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## A new in-beam proton therapy monitoring system based on digital MVT readout

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### Introduction

Positron Emission Tomography (PET) is one of the most accurate techniques used to retrieve the space distribution of the positron emitters produced by nuclear reaction within the target volume during and after proton irradiation and consequently to monitor the proton activity in biological targets. In-beam operation mode represents the modern frontier of proton therapy monitoring systems. PET detectors need to be integrated with the proton delivery equipment and the signal registration is performed either during irradiation or immediately after it without moving the patient. The in-beam signal registration is beneficial to increment the collected signal statistics and to reduce the effect of biological washout, with a consequent improvement of the image quality and accuracy. The key issue is here the high level of random coincidence background due to the prompt photons generated in nuclear interactions during proton irradiation. Modern solutions are based on two key-components. First the application of Silicon Photomultiplier (SiPM) sensors allows the miniaturization of the detection modules and the consequent improvement of the space and time resolution. Second the design of a fast digital readout electronics allows to increase the acquisition rate and enables an higher sensitivity during in-beam operation. As a possible solution to the high-rate challenge, we have previously proposed a digital multi voltage threshold (MVT) sampling method that takes samples of a pulse with respect to a set of four reference voltages. The total energy and the timing of the pulse can be obtained by the digital signal processing techniques. The combination of novel LYSO/SiPM sensor technology, MVT dedicated digital electronics and image reconstruction constitutes the Plug & Imaging (P&I) sensor.

**Keywords:** All-Digital PET, Proton Therapy Monitoring

### Design and Implementation

The basic module of the P&I imaging sensor system is composed of a 6\*6 LYSO array read out by a 6\*6 SiPM array (TM30035; SENSIL) and a printed circuit board (PCB) that provides the bias voltage to the SiPMs (Fig. 1a). The LYSO matrix contains 3.9\*3.9\*20\*mm<sup>3</sup> pixelated crystals with 0.3 mm crystal pads that are filled with barium sulfide to reflect the scintillation light and isolate each crystal optically.



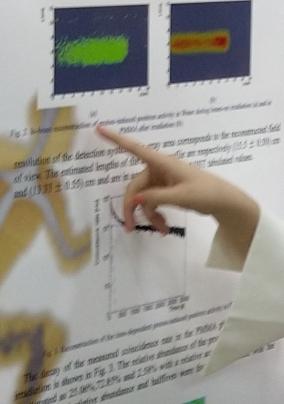
(a) Assembly of the detection module (a) and installation of the detector inside the proton therapy room of the Chang Gung Memorial Hospital (b). The protons are shown during the water phantom test at the initial position.

and imaging detection module (a) and installation of the detector inside the proton therapy room of the Chang Gung Memorial Hospital (b). The protons are shown during the water phantom test at the initial position.

a prototype of proton therapy monitoring system (Fig. 1b) consisting of a 6\*6 P&I PET heads, placed at a distance of 20 cm, and composed of a 6\*6 P&I target area of each head is approximately 20\*12.5 cm<sup>2</sup>. A central support is provided, which can be fixed to the movable system and placed at both sides of the patient bed, which can be fixed to the movable system. The whole structure is mounted on a heavy system at the proton therapy beam treatment room, aligned with the target area and we irradiated them with a 150 MeV proton beam aligned with its center and we prepared a Gaussian transversal profile with full width half maximum of approximately 2 mm and 0.3% energy spread. The irradiation was performed with an energy of approximately 800 eGy delivered within a time of approximately 15 s. Data were recorded both during the beam-on time and during a time of approximately 300 s after the beam turned off period. During the beam-on time we reached a saturated count of 5.2 MeV. When the beam was off, the beam-on time was increased to 3.2 MeV. After phantoms experiment, we performed a preliminary measurement of in-beam scattering time of 250 s. Data were collected with a 70 MeV pencil beam for a total irradiation time of 1000 s after irradiation (beam-off).

### Results and Conclusions

The reconstructed measured lateral profile of the positron emitters produced in the water phantom during irradiation (beam-on) is shown in Fig. 2a. The reconstructed measured lateral profile of the positron emitters produced in the P&I detector after irradiation (beam-off) is shown in Fig. 2b. The width of the activity distribution in the irradiation (beam-off) is wider than in the beam-on. The width of the activity distribution in the y-direction perpendicular to the beam axis reflects the beam spot size, the scattering of the secondary particles produced in the target volume and the intrinsic experimental



(a) Reconstruction of beam-on measured positron activity in water during beam-on and P&I after irradiation.

Fig. 2(b): Reconstruction of beam-off measured positron activity in water during beam-off and P&I after irradiation.

The width of the activity distribution in the y-direction perpendicular to the beam axis corresponds to the reconstructed field of view. The estimated lengths of the beam-on and beam-off are respectively  $(15.2 \pm 0.30)$  cm and  $(13.37 \pm 0.55)$  cm and are in agreement with the simulated values.



(b) Reconstruction of beam-off measured positron activity in water during beam-off and P&I after irradiation.

The decay of the measured coincidence rate in the P&I after irradiation is shown in Fig. 3. The relative abundance of the protons is 22.60%, 72.42% and 2.58% with a relative error of 0.5%.

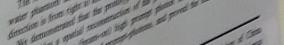
Both fitted relative abundance and halflives were in accordance with the physical expectation.



Fig. 3: Reconstruction of beam-off measured positron activity in water during beam-off and P&I after irradiation.

The reconstructed measured lateral profile of the positron emitters produced in the water phantom during irradiation (beam-on) is shown in Fig. 4a. The profile is shown from right to left.

We demonstrated that the prototype is able to be operated during beam-on and provides a spatial reconstruction of the proton-induced positron emitters during irradiation to the irradiation (beam-on) high-energy photons, and proves the feasibility of digital PET in proton therapy monitoring.



(a) Reconstruction of beam-on measured positron activity in water during beam-on and P&I after irradiation.

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