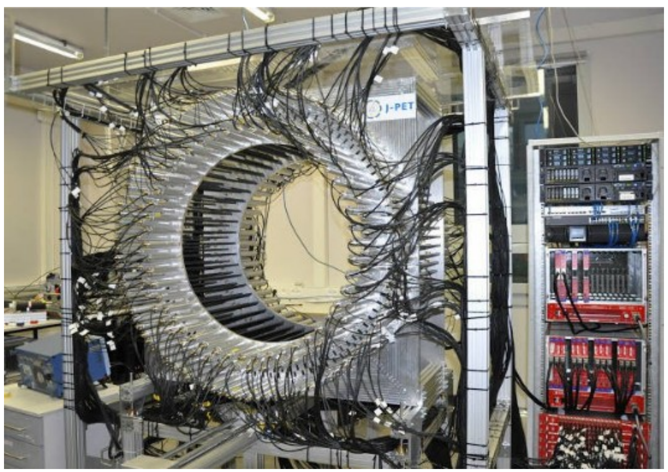
$$\Delta l = \frac{(t_2 - t_1) \cdot v}{2} \cong \frac{(t_2 - t_1) \cdot c}{4}$$

Cost-effective total body solution



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

First prototype



Acta Phys Pol. B 48 (2017) 1567

- 50 cm AFOV
- 192 plastic strips
- Readout → vacuum tube photomultipliers

Cost-effective total body solution

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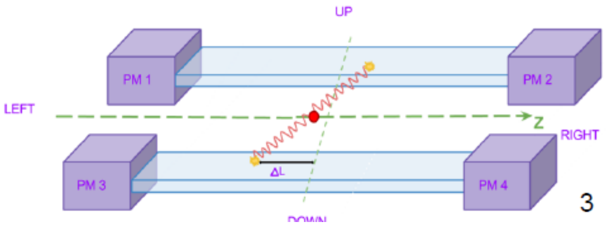

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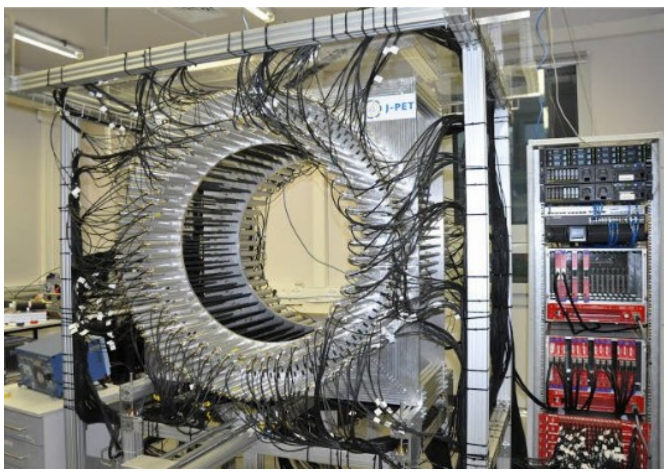

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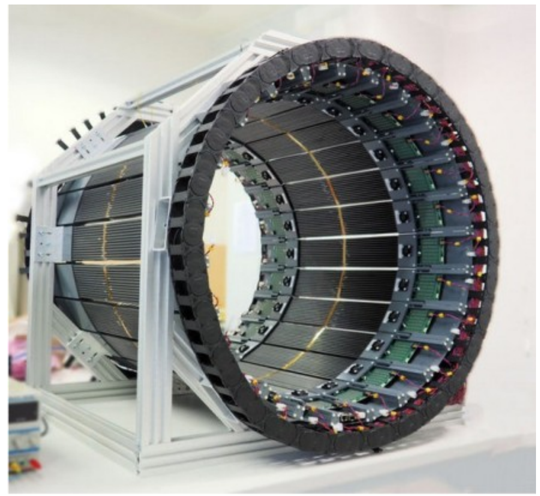
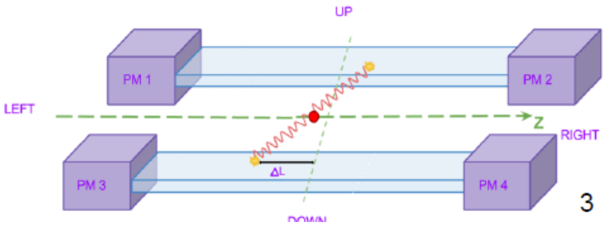
Modular J-PET



- 50 cm AFOV
- 24 modules x 13 strips
- Readout → silicon photomultipliers matrices

Cost-effective total body solution

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



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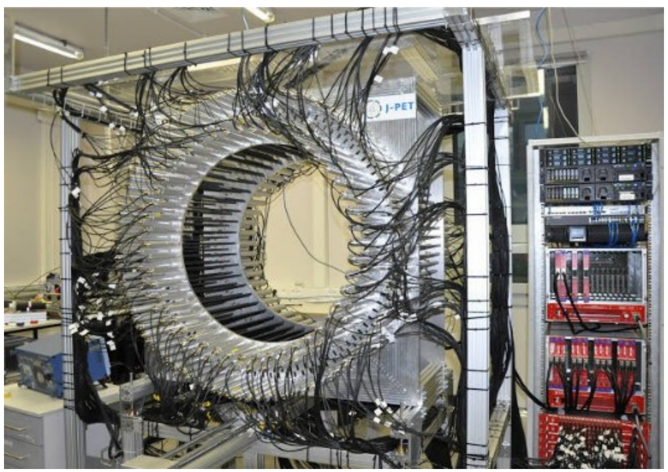
First prototype



Acta Phys Pol. B 48 (2017) 1567

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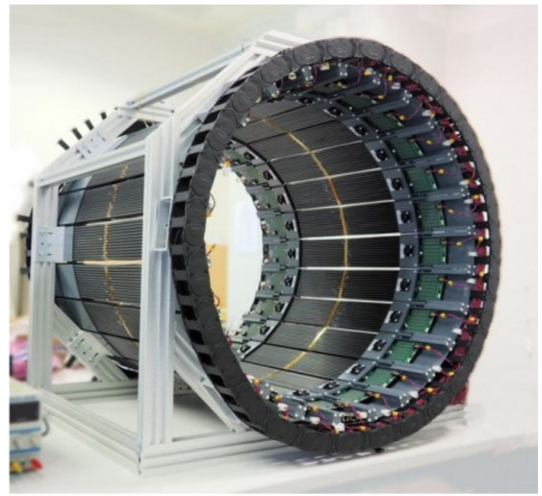
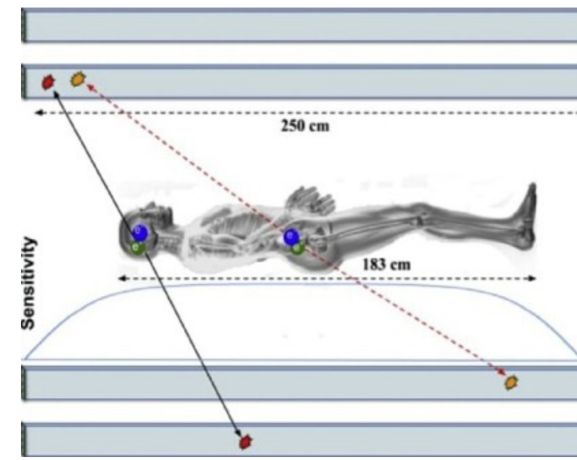
Modular J-PET



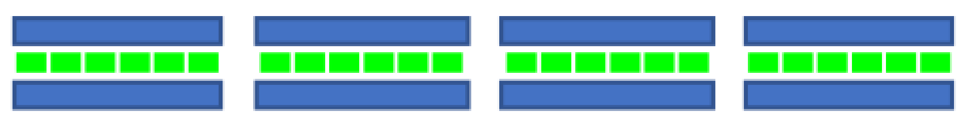
- 50 cm AFOV
- 24 modules x 13 strips
- Readout → silicon photomultipliers matrices

Total-body

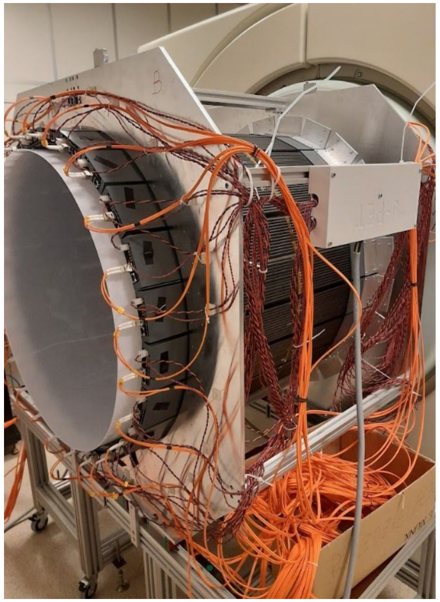


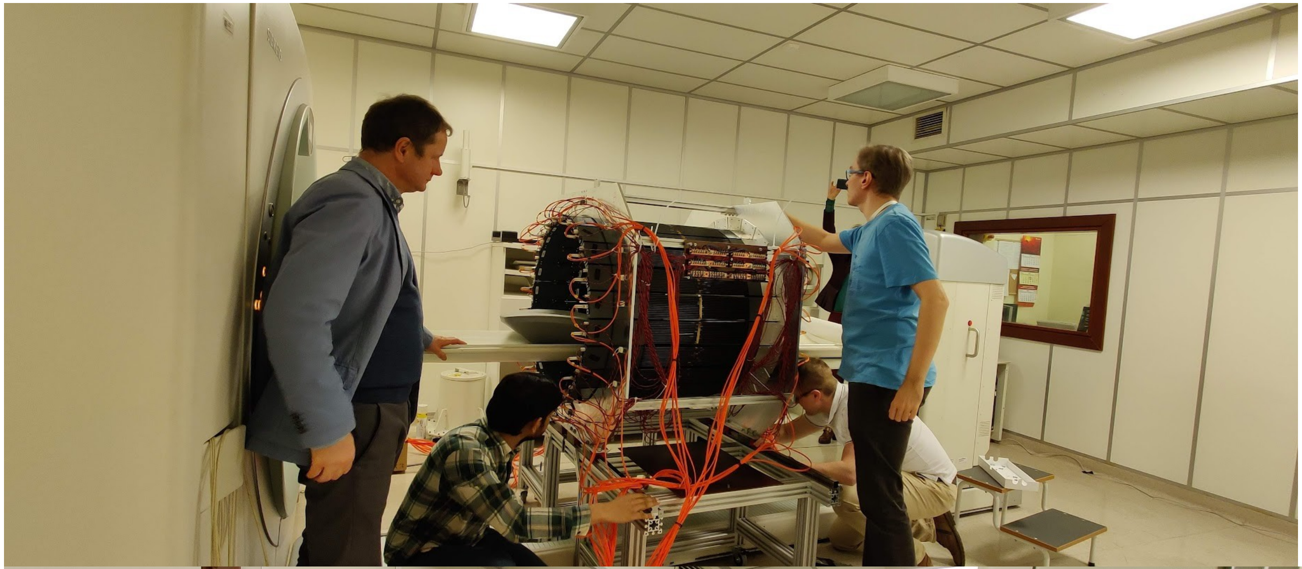
PET Clinics 15 (2020) 439
Phys. Med. Biol. 66 (2021) 175015

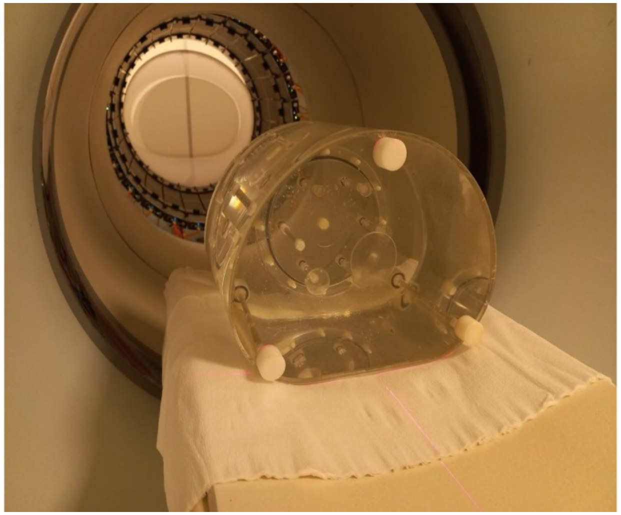
- 250 cm AFOV
- Additional layers of wavelength shifters → better axial resolution

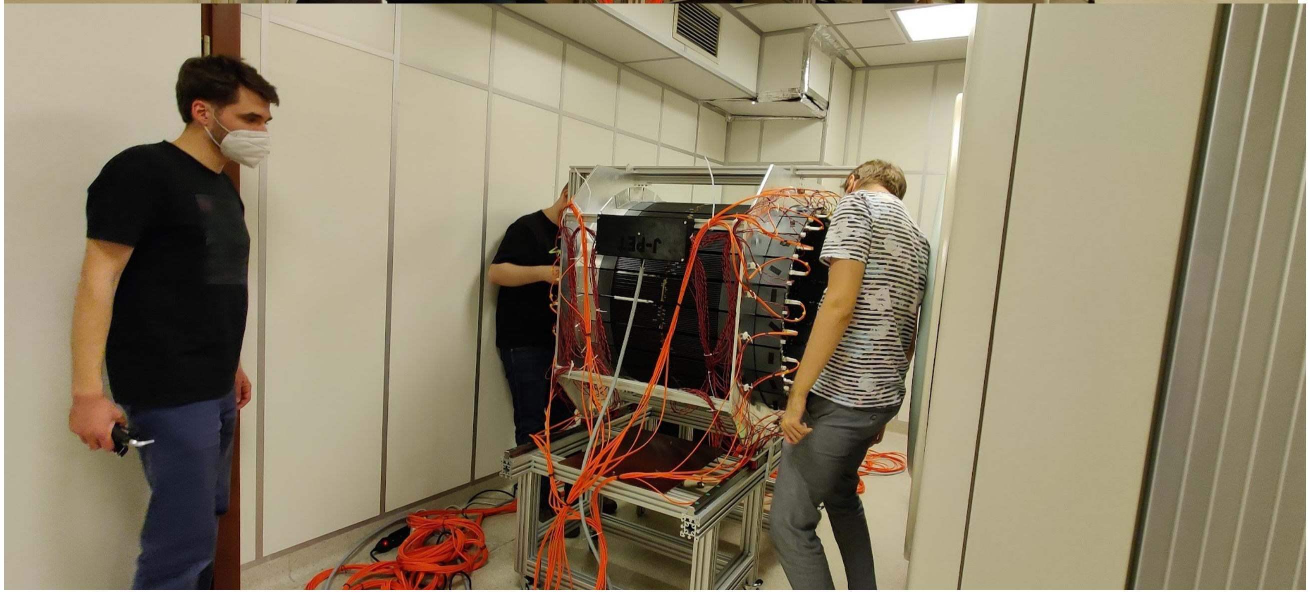


First test measurements with patients @Medical University of Warsaw



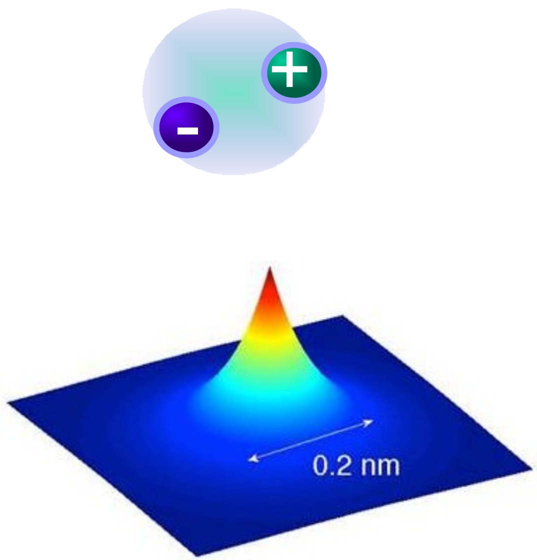




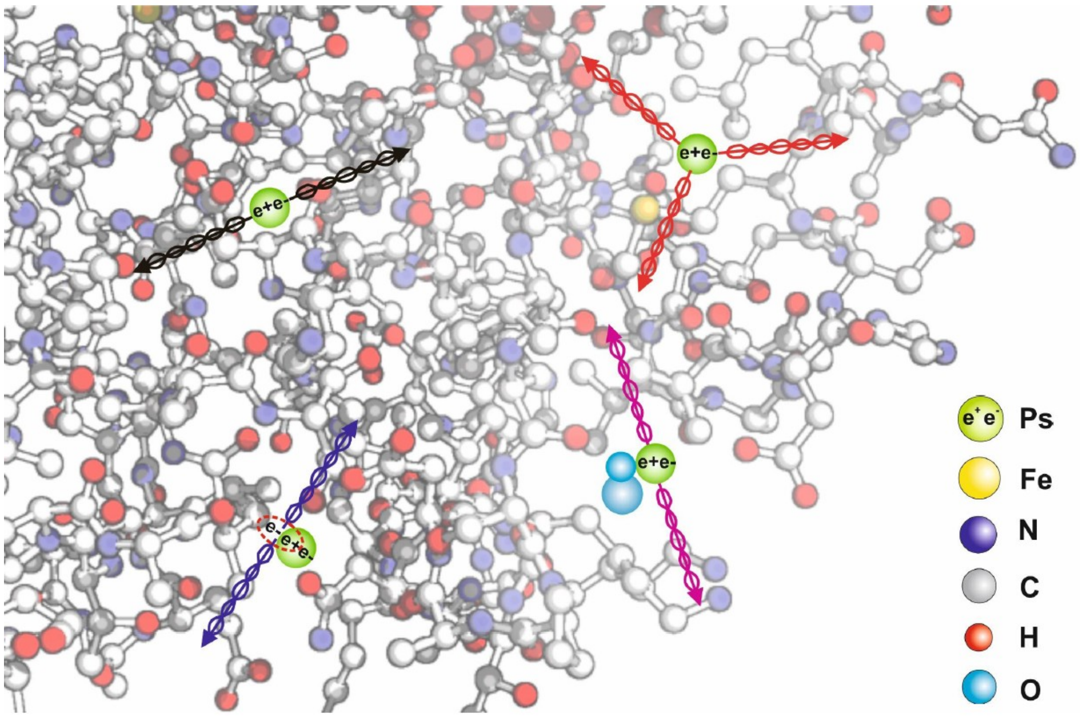


- ^{68}Ga and FDG – phantoms and patients
- Scandium 44 – phantoms
- data also taken with Biograph Truepoint PET-CT

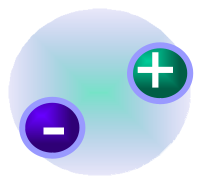
Multi-photon imaging

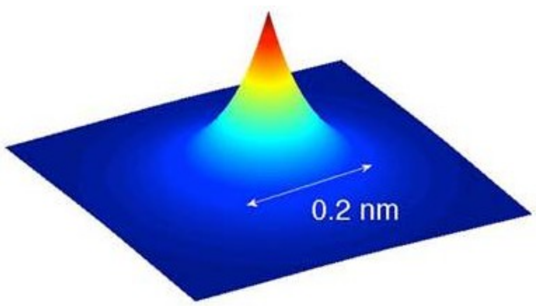


Model of the hemoglobin molecule



Positronium in PET

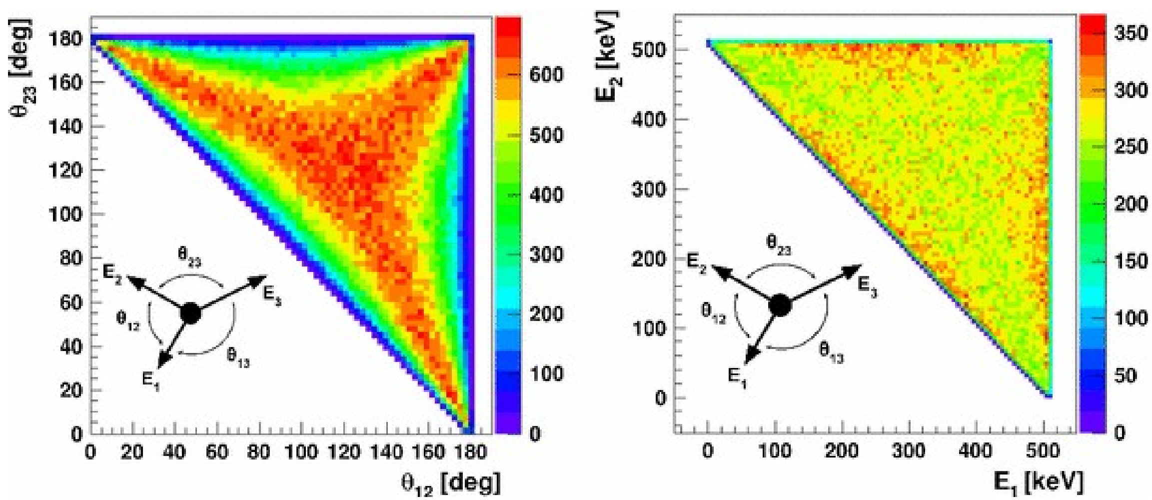




Para-positronium:
- lifetime ~125 ps
- two-photon decay

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

Daria Kisielewska



Implementation of QED-complient description of orto-positronium decay

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

Mateusz Bała

Source Extensions in GATE

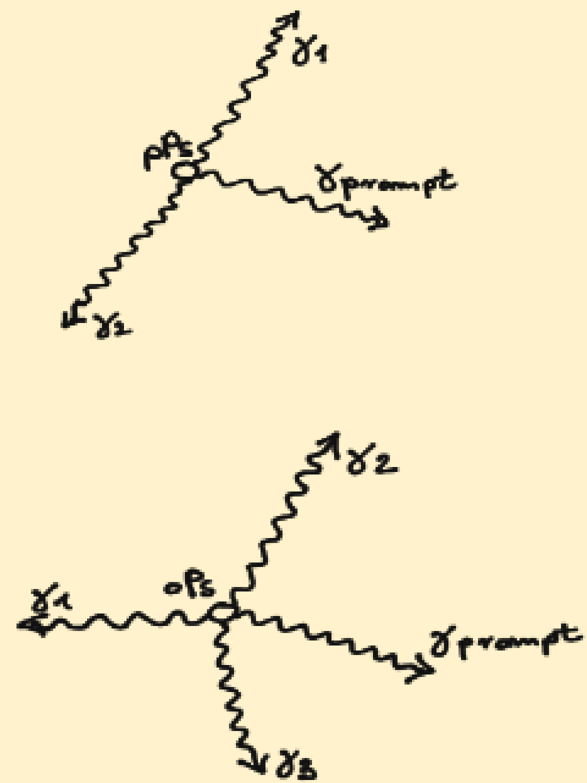
GateExtendedVSource

- Positronium decays (pPs, oPs, mixed)
- Polarization supported
- Configurable decay properties:
  - prompt gamma emission
  - prompt gamma energy
  - positronium life time
  - fraction of pPs and oPs decays

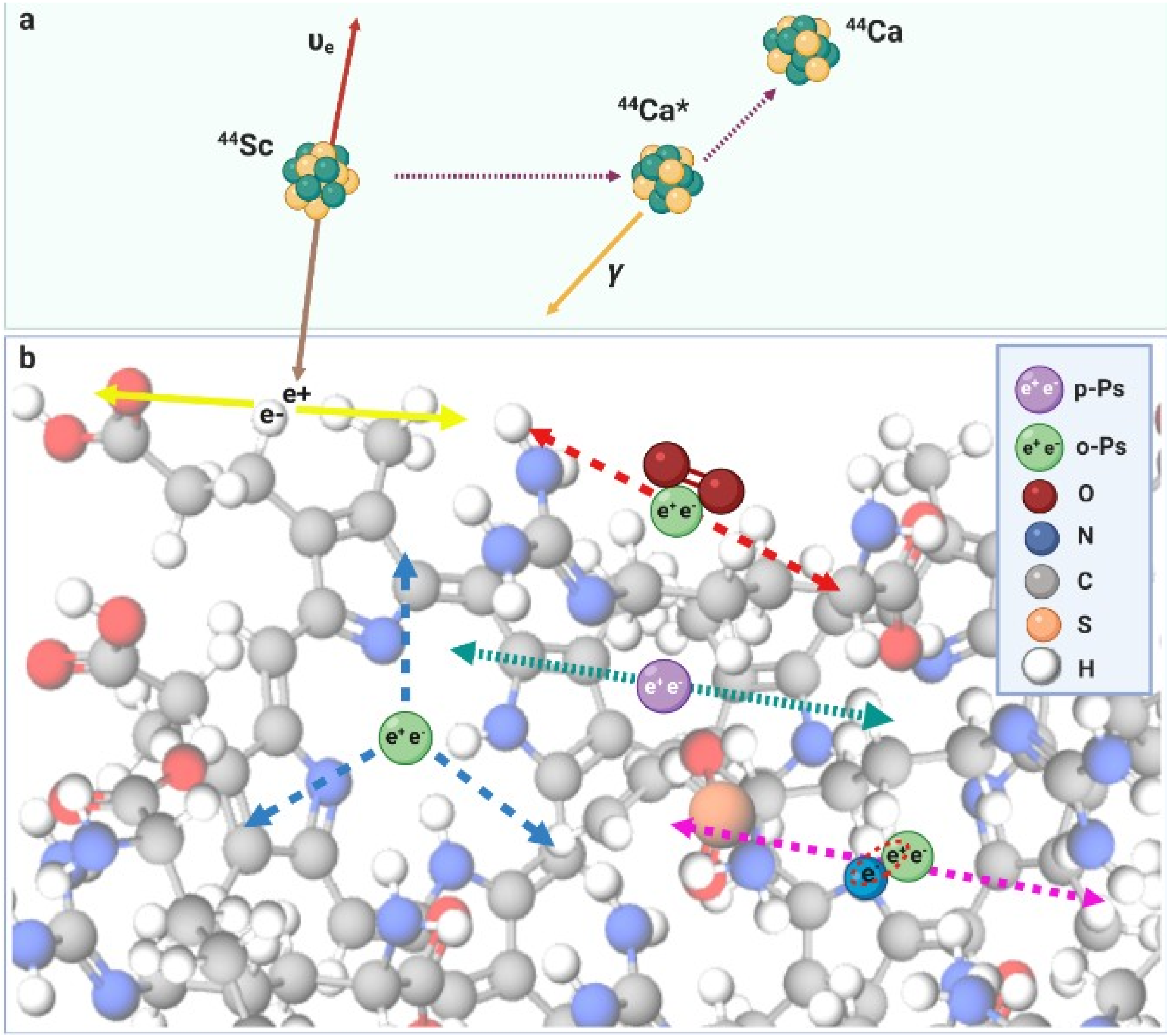
GateVSource

Inherited Gate Source class functionality

Positronium decays



available in GATE >= v9.0



From article in Rev. Mod.Phys. S. Bass, S. Mariazzi, P. Moskal, E. Stępień

https://arxiv.org/pdf/2302.09246.pdf

REVIEWS OF MODERN PHYSICS

Accepted Paper

Colloquium: Positronium physics and biomedical applications

Rev. Mod. Phys.

Steven D. Bass, Sebastiano Mariazzi, Pawel Moskal, and Ewa Stepien

Accepted 16 February 2023

ABSTRACT

ABSTRACT

Positronium is the simplest bound state, built of an electron and a positron. Studies of positronium in vacuum and its decays in medium tell us about Quantum Electrodynamics, QED, and about the structure of matter and biological processes of living organisms at the nanoscale, respectively. Spectroscopic measurements constrain our understanding of QED bound state theory. { Searches for rare decays and measurements of the effect of gravitation on positronium are used to look for new physics phenomena. In biological materials positronium decays} are sensitive to the inter- and intra-molecular structure and to the metabolism of living organisms ranging from single cells to human beings. This leads to new ideas of positronium imaging in medicine using the fact that during positron emission tomography (PET) as much as 40% of positron annihilation occurs through the production of positronium atoms inside the patient's body. A new generation of the high sensitivity and multi-photon total-body PET systems opens perspectives for clinical applications of positronium as a biomarker of tissue pathology and the degree of tissue oxidation.

Simultanous scans = standard image + lifetime image

Kamil Dulski

RESEARCH ARTICLE | BIOPHYSICS

Positronium imaging with the novel multiphoton PET scanner

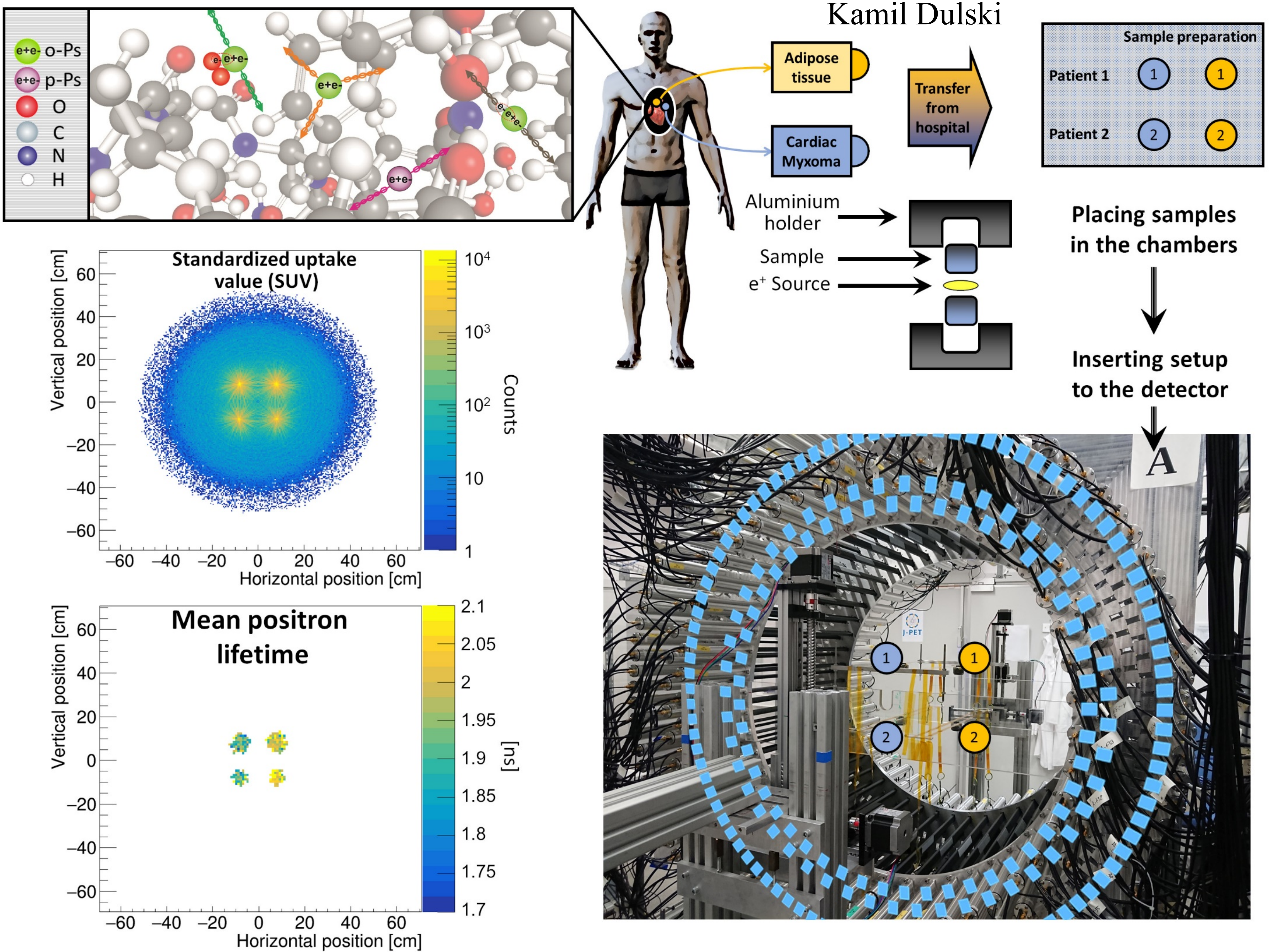
PAWEŁ MOSKAL, KAMIL DULSKI, NEHA CHUG, CATALINA CURCEANU, ERYK CZERWIŃSKI, MEYSAM DADGAR, JAN GAJEWSKI, ALEKSANDER GAJOS, GRZEGORZ GRUDZIEŃ, [...] WOJCIECH WIŚLICKI +27 authors Authors Info & Affiliations

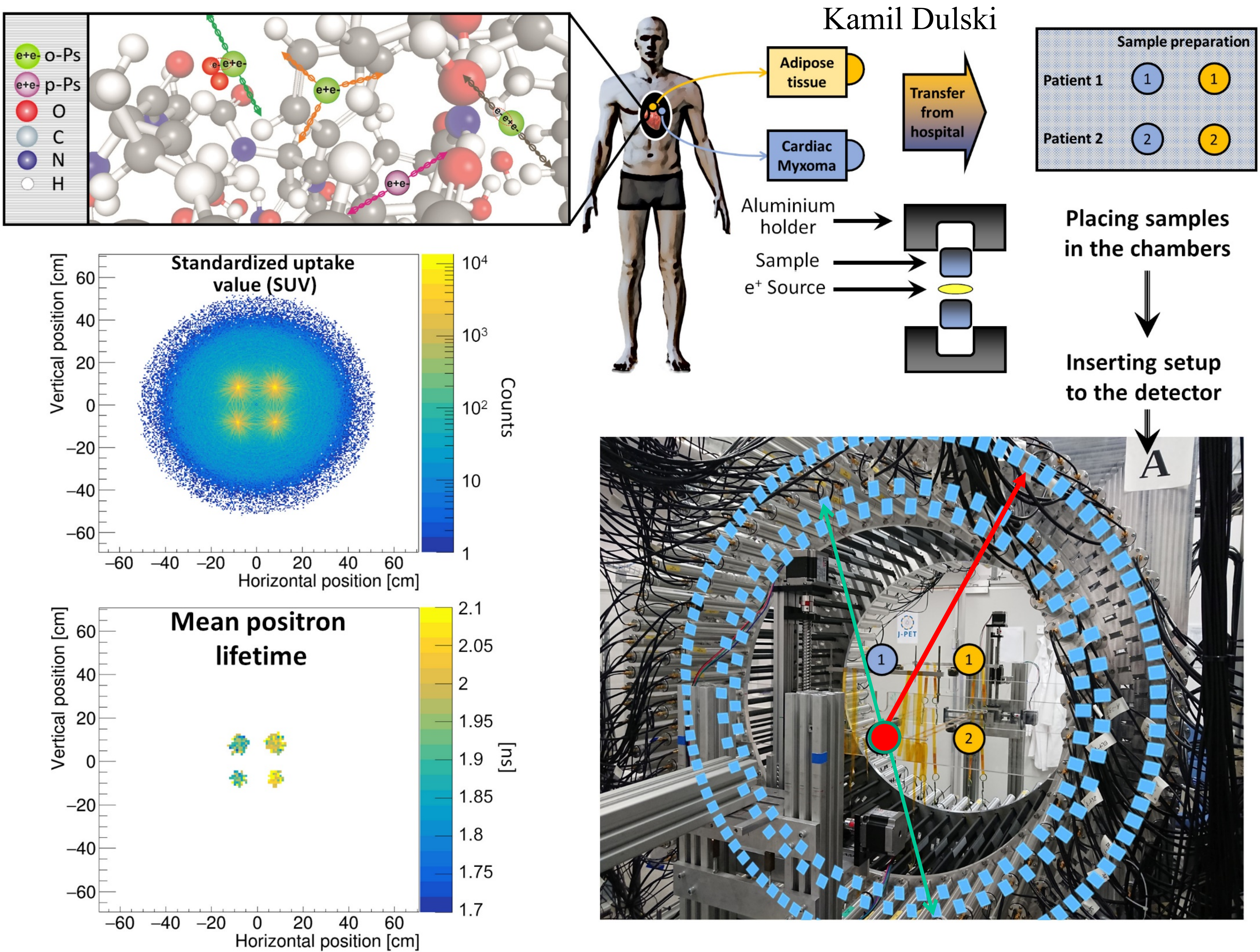
SCIENCE ADVANCES • 13 Oct 2021 • Vol 7, Issue 42 • DOI: 10.1126/sciadv.abh4394

Abstract

In vivo assessment of cancer and precise location of altered tissues at initial stages of molecular disorders are important diagnostic challenges. Positronium is copiously formed in the free molecular spaces in the patient's body during positron emission tomography (PET). The positronium properties vary according to the size of inter- and intramolecular voids and the concentration of molecules in them such as, e.g., molecular oxygen, O_2; therefore, positronium imaging may provide information about disease progression during the initial stages of molecular alterations. Current PET systems do not allow acquisition of positronium images. This study presents a new method that enables positronium imaging by simultaneous registration of annihilation photons and deexcitation photons from pharmaceuticals labeled with radionuclides. The first positronium imaging of a phantom built from cardiac myxoma and adipose tissue is demonstrated. It is anticipated that

Kamil Dulski





Kamil Dulski
e+e- o-Ps
e+e- p-Ps
O
C
N
H
Adipose tissue
Cardiac Myxoma
Transfer from hospital
Sample preparation
Patient 1
Patient 2
1
2
Aluminium holder
Sample
e⁺ Source
Placing samples in the chambers
Inserting setup to the detector
Standardized uptake value (SUV)
Vertical position [cm]
Horizontal position [cm]
Counts
Mean positron lifetime
[ns]
J-PET
A

First in the world orthpositronium image of the object

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

RECEIVED
31 May 2018

REVISED
21 December 2018

ACCEPTED FOR PUBLICATION
14 January 2019

PUBLISHED
7 March 2019

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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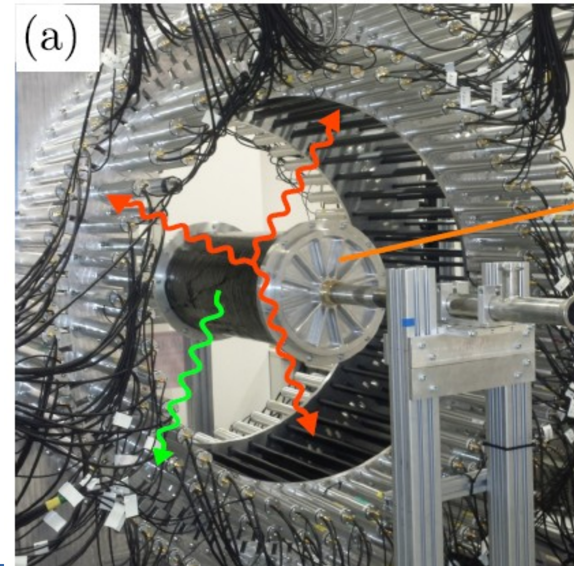
Keywords: positron emission tomography, positronium atom, J-PET

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



Aleksander Gajos

Article | Open Access | Published: 27 September 2021

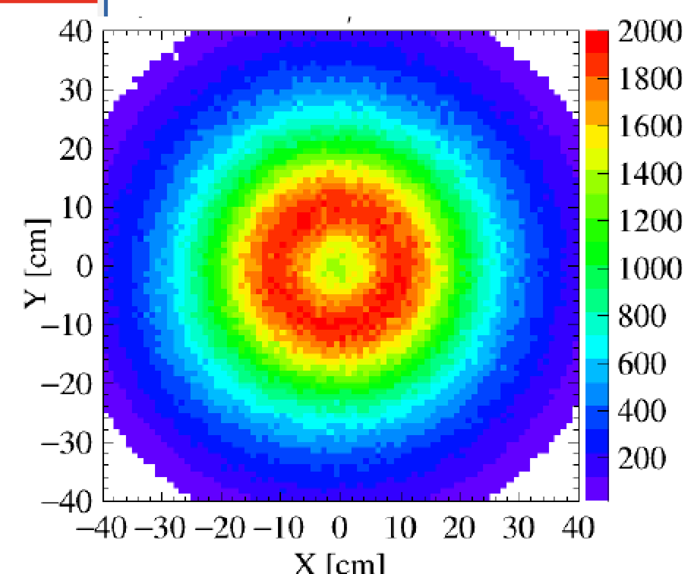
Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography

P. Moskal, A. Gajos, [...] W. Wiślicki

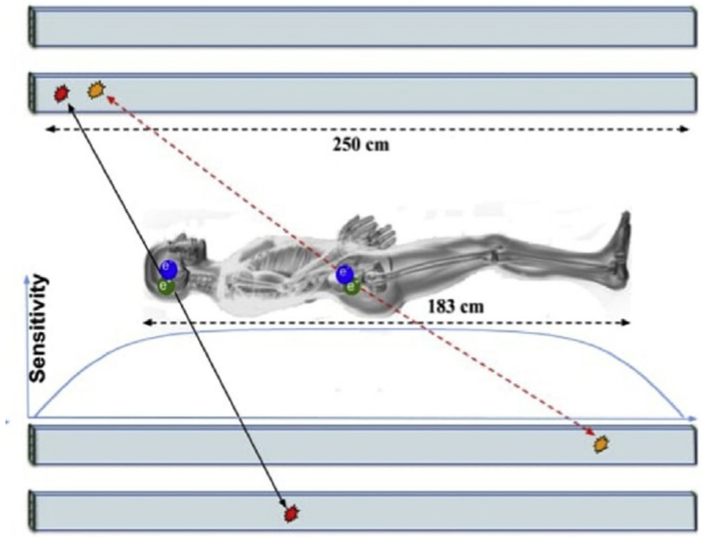
Nature Communications 12, Article number: 5658 (2021) | Cite this article

Abstract
Introduction
Results
Discussion
Methods
Data availability
References
Acknowledgements
Author information
Ethics declarations
Additional information
Supplementary information
Rights and permissions
About this article

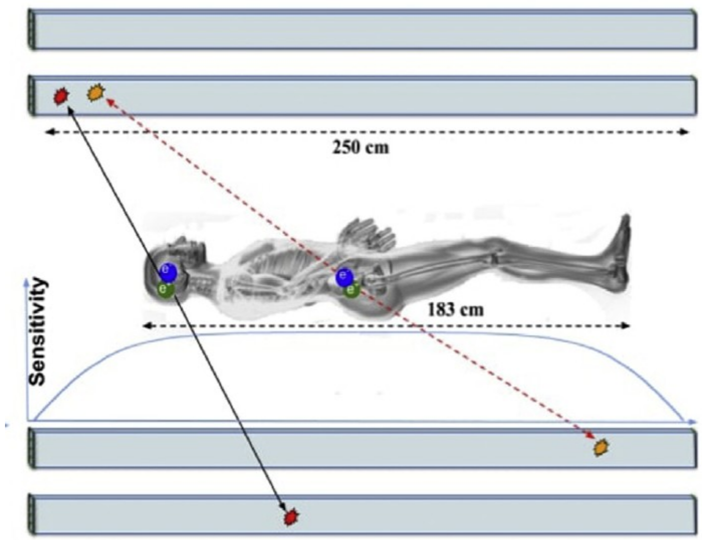
Abstract
Charged lepton system symmetry under combined charge, parity, and time-reversal transformation (CPT) remains scarcely tested. Despite stringent quantum-electrodynamic limits, discrepancies in predictions for the electron–positron bound state (positronium atom) motivate further investigation, including fundamental symmetry tests. While CPT noninvariance effects could be manifested in non-vanishing angular correlations between final-state photons and spin of annihilating positronium, measurements were previously limited by knowledge of the latter. Here, we demonstrate tomographic reconstruction techniques applied to three-photon annihilations of ortho-positronium atoms to estimate their spin polarisation without magnetic field or polarised positronium source. We use a plastic-scintillator-based positron-emission-tomography scanner to record ortho-

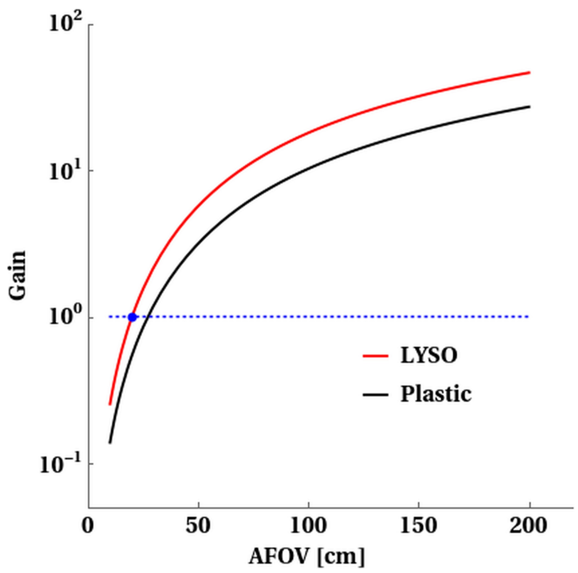


Towards Total Body J-PET

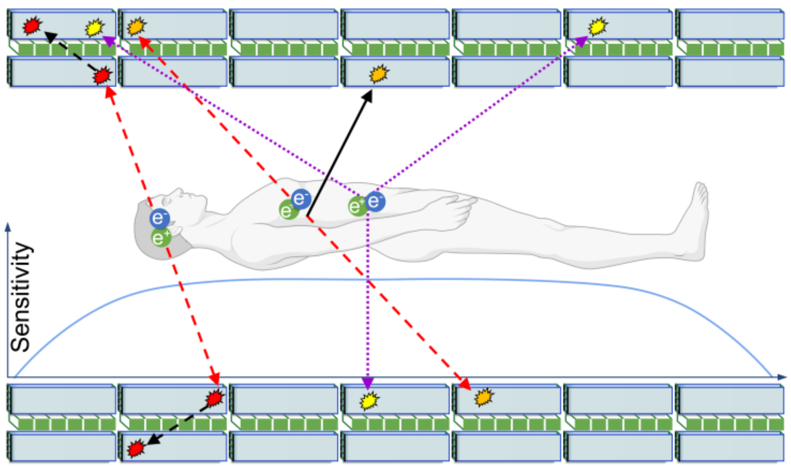


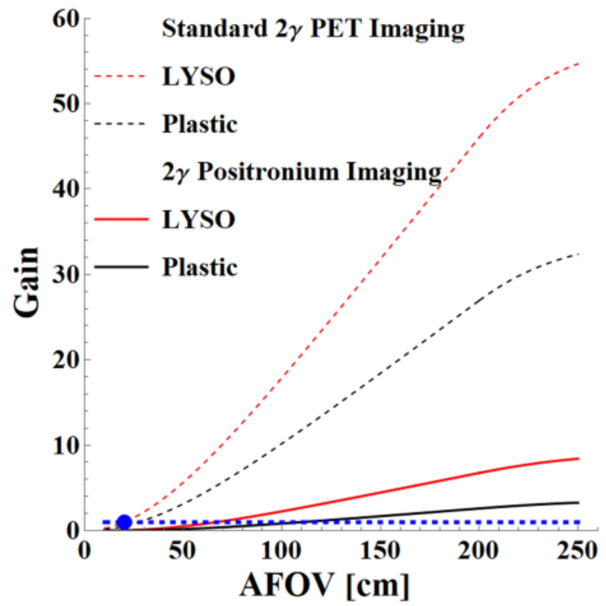
J. Nucl. Med. 60 (2019) 299–303.





P. Moskal, E. Ł. Stępień,
PET Clinics 15 (2020) 439





Rev. Mod.Phys. (2023) S. Bass, S. Mariazzi, P. Moskal, E. Stępień

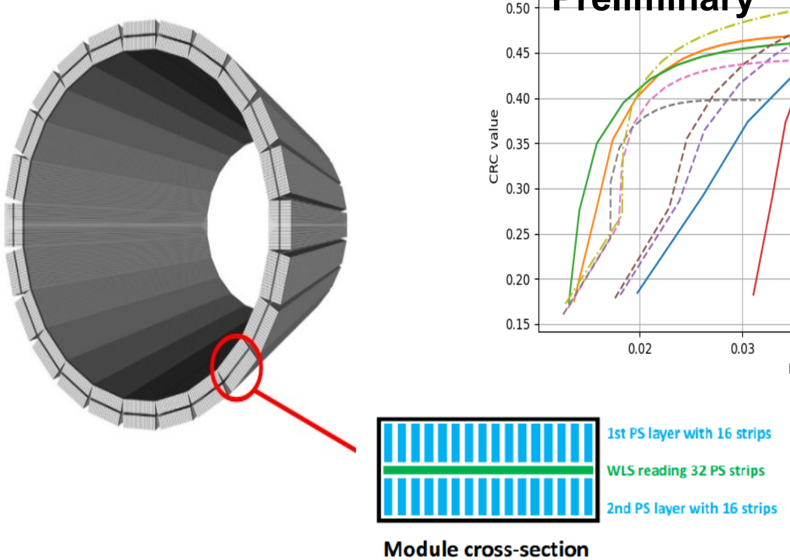
Software for total-body J-PET

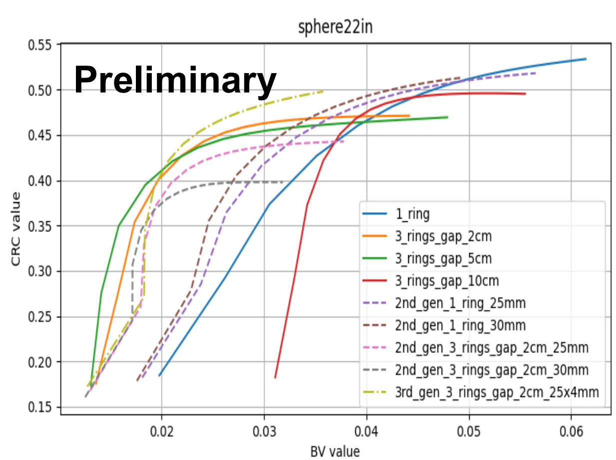
- scatter and random correction for total-body scanners **(see Szymon Parzych talk tomorrow)**
- Normalization corrections (**see A. Coussat's talk this afternoon**)
- point-spread functions
- system matrix parametrization
- Multi-photon + conventional PET reco. algorithms
- **Machine learning techniques for background reduction**
- Various software tools

Coordinator: W. Krzemien
- Jakub Baran
- Lech Raczynski
- Szymon Parzych
- Mateusz Bała
- Paweł Kowalski
- Aurelien Coussat
- Damian Trybek

GATE

Extensive usage of GATE simulations





Python

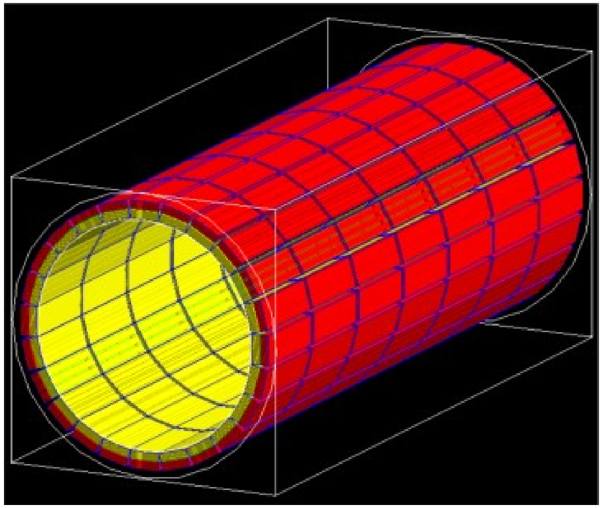
C++

MATLAB

GitHub

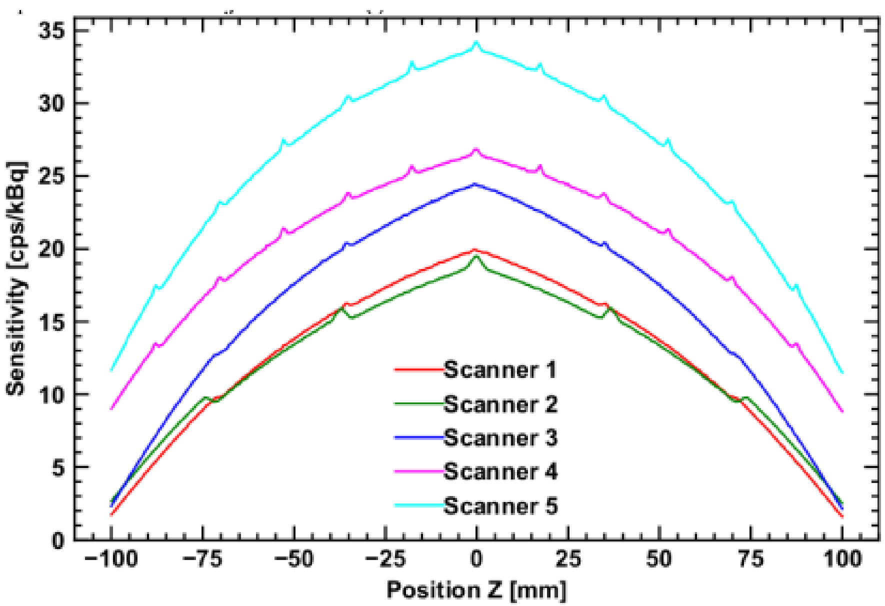
Jakub Baran & Wojciech Krzemień et al.

Total-Body J-PET Geometry Optimization

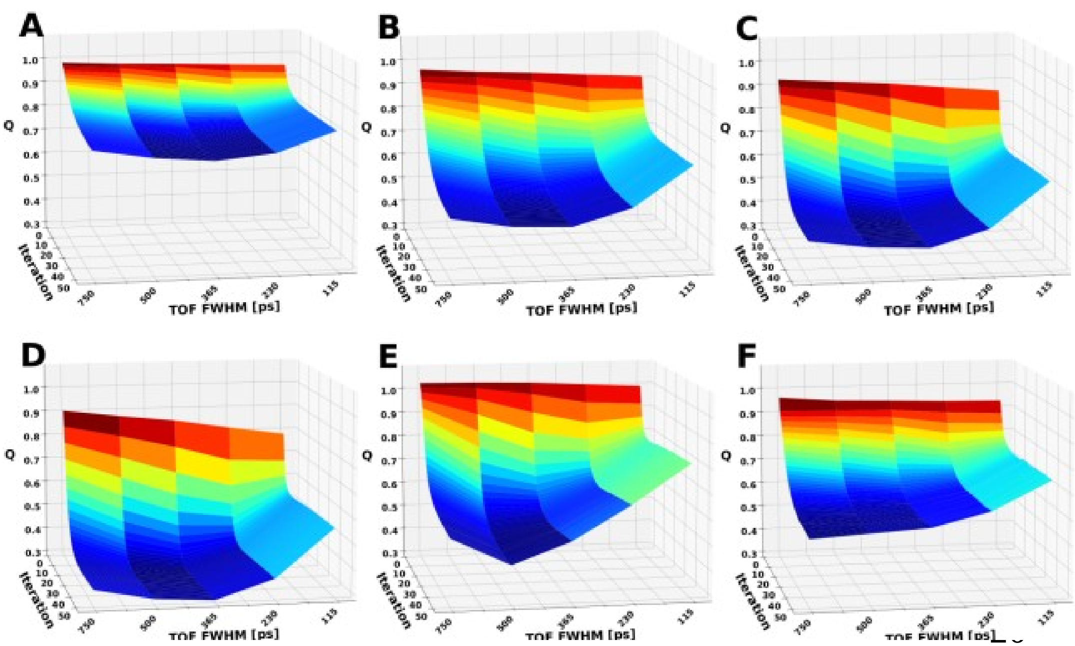


Property	Scanner geometry				
	S1	*S2*	*S3*	*S4*	*S5*
Radius [mm]	506	506	425	414.65	414.65
Axial FOV [mm]	2099.2	2159.2	2099.2	2430	2430
Scintillator length [mm]	686.4	686.4	686.4	330	330
Scintillator cross-section [mm]	25x5.7	25x5.7	25x5.7	25x6.0	30x6.0
No of adjacent rings	3	3	3	7	7
Gap between adjacent rings [mm]	20	50	20	20	20

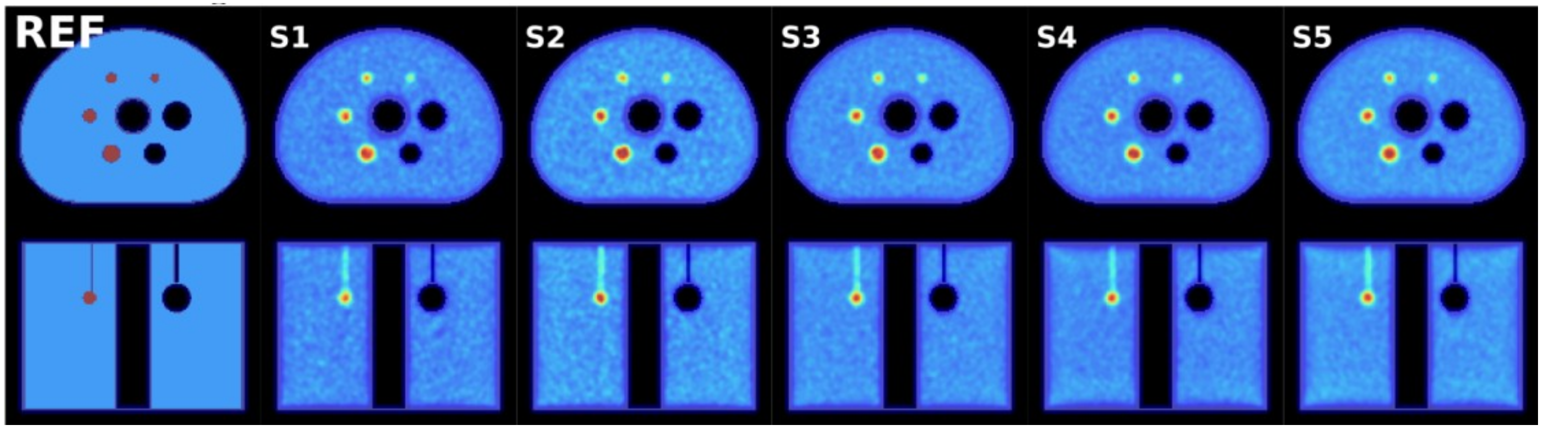
preliminary Sensitivity



TOF kernel choice

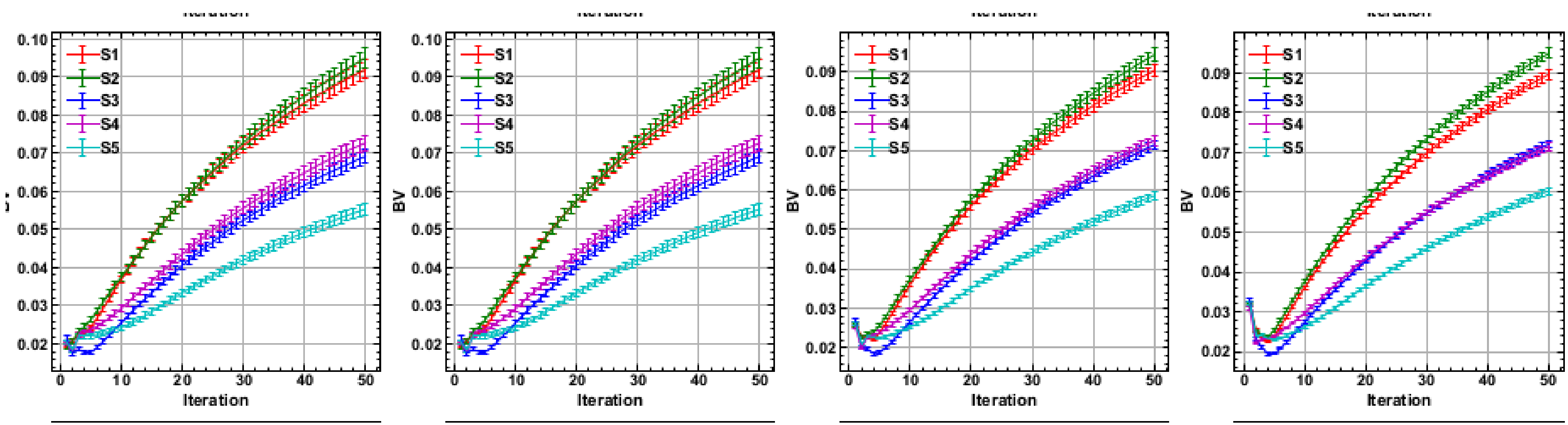


Total-Body J-PET Geometry Optimization – NEMA IEC



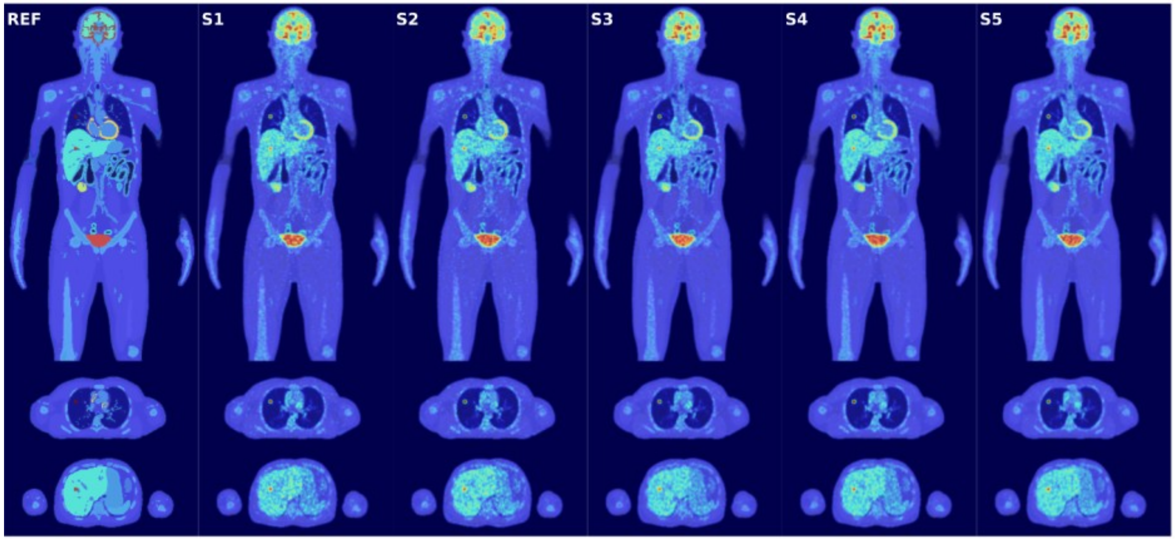
preliminary

Background variability



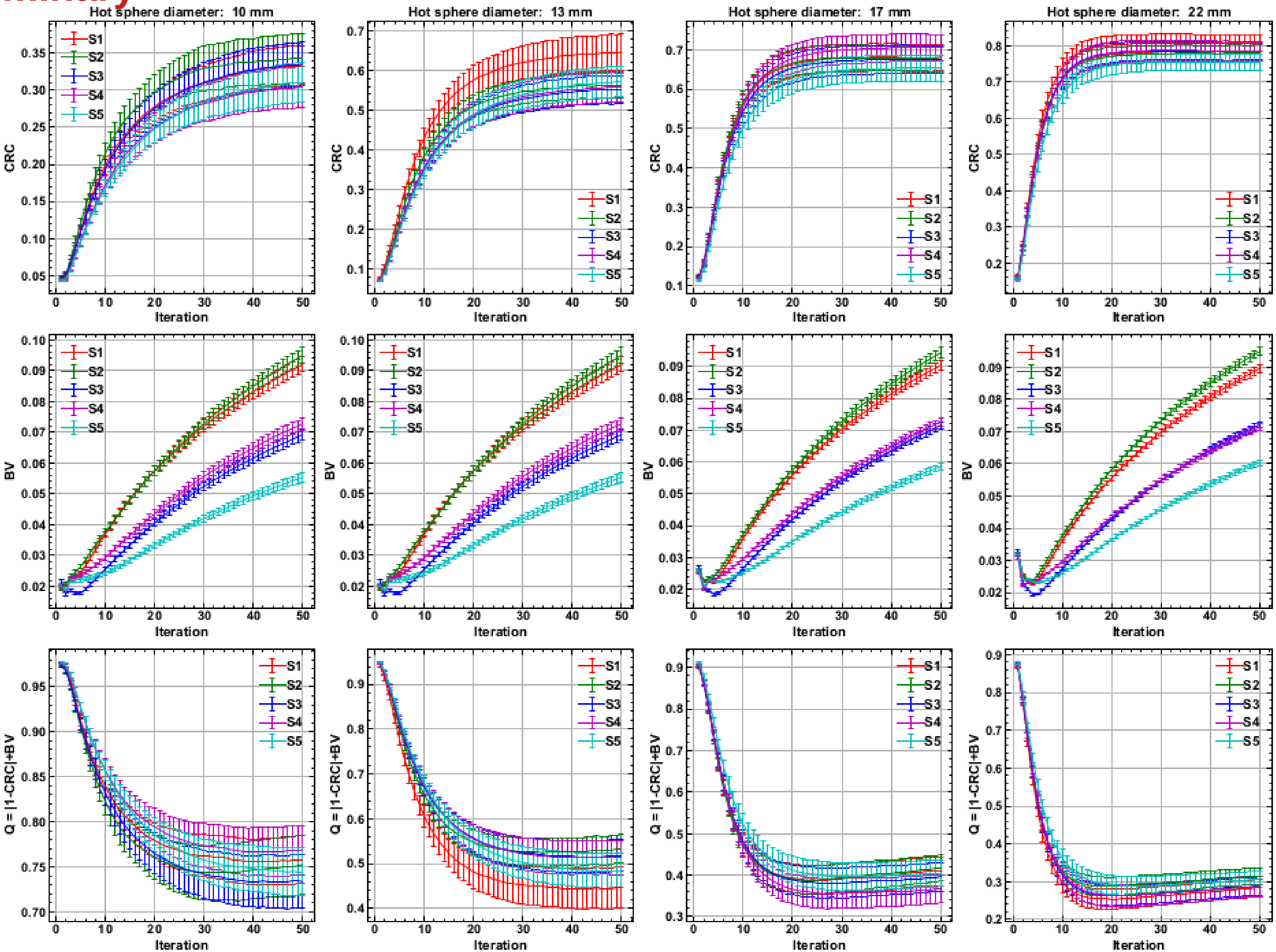
Total-Body J-PET Geometry Optimization – XCAT phantom

preliminary



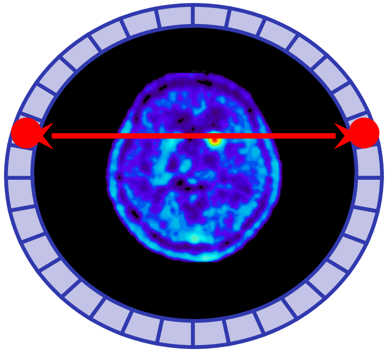
Total-Body J-PET Geometry Optimization – XCAT phantom

preliminary

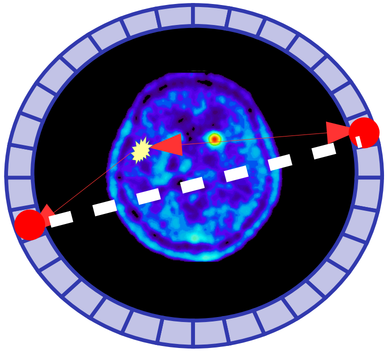


Coincidence classification for total-body J-PET

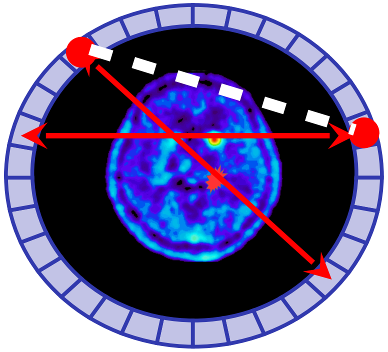
True events



Scattered events



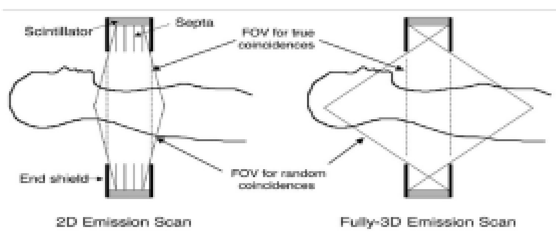
Random events



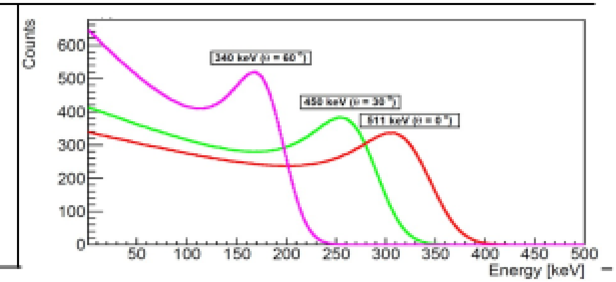
Coincidence classification for total-body J-PET

For total-body J-PET scanner we expect
higher background level from non-genuine coincidences

In J-PET



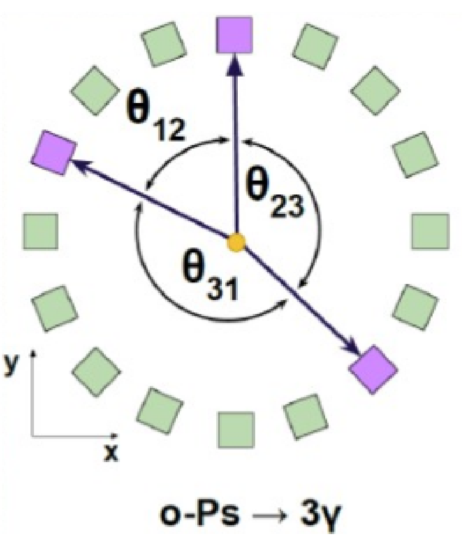
Multiple scattering in the phantom is not negligible



D. Brasse et al. J Nucl Med 2005; 46:859–867

Situation much more complicated for multi-photon coincidences...

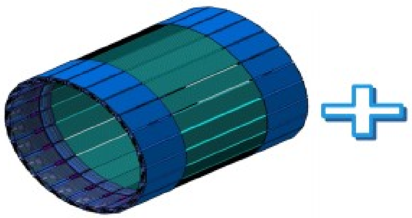
- More photons ➡ More combinations
- Less strictly defined geometry
- Photon energies have a distribution

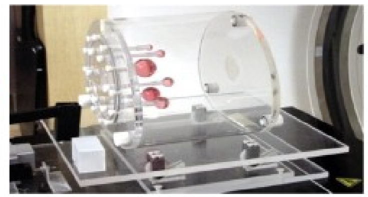


Idea: apply ML techniques to reduce background
(ACCIDENTAL, SCATTER)

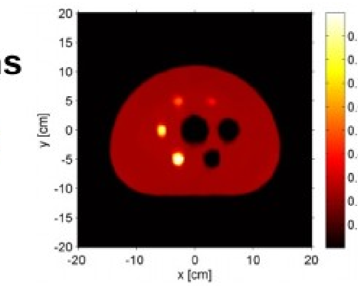
Wojciech Krzemień, Konrad Klimaszewski et al.

Training data generation





Monte Carlo Simulations



Modular J-PET

- 50 cm AFOV
- 24 modules x 13 strips
- 24 x 6 x 500 mm strips

NEMA IEC Phantom

- 4 hot spheres
- 2 cold spheres
- Activity - 59 Mbq
- acquisition time - 500 seconds
- contrast between hot and cold regions – 4:1

GATE MC Simulation

- 30M coincidences
- Phenomenological time, energy and positional resolution
- Geometry cuts → reduce accidental fraction

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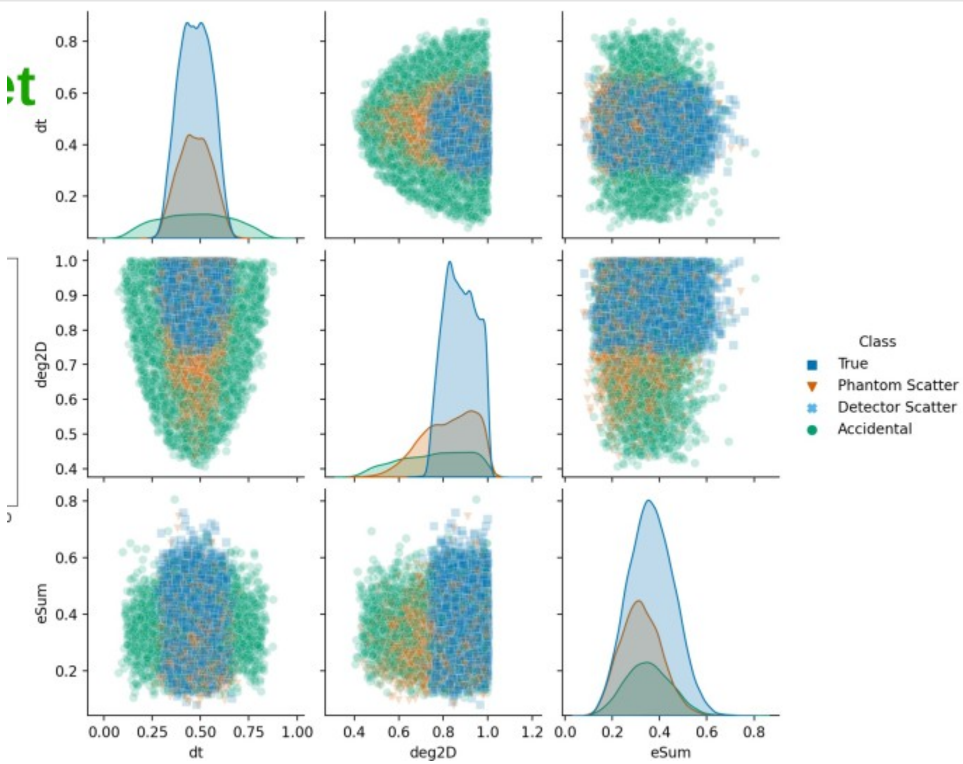


Classificators

Wojciech Krzemień, Konrad Klimaszewski et al.

- Feedforward Neural Network

Keras + SciKeras + scikit learn

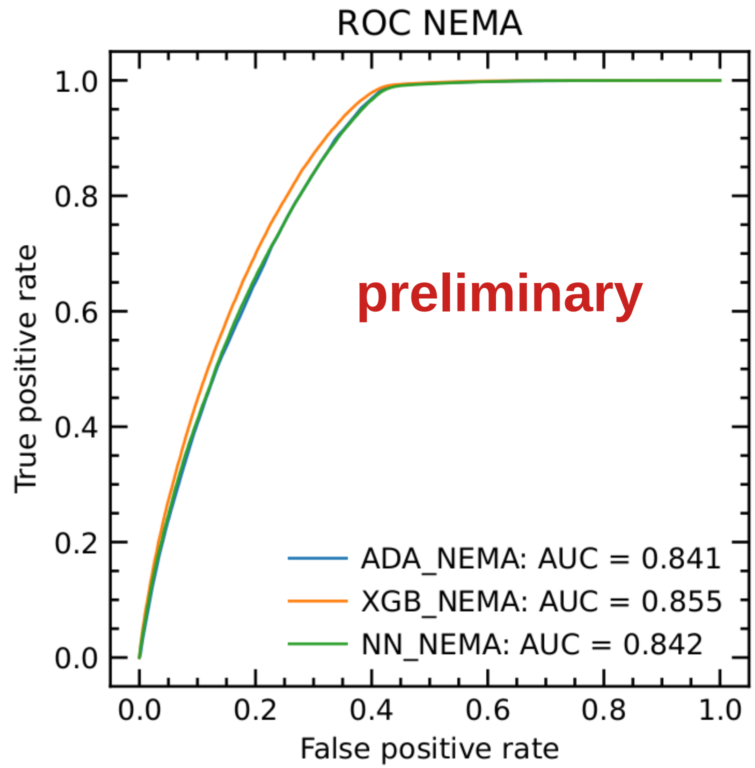
- ADABoost

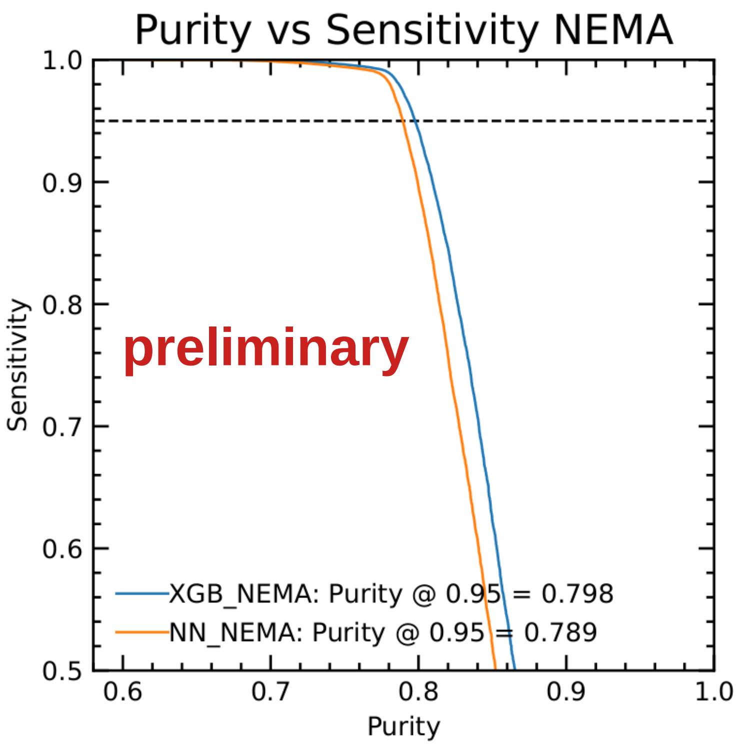
scikit learn

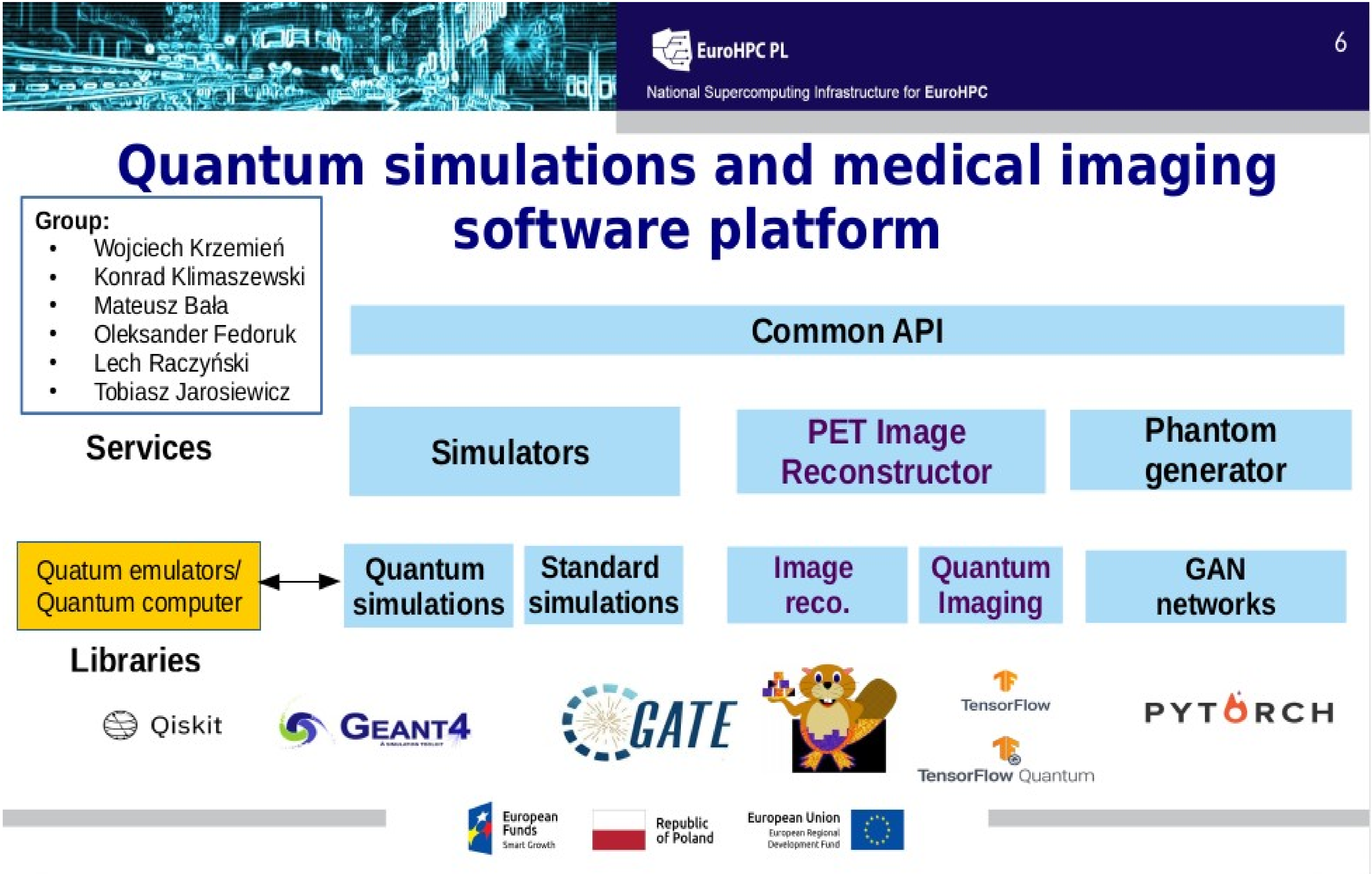
- XGBoost

dmlc XGBoost + scikit learn

Base line: 65%






EuroHPC PL
National Supercomputing Infrastructure for EuroHPC
6
Quantum simulations and medical imaging software platform
Group:
• Wojciech Krzemień
• Konrad Klimaszewski
• Mateusz Bała
• Oleksander Fedoruk
• Lech Raczyński
• Tobiasz Jarosiewicz
Common API
Services
Simulators
PET Image Reconstructor
Phantom generator
Quatum emulators/ Quantum computer
Quantum simulations
Standard simulations
Image reco.
Quantum Imaging
GAN networks
Libraries
Qiskit
GEANT4
GATE
TensorFlow
TensorFlow Quantum
PYTORCH
European Funds Smart Growth
Republic of Poland
European Union European Regional Development Fund

Thank you for attention

J-PET

More materials available at:

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