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Application of WLS strips for position determination in strip PET tomograph based on plastic scintillators

Abstract: A method of the determination of a γ-quantum absorption point in a plastic scintillator block using a matrix of wavelength-shifting (WLS) strips is proposed. An application of this method for the improvement of position resolution in newly proposed positron emission tomography (PET) detectors based on plastic scintillators is presented. The method enables to reduce parallax errors in the reconstruction of images, which occurs in the presently used PET scanners.

Keywords: scintillator detectors; time-of-flight positron emission tomography.

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Introduction

Plastic scintillators are characterized by relatively short light pulses with decay time on the order of a nanosecond; therefore, they are widely used in nuclear and particle physics experiments for fast timing measurements. Typically, they have a form of a strip with rectangular cross-section and are read out at both ends by photomultipliers (PMs) (see, e.g., [1]). Also, other solutions are used such as scintillator plates read out by arrays of PMs [2, 3].

The high timing resolution offered by the plastic scintillators is exploited in a newly invented type of positron emission tomography (PET) using such scintillators for the detection of the 511 keV γ-quanta originating from positron annihilation. Two alternative solutions of the tomograph were proposed [4]. One solution, called the strip PET [5], contains scintillator strips read out by pairs of PMs and arranged around a cylindrical surface forming a tomograph tunnel. The position of the γ-quantum interaction point in the strip – later we call it "the interaction point" for short – is determined based on a time difference in the propagation of light pulses registered by the pair of PMs.

The second solution, called the matrix PET [6], uses plastic scintillator plates read out by arrays of PMs. The registered amplitude and time of propagation of light pulses allow for the localization of the interaction point in the plate. A key feature of both solutions is a high precision in the measurement of difference in a time-of-flight (TOF) of the annihilation quanta, allowing for the determination of the position of the positron annihilation along a line of response (LOR). This feature allows for the substantial suppression of background in the reconstructed PET images and is one of the main advantages of the plastic scintillators compared to essentially slower inorganic crystals, which are used in the contemporary commercial PET scanners.

A disadvantage of the plastic scintillators compared with the inorganic crystals is the substantially lower detection efficiency for the γ-quanta. It can be compensated by increasing a length and a thickness of the scintillator segments. However, it leads to the worsening of the timing resolution as well as of the impact point position resolution. Even if a very high precision for the measurement of the time difference of 100 ps (full width at half-maximum, FWHM) is assumed, the resulting position resolution is only moderate and equals 7.5 mm (FWHM). This estimation was done by taking into account that a speed of propagation of light in a scintillator strip is roughly two times smaller than in vacuum. We propose to improve the position resolution by the additional detection of scintillation light escaping the scintillator segments with matrixes of wavelength-shifting (WLS) strips.

The readout of scintillators by means of WLS elements is a well-established technique that is applied in various particle detectors including calorimeters (see, e.g., [7, 8]), cosmic rays detectors [9, 10], and neutron detectors [11, 12]. The usage of the WLS strips was also proposed for the readout of arrays of inorganic crystals in PET scanners [13, 14].

Position determination by means of WLS strips

For the determination of a position of the interaction point in a plastic scintillator, we propose to use a set of parallel WLS strips that register scintillation photons escaping the scintillator. This concept is illustrated in Figure 1, showing a side view of a scintillator strip and a set of parallel WLS strips placed above the scintillator. In Figure 1, we introduced the y-z coordinate system with the origin (y=z=0) located in a geometrical center of the scintillator strip and the z-axis oriented along the strip.

For an illustration of the propagation of the scintillation photons in the strip, the trajectories of photons emitted from the geometrical center at every 10° with respect to the y-axis are indicated. For emission angles larger than the critical angle, which are for plastic scintillator materials with refractive index n=1.58 equals 39.2°, the emitted photons undergo total internal reflections from the walls of the scintillator strip and propagate toward the PMs. Their trajectories are indicated with thin, black lines. For emission angles smaller than the critical angle, scintillation photons can escape the scintillator strip through a sidewall and are absorbed in the WLS strips. The trajectories of such photons are indicated as thick, blue lines, and the WLS strips, which absorb these photons, are marked with yellow color. The applied WLS material is selected in such a way that it absorbs photons with a wavelength range characteristic of the emission spectrum of the scintillator (Figure 2). Secondary photons emitted isotropically by the WLS strips propagate toward the PMs attached at their both ends. The isotropic emission of photons with the wavelength corresponding to a small absorption in the WLS constitutes the crucial feature of the presented solution, and it causes some of the secondary photons to be trapped in the WLS fiber and propagate via internal reflections toward its edges.

The coordinate of the interaction point along the scintillator strip (z-axis) is determined as a weighted average of z-coordinates of WLS strips, with weights equal to the amplitudes of signals registered in the WLS strips being proportional to the number of absorbed scintillation photons. We expect that, with a width of the WLS strip of w=5 mm, the resolution of the z-coordinate should be about 5 mm (FWHM); thus, it will be better than the one derived from the time difference measured at the strips' ends. However, the time information from the PMs reading out the scintillator strips remains important for the TOF measurement of the annihilation γ-quanta.

The position of the interaction point along the y-axis is determined from the number of WLS strips that registered the photons. For the emission from the center of

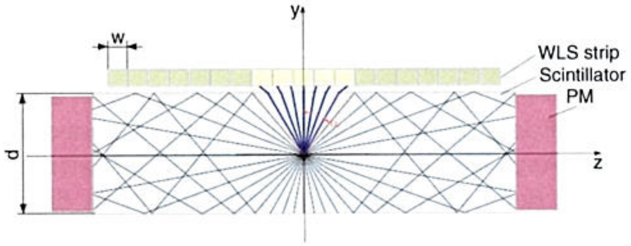

Figure 1 Schematic drawing illustrating the application of WLS strips for the determination of coordinates of the interaction point in a scintillator strip.

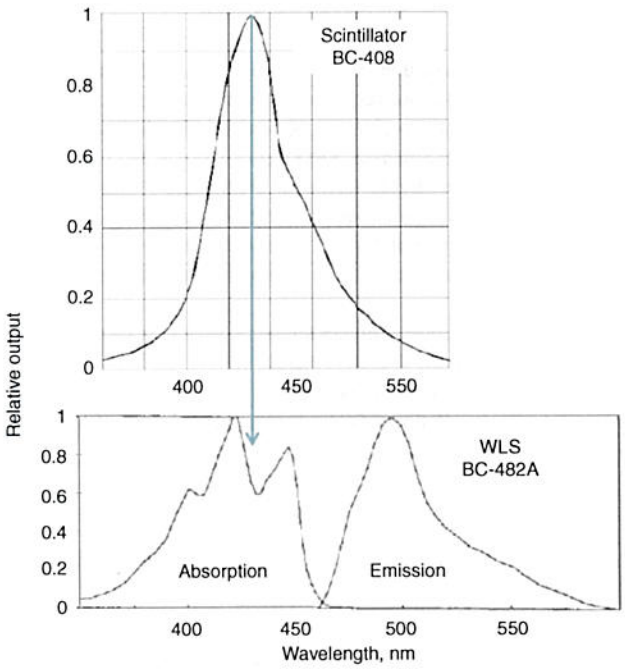

Figure 2 Emission and absorption spectra for the exemplary plastic scintillator and wavelength shifter.
Adapted from Ref. [15].

the scintillator strip (y=0) with a scintillator thickness of d=30 mm and width of WLS strips of w=5 mm, the scintillation photons reach, on average, five WLS strips as shown in Figure 1. For scintillations occurring close to the scintillator surface adjacent to the WLS strips ($y=+d/2$), the signal is measured only in one or two WLS strips. For the emission occurring near the opposite scintillator surface ($y=-d/2$), the photons reach about 10 WLS strips. The above examples indicate that, in principle with WLS strips of 5 mm width, a resolution of about 5 mm may also be achieved for the determination of y-coordinate of the interaction point. For example, one may use the following formula: depth of interaction (DOI)≡$y=d^*(n_{max}-2n)/2n_{max}$, where n denotes the number of WLS strips that gave a signal and n_{max} stands for the maximum value of strips that can see photons produced in a single interaction. In the example shown in Figure 1, n_{max}=10. The measurement of the y-coordinate is of high importance in PET scanners since it allows to correct the LOR for a DOI and thus to avoid parallax errors.

The scintillation photons escaping the scintillator bar through a side surface and reaching the matrix of the WLS strips are confined in a cone with the axis perpendicular to the surface of the bar and with the half-angle equal to the critical angle θ_c. The fraction of photons escaping the bar equals (see [16]):

$$\frac{d\Omega}{4\pi}=\frac{1}{2}(1-\cos\theta_c).$$

For plastic scintillator (θ_c=39.2°), it amounts to 0.113. The photoelectron yield of the array of WLS strips is estimated as

$$N/E_{\gamma}(MeV)=Y_L\frac{d\Omega}{4\pi}\varepsilon_{fluor}\varepsilon_{trap}\varepsilon_{\det},$$

where the plastic scintillator light yield Y_L=9000 MeV^{-1}, fluorescence efficiency of the WLS material $\varepsilon_{\rm fluor}$=0.8, trapping efficiency in the WLS strips $\varepsilon_{\rm trap}$=0.5, and photon detection efficiency of the photon counters (silicon PMs, SiPMs) $\varepsilon_{\rm det}$=0.3. For the energy deposit in the plastic scintillator of 0.3 MeV, which is typical for the Compton scattering of the annihilation γ-quanta, the photoelectron yield equals n=37 and is sufficient to reach a detection efficiency close to 100%.

Application of WLS strips in PET detectors

For the application of the WLS readout in the strip PET, the scintillator strips have to be grouped in planar segments. Each segment is read out by a set of WLS strips that are oriented at a right angle with respect to the scintillator strips. A schematic drawing of a segment containing 26 scintillator strips and 35 WLS strips is shown in Figure 3A. With a chosen width of the scintillator and WLS strips of 5 mm, the segment covers an active area of 130×175 mm. The coordinate of the interaction point along the scintillator strip (z-axis in Figure 3A) and in a direction perpendicular to the detection segment (y-axis) is derived from signals of the WLS strips as described in the previous section. The x-coordinate is determined by the identification of the scintillator strip that registered the γ-quantum. For the detection of light emitted by the scintillator and WLS strips instead of traditional vacuum PMs, the SiPMs can be applied. Due to very small sizes, the SiPMs allow to construct compact detection segments, and thanks to a capability to work in high magnetic fields, they can be used in a combined PET/nuclear magnetic resonance (NMR) scanner.

An example of an arrangement of 16 detection segments in a PET scanner is shown schematically in Figure 4. With a width of the segments s=130 mm, a cylindrical surface representing a scanner tunnel has a radius of R=327 mm.

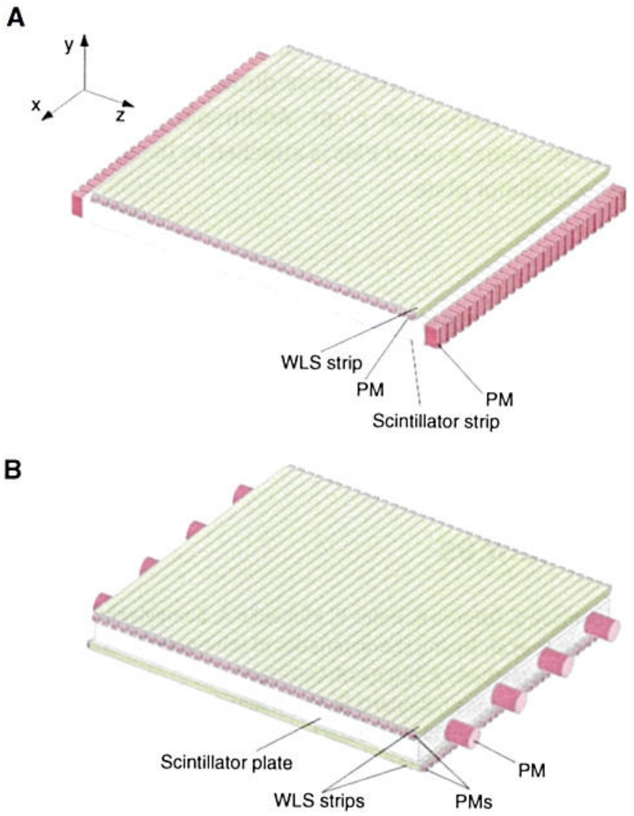

Figure 3 Arrangement of WLS strips for position reconstruction in a set of parallel scintillator strips (A) and in a scintillator plate (B).

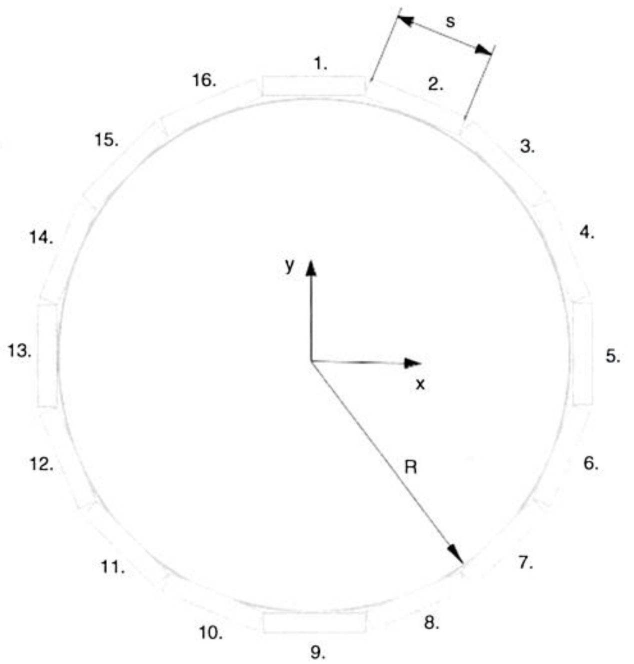

Figure 4 Arrangement of 16 detection segments around a tunnel of PET tomograph.

In the matrix PET [6], the arrays of PMs are replaced by two planes of WLS strips. The planes are parallel to each other, while the WLS strips from one plane are perpendicular to the WLS strips of the second plane (Figure 3B). This arrangement allows for a three-dimensional reconstruction of the interaction point. Additionally, for the TOF measurements, a set of PMs is attached to the sidewalls of the scintillator plate.

Conclusions

The application of the WLS strips in the strip PET and in the matrix PET has been proposed for a three-dimensional reconstruction of the γ-quantum interaction point. In particular, it allows to determine a DOI that is important for the elimination of parallax errors in the reconstruction of images, which occurs in the present PET scanners. With a choice of a width of the scintillator strips and of the WLS strips of about 5 mm, a position resolution on this level is feasible and thus is comparable with the precision of PET scanners based on blocks of inorganic crystals.

A prototype PET scanner based on plastic scintillators is being constructed in the Institute of Physics of the Jagiellonian University in Cracow, Poland. Studies of the application of WLS strips for the improvement of the position resolution in the scanner are also ongoing.

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Conflict of interest statement

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