J-PET detector system for studies of the electron-positron annihilations

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Abstract

Jagiellonian Positron Emission Tomograph (J-PET) has been recently constructed at the Jagiellonian University as a prototype of a cost-effective scanner for the simultaneous metabolic imaging of the whole human body [1,2,3]. It will be used for studies of discrete symmetries and multi-partite entanglement of photons originating from the decays of ortho-positronium atoms. J-PET is optimized for the measurement of momentum and polarization of photons from the electron-positron annihilations. It is built out of strips of organic scintillator, forming three cylindrical layers.

J-PET

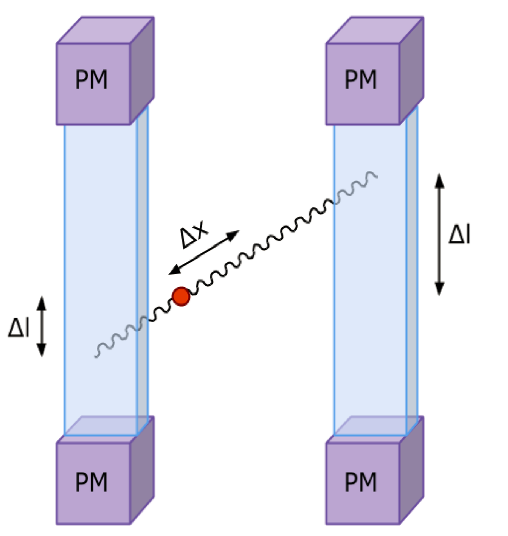

Fig. 1. Light signals from each strip are converted to electrical signals by photomultipliers placed at opposite ends of the strip. The position and time of reaction of photons in the detector material is determined based on the arrival time of light signals to the ends of the scintillator strips. In the case of the two-photon annihilation, the position (Δx) along the line of annihilation is determined from time difference measured between two modules. In the case of three photon annihilation, the positronium decay point is reconstructed based on the trilateration method [4].

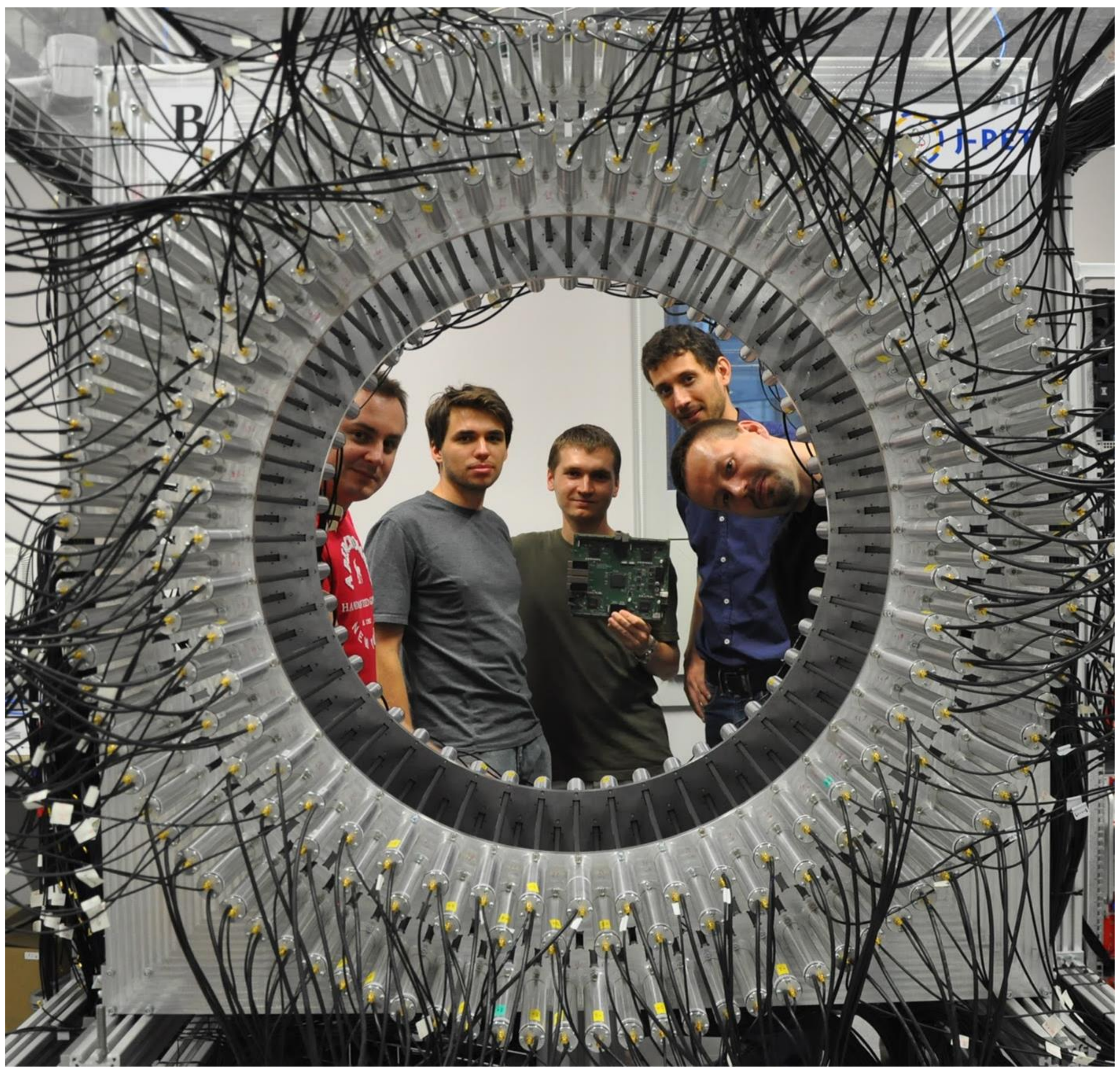

Fig. 2. J-PET detector.

The active inner part of the J-PET detector has a cylindrical shape with the length of 50 cm and diameter of 85 cm.

Linear polarization of ortho-positronium atoms

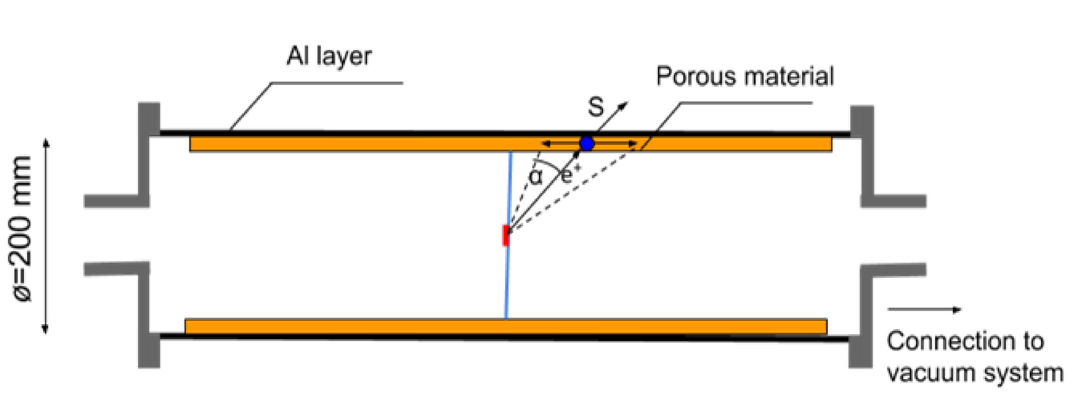

Fig. 3. The longitudinally polarized positron emitted from the beta-plus radioactive source placed in the center of the detector interacts in the cylindrical layer of the porous material [5].

The created ortho-positronium with spin S annihilates into three photons and the time and position of their interactions in the scintillator strips enables to reconstruct the position of annihilation by means of the trilateration method.

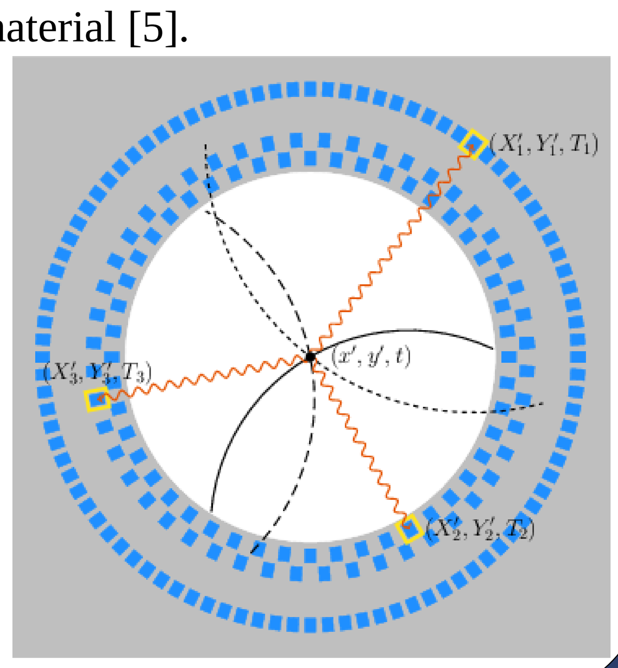

Fig. 4. Scheme of the reconstruction of ortho-positronium annihilation time and point (x′, y′, t′) inside the decay plane. Three circles with radii dependent on decay time lying in the decay plane [4].

Polarization of photons

Since gamma quantum is a transverse electromagnetic wave, and since Compton scattering is most likely in the plane perpendicular to the electric vector of the photon [6], we can determine the direction of its linear polarization $\vec{\varepsilon}_i$ e.g. by constructing $\vec{\varepsilon}_i = \vec{k}_i \times \vec{k}_i'$, where $\vec{k}_i$ and $\vec{k}_i'$ denote momentum vectors of ith gamma quantum before and after the scattering, respectively.

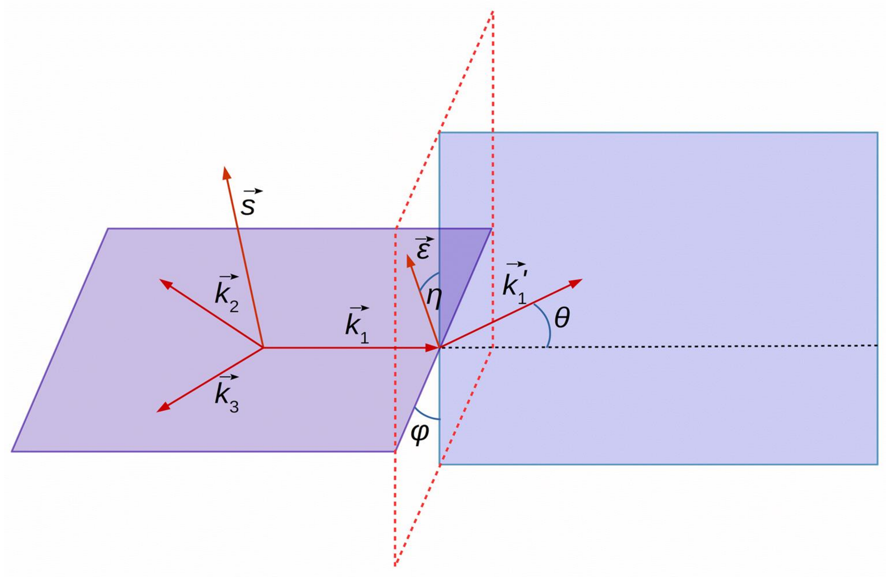

Fig. 5. θ denotes the scattering angle between the directions of propagation of the primary photon k and the scattered photon k′.

The corresponding cross section reads [6]:

$$d\sigma/d\Omega \sim (k'/k)^2 (k/k' + k'/k - 2\sin^2\theta\cos^2\eta),$$

where η denotes the angle between the scattering plane and the electric vector of photon with momentum $\vec{k}_1$, and $\vec{s}$ indicates the spin of ortho-positronium.

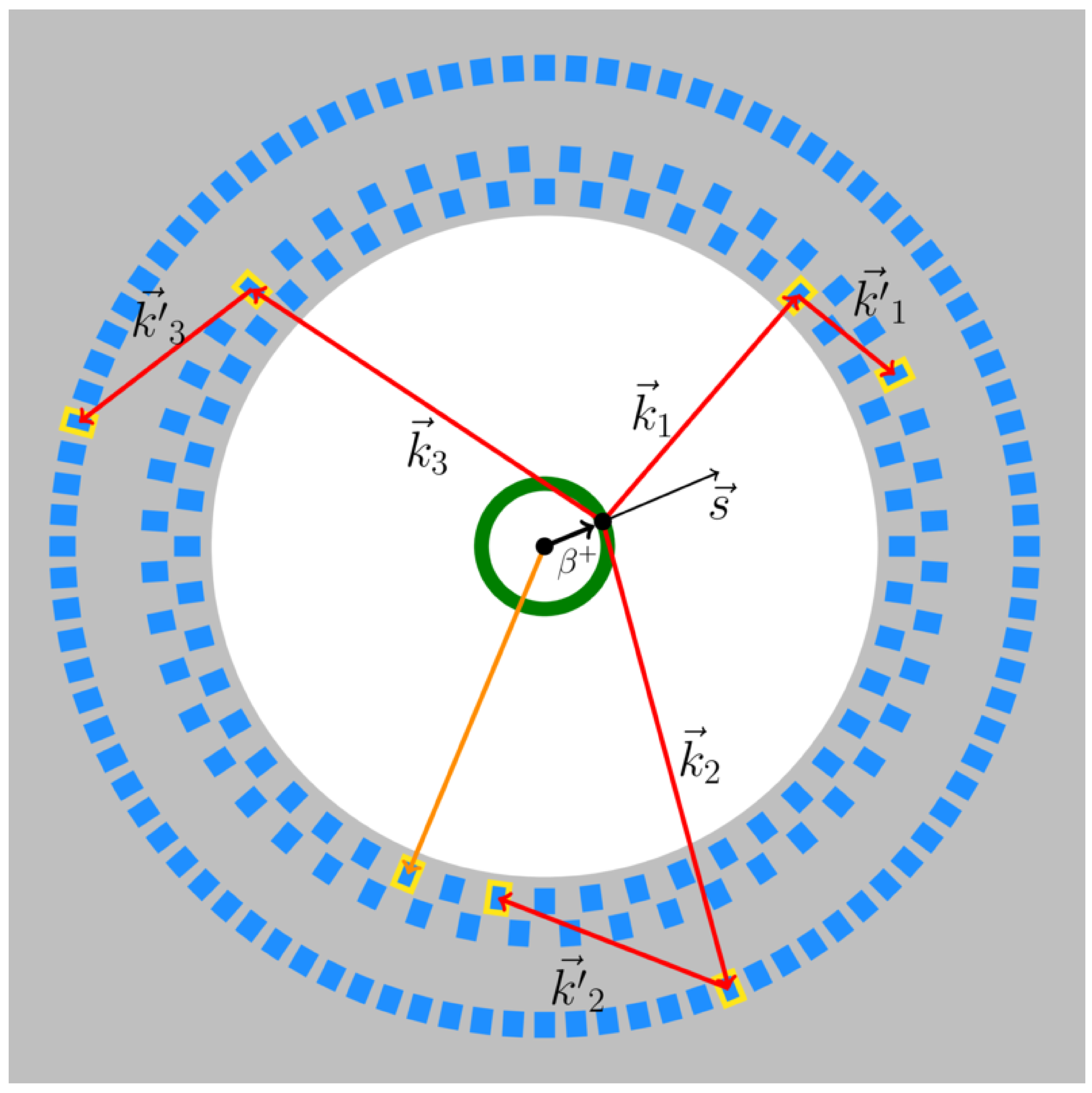

Fig. 6. Pictorial presentation of an ortho-positronium production and decay event with subsequent scattering of photons in the detector. Black dot in the center indicates ^{22}Na radioactive source emitting positron(β^+) and prompt gamma quantum (orange arrow). Positronium is produced in the porous cylinder and decays into three photons ($\vec{k}_1$, $\vec{k}_2$, $\vec{k}_3$) which may interact in the scintillator strips. Secondary photons ($\vec{k}_1'$, $\vec{k}_2'$, $\vec{k}_3'$) may also react in the scintillators.

Discrete symmetries

The J-PET enables to perform tests of discrete symmetries via the determination of the expectation values of the discrete-symmetries-odd operators, which may be constructed from the spin of ortho-positronium atom and the momenta and polarization vectors of photons originating from its annihilation [7]. Moreover, the ability of the J-PET detector to determine the angle between the decay and scattering planes of photons, opens possibilities for experimental definition of orthogonal states of high energy photon and, hence, enables studies of the multi-partite entanglement of gamma quanta originating from the positronium annihilation.

Table 1. Operators for the o-Ps→3γ process and their properties with respect to the C, P, T, CP and CPT symmetries. New operators (including $\vec{\varepsilon}_i$) available at J-PET are shown in the last three rows.

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

Summary

The Jagiellonian Positron Emission Tomograph (J-PET) is optimized for the detection of photons from the electron–positron annihilation with high time- and angular-resolutions, thus providing new opportunities for research with photons originating from the decays of positronium atoms in fundamental physics, as well as in life and material sciences [8–10].

References

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