A Novel TOF-PET Detector Based on Plastic Scintillators

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***Abstract*—The Jagiellonian-PET (J-PET) collaboration is developing a novel TOF-PET tomography scanner based mainly on the timing of signals instead of their amplitudes for the reconstruction of Lines-of-Response, therefore a very precise time resolution is one of the main challenges of the project. The novelty of the concept lies in employing long strips of plastic scintillators instead of crystals as detectors of the annihilation quanta. The diagnostic chamber consists of plastic scintillator strips readout by pairs of photomultipliers arranged axially around a cylindrical surface. To take advantage of the superior timing properties of plastic scintillators, the signals are sampled in the voltage domain with an accuracy of 20 ps by novel ultra-fast electronics, and the data are collected by the FPGA-based trigger-less data acquisition system. The hit-position and hit-time are reconstructed by the dedicated reconstruction methods based on the compressing sensing theory and a library of synchronized model signals. The solutions are subject of sixteen patent applications. So far, a time-of-flight resolution of 125 ps (σ) was achieved for a double-strip prototype with 30 cm field-of-view (FOV). It is by more than a factor of two better than the TOF resolution achievable in current TOF-PET modalities and at the same time, the FOV of 30 cm long prototype is significantly larger with respect to typical commercial PET devices. The axial geometry gives unique possibilities of combining J-PET with Computed Tomography or with Magnetic Resonance Imaging, allowing to perform the simultaneous scan of the patient with both methods.**

***Index Terms*—TOF-PET, plastic scintillators**

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I. INTRODUCTION

THE current commercial PET devices use inorganic crystal scintillators for the detection of gamma quanta. In contrast, the Jagiellonian-PET (J-PET) collaboration is developing a prototype TOF-PET scanner based on long plastic scintillators [1], [2], [3], [4], [5], [6], [7], [8], [9]. This novel approach exploits the excellent time properties of the plastic scintillators, which permit very precise time measurements of the signals allowing for the determination of position and time of the reaction of the gamma quanta in the detector, and at the same time the construction of the cost-effective detector with a large field of view (FOV). The J-PET detector consists of plastic scintillator strips readout by pairs of photomultipliers arranged axially around a cylindrical surface. The plastic scintillators were not considered as potential sensors for PET detector due to their low density (1.03 $\frac{g}{cm^3}$) and small atomic number of elements constituting the material. Fast organic scintillators are composed mainly of carbon and hydrogen. Small atomic number corresponds to small probability that the gamma quanta transfer all their energy to the electrons in the scintillator through the photoelectric effect. Moreover, small density implies a small efficiency for the detection of gamma quanta. However, disadvantages due to the low detection efficiency and negligible probability for photoelectric effect can be compensated by large acceptance and improved time resolution achievable with plastic scintillator detectors [9]. In addition plastic scintillators are much cheaper (price per unit of volume is more than a factor of 30 lower than for BGO crystals and more than a factor of 80 lower than for LSO) and can be easily produced in large sizes and various shapes, contrary to expensive inorganic crystals. In the 3D mode the geometric acceptance of e.g. 50 cm long chamber would increase on average by a factor of about three in the comparison to the present PET detectors. Thus, large acceptance would partially compensate the smaller efficiency, which in addition can also be increased by adding more scintillator layers [9]. Additionally: a larger longitudinal field of view would allow for simultaneous imaging of a larger fraction of the body. In the case of current PET scanners such image of a whole body requires performance of many independent measurements in steps taken moving the patient inside the scanner by about half the width of the ring. Thus, in case of the whole body examination, an increase of the longitudinal field view by a given factor would increase statistics of registered

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events by the same amount [9]. In addition plastic detectors will improve the time-of-flight resolution and hence the noise equivalent count rate which is inversely proportional to the time resolution [10].

II. Front-end Electronics

The precision time measurement required by the J-PET scanner imposes severe conditions on the read-out electronics. A typical rising time from the polymer scintillator used in the project is about 0.5 ns and combined with the rising time of fast photomultiplier (e.g R4998) of about 0.7 ns, results in a signal rising time of about 1 ns. The current version of the FFE board permits to probe the signal by employing four thresholds. All threshold levels are set with the FPGA-based board. The proposed solution enables sampling of signals in the voltage domain with precision of 20ps [11]. The design is a novel technique for precise measurement of time and charge based solely on FPGA device and few satellite discrete electronic components [11], [12]. The read-out electronics permit a multi-threshold sampling, which probes the signal event waveform with respect to a small number of amplitude thresholds. According to the Compressive Sensing Theory [13], the collected data points could be used to reconstruct the full signal shape e.g. by applying the transformation to a sparse representation. The information about the shape of the signals is highly correlated with the hit position of the annihilation gamma quantum along the scintillator strip. Thus, with this information a better filtering of coincidence of the two signals and also a more accurate reconstruction of the position are possible [4], [6], [5].

III. Conclusions

From the performance tests so far, a time-of-flight resolution of 125 ps (σ) was achieved for a double-strip prototype with 30 cm field-of-view (FOV) [4], [7]. It is by more than a factor of two better than the TOF resolution achievable in current TOF-PET modalities and at the same time, the FOV of 30 cm long prototype is significantly larger with respect to typical commercial PET devices. Superior timing properties of plastic scintillators together with the possibility of making large acceptance detectors in a cost effective way makes the J-PET detector a very promising solution for simultaneous imaging of the whole human body. In addition, the axial geometry of the J-PET diagnostic chamber permits to install all the electronic devices and magnetic materials outside the detector and therefore it gives unique possibilities of combining J-PET with Computed Tomography or with Magnetic Resonance Imaging, allowing to perform the simultaneous scan of the patient with both methods [14], [15].

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