

Feasibility studies for imaging e^+e^- annihilations with modular multi-strip detectors

Sushil Sharma
on behalf of the J-PET collaboration

25.05.2023



Symposium on Radiation Measurements and
Applications (SORMA XIX)

- **J-PET** : **J**agiellonian **P**ositron **E**mission **T**omograph
First tomograph made of plastic scintillators

- **Studies** based on e^+e^- annihilations

Direct annihilation or through the formation positronium atoms (Ps)



- **Modular J-PET detection Units**

*Test **Performance in imaging e^+e^- anni.** with modular detectors*

- **Result and summary**

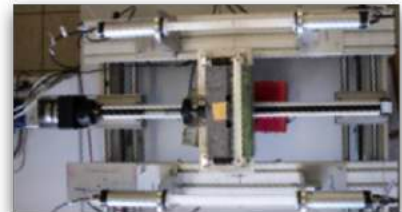


J-PET prototypes : from 2 strips to total-body



2 strip based

Characterize scintillators prop:
hit time, hit-position,
Energy resolution,..



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Prototype with 24 plastic strips

Data acquisition validation
for multi-modules



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P. Moskal et al., IEEE TIM 70 (2021) 1-10

3.1 layer

Fundamental symmetries and

7

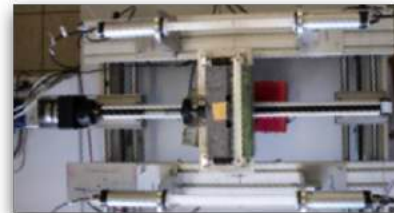


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3-Layer prototype (192 strips)

Fundamental symmetries and

Positronium imaging

Acta Phys. Pol. B 47 (2016) 509; Nature comm. 12 (2021) 5658

Science advances 7 (2021) eabh4394



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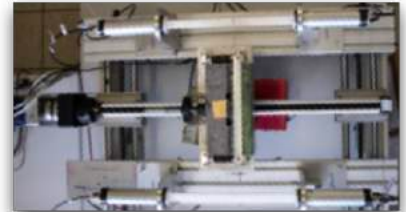


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Modular J-PET

J-PET's Plastic Revolution - CERN COURIER
<https://cerncourier.com/a/j-pets-plastic-revolution/>



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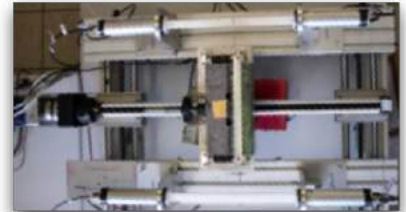


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First data taking campaign in research labs and hospital



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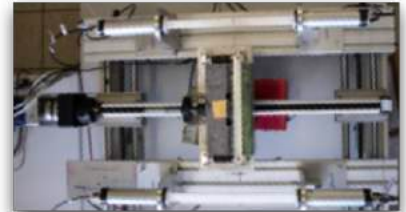


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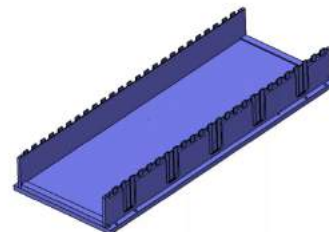
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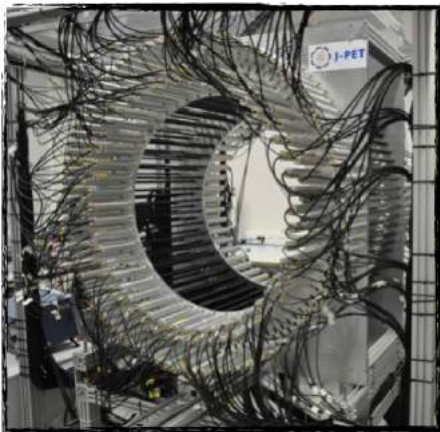
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Towards
total-body PET



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Single *detection module*



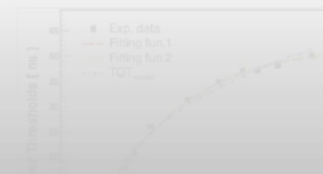
$$\text{Hit-position}_z = (t_i - t_j) \times V_{\text{eff}}^{\text{Light}} / 2$$

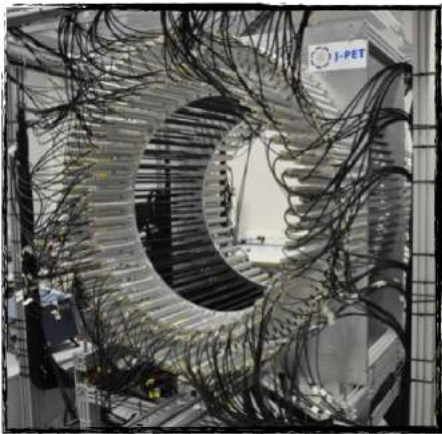
$$\text{Hit time} = (t_i + t_j) / 2 - L / 2V_{\text{eff}}^{\text{Light}}$$

- **192** detection modules in 3 concentric cylinders (diameter of innermost is 85 cm)
- Each detection module consist of one plastic scintillator (50 x 1.9 x .7 cm³) read-out at each end by photomultipliers
- Trigger less and reconfigurable DAQ

Time Over Threshold (TOT) is used, as a measure of energy deposition :

$$TOT = \sum_{PMT=A,B} \sum_{Thr_1 \rightarrow 4}^{TOT_{PMT,Thr}}$$





Single *detection module*

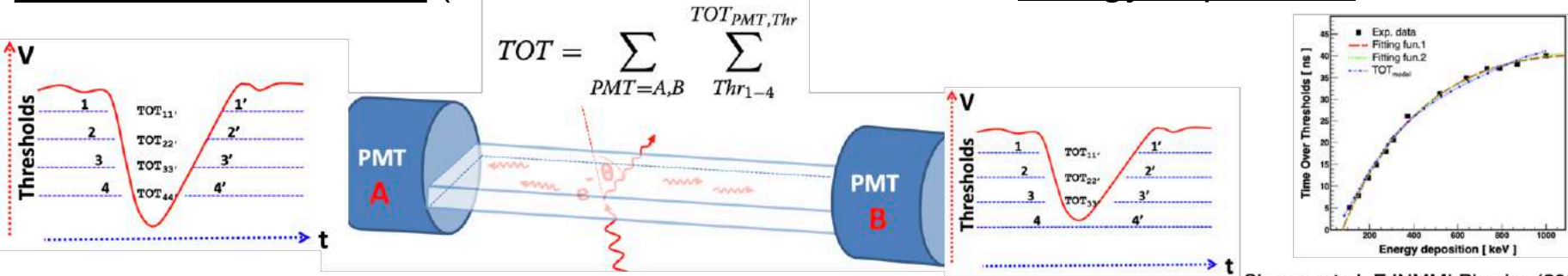


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Sharma et al. EJNMMI Physics (2020) 7:39

A dedicated J-PET data analysis framework : an open source software platform

written in C++ , based on ROOT package

W. Krzemień et al., SoftwareX 11 (2020) 100487

- Signal reconstruction, Calibrations, filtering procedures,
- **User-level data analysis by accessing the in-built function**

Monte Carlo simulations package based on *Geant4-toolkit*, adapted to simulation of Ps decays



e^+e^- annihilations are explicitly used in PET imaging

e^+ interacting with electron e^- , can form the Positronium atom (Ps):

Para-Ps (p-Ps) : Lifetime 122 ps

Ortho-Ps (o-Ps): Lifetime 142 ns (vacuum)



Requirement of invariance of charge conjugation, the decays of Ps atoms following the selection rule : $(-1)^{L+S} = (-1)^n \gamma$

Applications:

Odd-symmetric operators constructed of

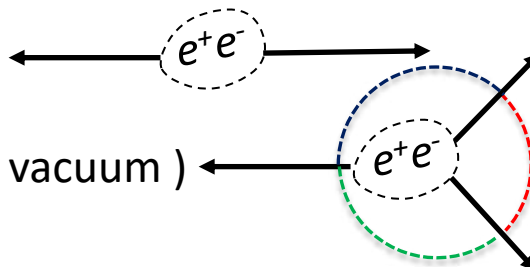


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Moskal et al., Nature communications 12, 5658 (2021)



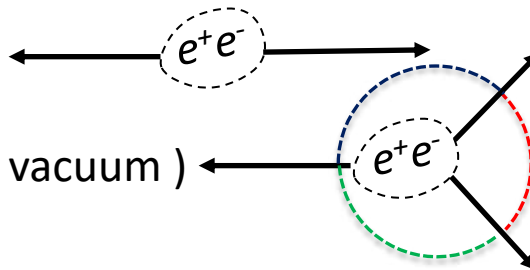


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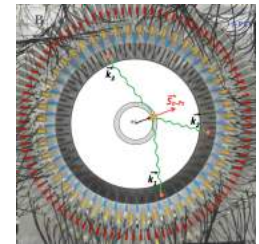
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Quantum entanglement:

✓ Photon's (511 keV) polarization, Compton scattering as Polarizer

✓ Polarization correlation of anni. photons

Boyd et al., Rev of Modern Physics **95** (2023)

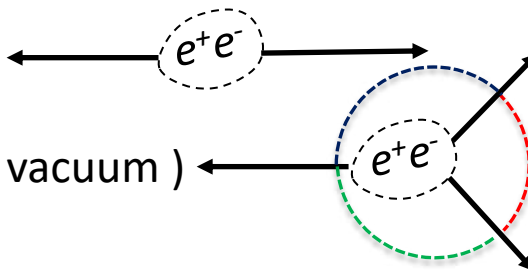


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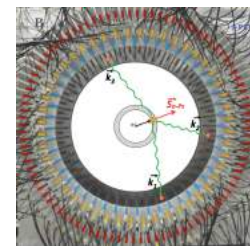
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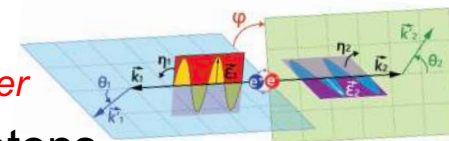
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Positronium Lifetime

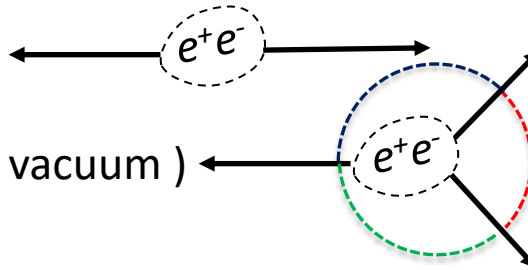
Simultaneous measurement of Ps decays, opens up several interesting studies eg. Decay rate of o-Ps in vacuum, rare decay studies

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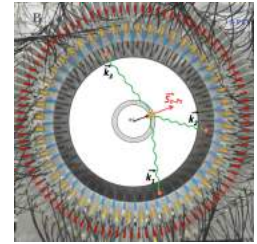
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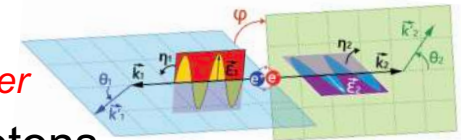
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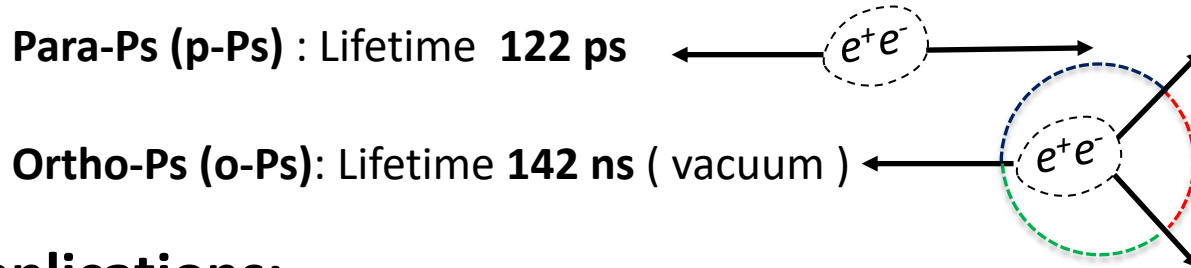
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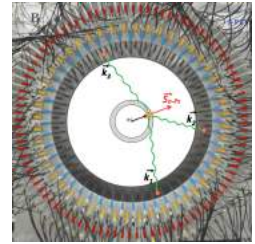
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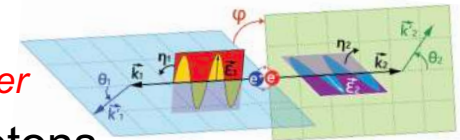
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Positronium Lifetime: Simultaneous measurement of Ps decays, opens up several interesting studies eg., Decay rate of o-Ps in vacuum, rare decay studies,.

Inertial Sensing on Ps atoms : Lifetime manipulation of Ps followed by atomic interferometry.

Mariazzi et al., EPJ D 74, 79 (2020)

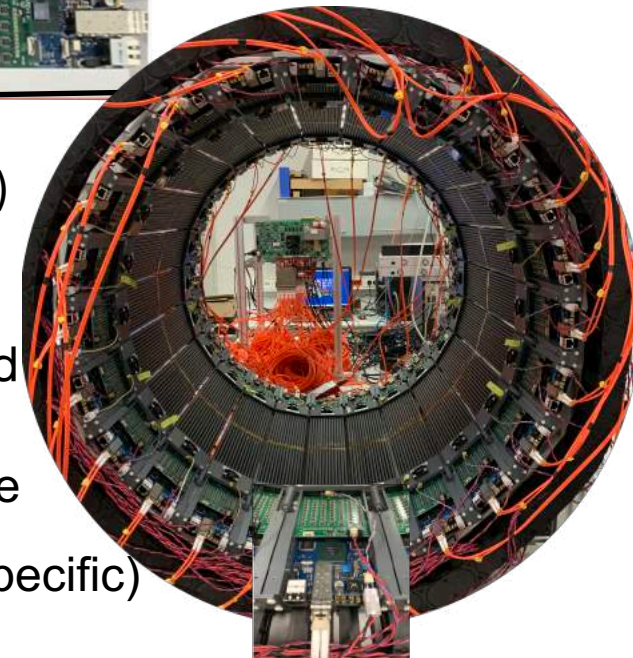
Sharma et al., JINST 18 C02027 (2023)

Modular J-PET can be potential detector ?

- ❖ Composed of **24** individual (**standalone**) detection modules



- ❖ Each module is made of **13 plastic scintillators** (BC-404) (50 x 24 x 6 mm³)
- ❖ Scintillators are read out by matrix of SiPM on each end
- ❖ Modular construction (**FEE* attached**) allows to configure one layer (24) or multiple layer(e.g, 8+16 , requirement specific)

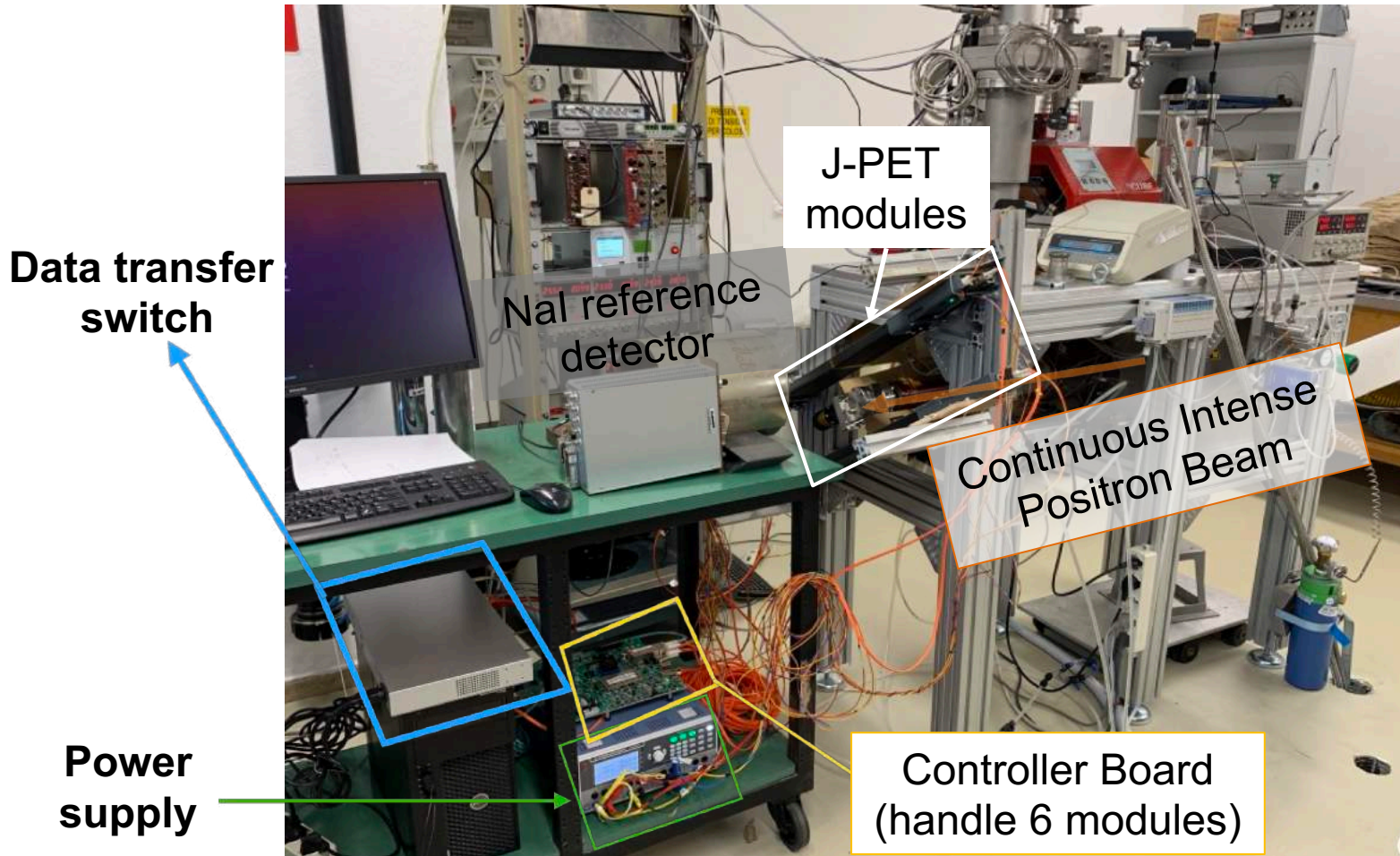


- ❖ Easy to transport (full barrel around 60 kg), can be assembled in a time span of 2-3 hours.

**FPGA based
Data acquisition**

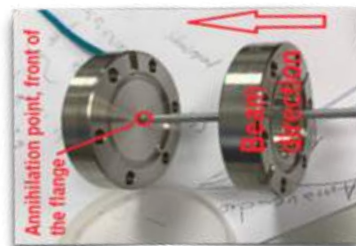
- ❖ Modules can be operated individually enabling to utilize as multi-role detector

e^+ beam @ AML



Two different flanges

(i)

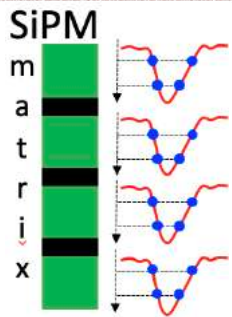


(ii)

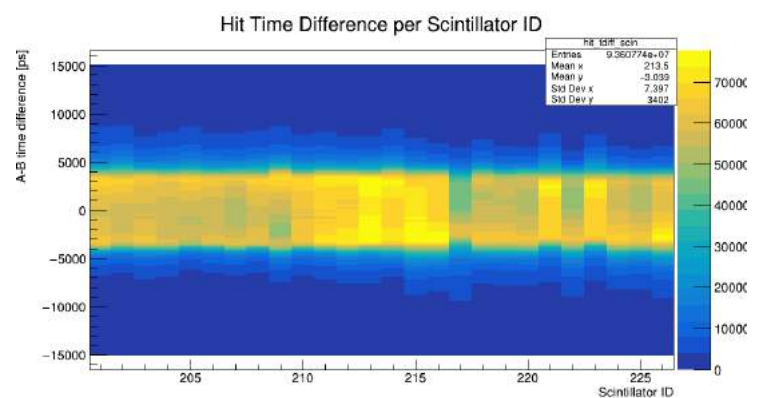
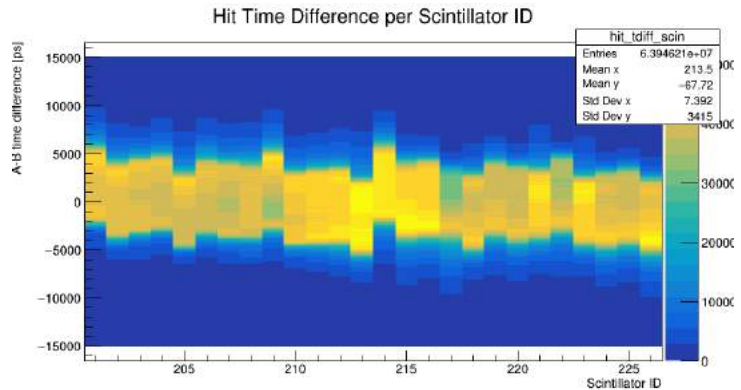


Each side read out by matrix of 4×1 SiPMs and each signal is probed at two thresholds (30 mV and 70 mV)

- DAQ was triggerless and signals were reconstructed individually for SiPMs
- Up to 4 signals from the SiPMs in the same matrix combined to one Matrix Signal

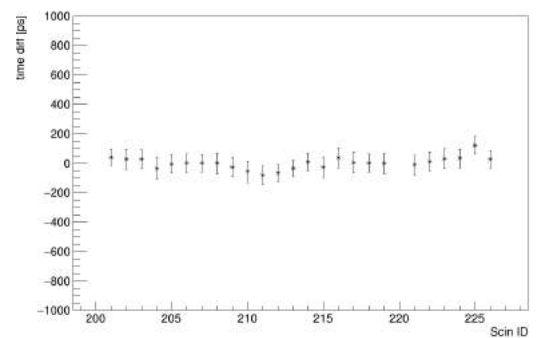
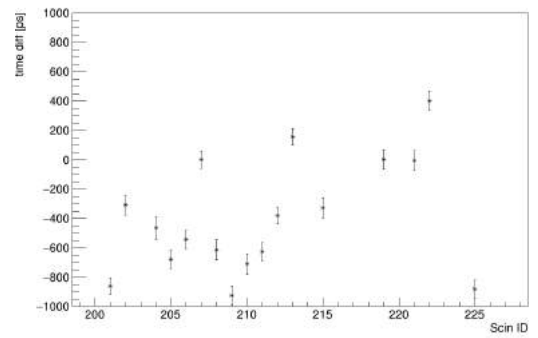
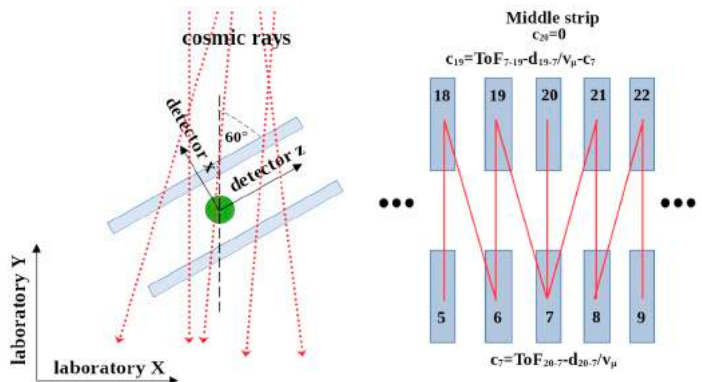


Cosmic radiations used to **synchronize timing information**



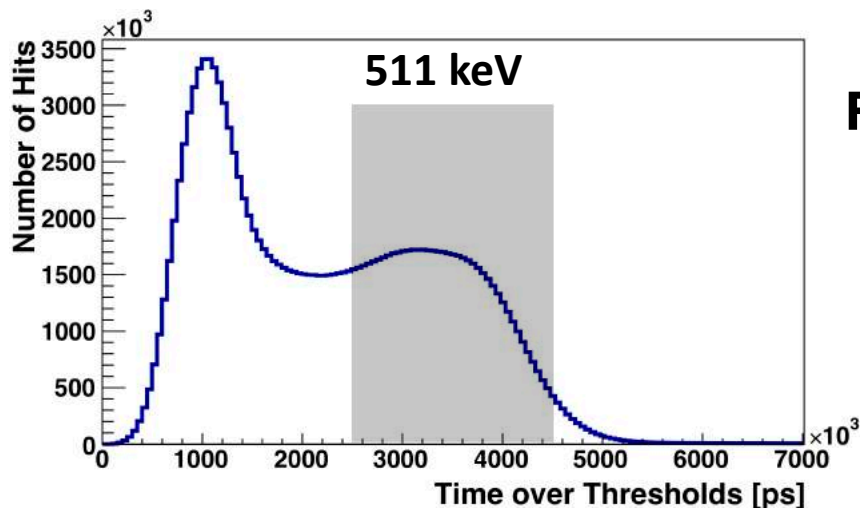
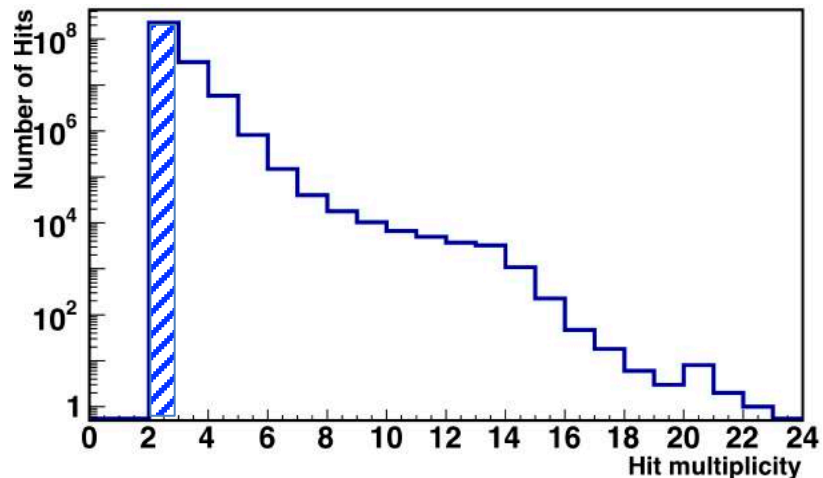
Time Of Flight synchronization between strips

Courtesy to K. Kacprzak



Data is being analyzed using the J-PET analysis Framework:

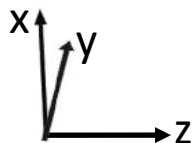
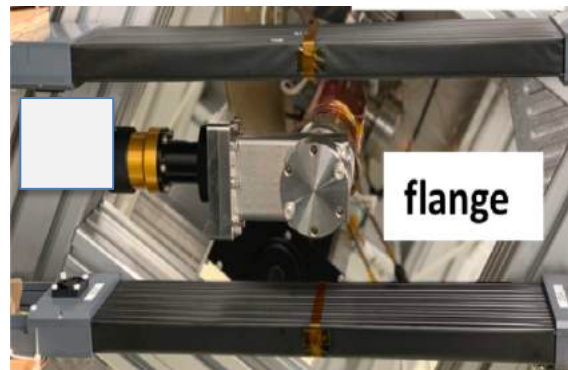
To reconstruct the annihilation point, Events with only 2 hits were studied.



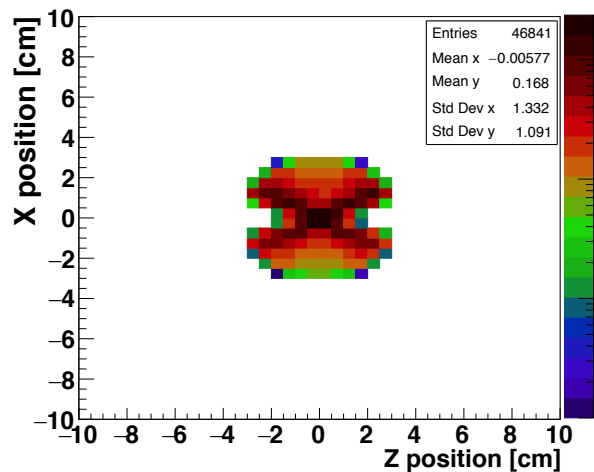
For the selection of 511 keV photons:

1. Angular correlation between anni. photons,
2. **TOT** (a measure of energy deposition)

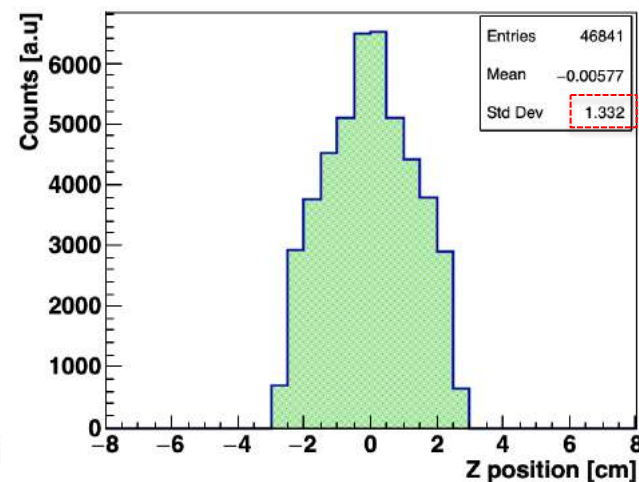
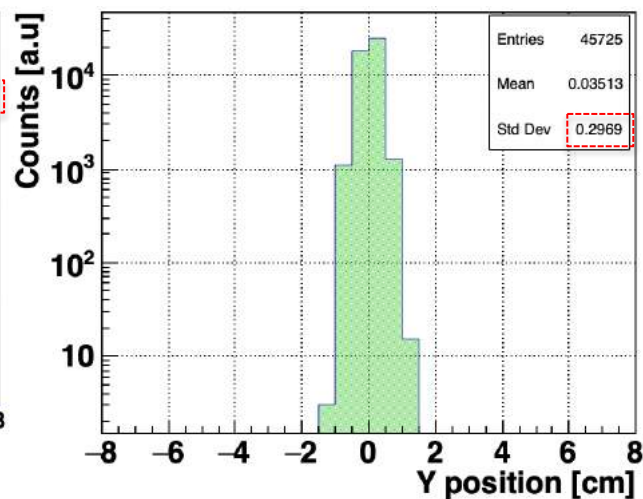
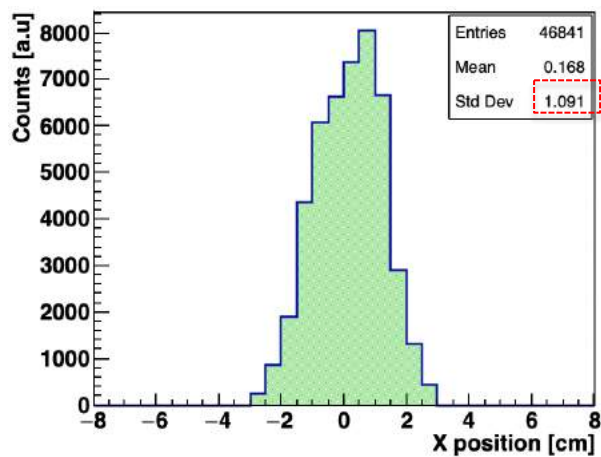
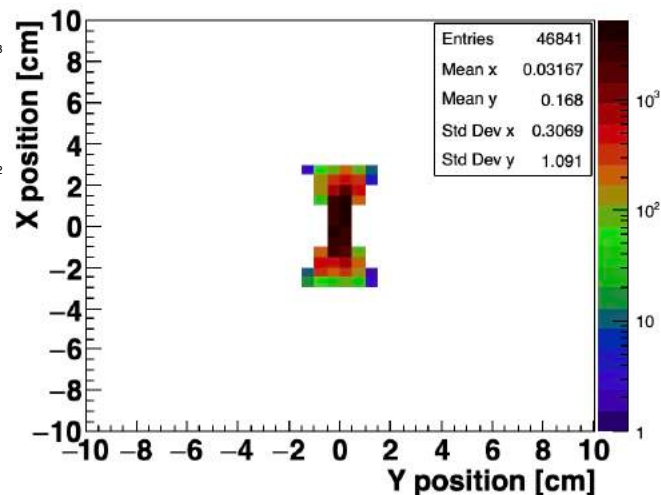
Detectors placement



Reconstructed ann. ZX



Reconstructed ann. YX





Summary and conclusion



- ❑ First **successful demonstration** of transferring modular J-PET detection units together with a complete signal readout chain.
- ❑ Based on the preliminary results of the measurements with 2 modules, it is clear that **J-PET modules** can potentially be used with the proposed experiment for *inertial sensing measurement on Ps atoms*.
- ❑ Recently, 24 modules were successfully deployed at the Cyclotron Center (Krakow) for test measurements to ***monitor the range of proton beam***.
(Data analysis is in progress)
- ❑ J-PET laboratory is continuously measuring data with Modular prototype aimed at several research problems:
 - I. Discrete symmetry tests (C, P, T, CP, CPT),
 - II. Positronium imaging in view of a new biomarker,
 - III. Quantum entanglement of annihilation photons,...

Thank you on behalf of J-PET collaboration



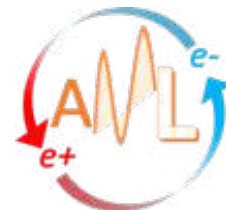
JAGIELLONIAN
UNIVERSITY
IN KRAKÓW



Istituto Nazionale di Fisica Nucleare



universität
wien



Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK

JRC collaboration partner



The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences