Fast Neutron Detector Based on TimePix Pixel Device with Micrometer Spatial Resolution

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Abstract – Fast neutrons are increasingly used in many fields. Fast neutrons are conventionally detected by scintillators with relatively large volume and low spatial resolution. In this paper we present a novel detection technique based on tracking of protons recoiled by fast neutrons. The tracking is performed by the silicon pixelated detector Timepix [1] (300 um thick silicon sensor, 256 x 256 square pixels with 55 um pitch) covered by a hydrogen rich converter (e.g. plastic material). The performance of the TimePix device for detection of highly ionizing particles such as protons was already published [2]. The technique utilizes the charge sharing effect and it is based on proper analysis of individual recorded tracks (clusters). The range of protons recoiled by fast neutrons is often greater than the pixel size allowing to determine not only energy and position but also the impact angle (precision is better than 2 degrees for 5 MeV protons).

Protons lose part of their energy in the plastic before reaching the Si sensor. This energy can be measured if a plastic scintillator with an attached silicon photomultiplier (SiPM) is used. The two devices (SiPM and Timepix) can be operated in coincidence reducing significantly the undesired background radiation.

Having all information about the recoiled proton and knowing the original direction of the neutron it is possible to reconstruct the exact position of the neutron-proton collision in the converter and the original neutron energy. The final spatial resolution of the neutron position determination reaches the subpixel level (about 20 µm). The expected energy resolution is about 0.5 MeV for 10 MeV neutrons. Preliminary experimental results are presented.

I. INTRODUCTION

The hybrid silicon pixel device Timepix [1] was developed by the Medipix collaboration as a successor to the successful Medipix2 detector. The device consists of a semiconductor detector chip (usually 300 µm thick silicon) bump-bonded to a readout chip (see Fig. 1). The detector chip is equipped with a single common backside electrode and a front side matrix of electrodes (256 x 256 square pixels with pitch of 55 µm). Each element of the matrix (pixel) is connected to its respective preamplifier, discriminator and digital counter integrated on the readout chip. Each pixel can work in one of three modes: Medipix mode (counter counts incoming particles), Timepix mode (counter works as a timer and measures the time when the particle is detected) and Time over threshold (TOT) mode (counter is used as a Wilkinson type ADC allowing direct energy measurement in each pixel).

The Timepix detector running in the TOT mode measures the charge collected by individual pixels. As the device contains 65536 independent channels and their response can be never identical it is necessary to perform an energy calibration for each pixel [3]. The charge created by a single ionizing particle spreads out during the charge collection process and the charge can be finally collected by several adjacent pixels forming a cluster. The total charge is then determined by summation of all these fractional charges.

Fig. 1. The hybrid semiconductor device TimePix consists of two chips: The pixelated sensor chip (usually 300 µm thick Silicon, but also other materials are available e.g. GaAs and CdTe) and the read-out chip. Both chips are connected using bump-bonding technique.

II. DETECTOR DESIGN

The proposed setup for detection of fast neutrons is based on protons recoiled by fast neutrons in a suitable conversion material. The neutron converting material can be any hydrogen-rich material, for instance a plastic scintillator.

Fig. 2. Principle of the fast neutron detection using the proton recoil (PE – polyethylene convertor, Si – Silicon detector).
The process of proton recoil is similar to billiard ball recoil and it is described mathematically in the same way (see Fig. 2). The masses of neutron and proton are almost the same and therefore proton can gain up to the full energy of neutron in a head-on collision.

Protons lose part of their energy in the plastic before reaching the Si sensor. This energy can be measured if a plastic scintillator with an attached photomultiplier (Silicon Photo-Multiplier) is used as the converter (Fig. 3). The signals are then processed in coincidence (Fig. 6).

The recoiled proton entering the pixelated device at an angle creates an asymmetric cluster. Such cluster can be analysed and the proton position, direction and energy can be determined.

It is possible to determine the impact point with precision of 1 µm for each recoiled proton with energy higher than about 3 MeV. The energy can be determined with precision of about 100 keV (FWHM) and the angle of incidence with precision of 2° (rms). Having all information about the recoiled proton and knowing the original energy and direction of the neutron it is possible to reconstruct the geometry of the neutron scattering and estimate the position of the neutron-proton collision in the converter with subpixel resolution (see Fig. 4). If the direction of incoming neutron is known it is possible to reveal not only the point of interaction but also the neutron energy.

Problem of all neutron detectors is their sensitivity to background radiation which always accompanies neutrons. In our case the gamma and electron background is suppressed by the track analysis. Background events from Si(n,p) and Si(n,α) reactions are suppressed by the coincidence technique (see Fig. 6).

**III. EXPERIMENTAL RESULTS**

The preliminary experiments proving described detector concept was performed with 14 MeV neutrons from a D-T generator. The ability of background suppression was verified by measurement described in Fig. 7.

The background from neutron interactions with silicon (Si(n,α) and Si(n,p) reactions) was greatly suppressed by the coincidence technique. The first image (a) was taken without convertor and shows only the background signal. The second image (b) was taken with the convertor attached showing that the proton signal was comparable to the background. The coincidence technique fully suppressed the background in the third case (c).
It is very difficult to prepare a collimated beam of fast neutrons with precision of tens of microns. Therefore, we used shaped convertors instead (see Fig. 8 and Fig. 10).

The first experiment was performed to verify the impact angle determination (Fig. 9A). Since the PE object was 4 mm above the detector surface all the sensitive area was irradiated almost homogenously by recoiled protons (see Fig. 9A). When cluster analysis was performed it was possible to compute the impact angle for each detected proton. The back projection of all these angles revealed the shape of the PE converter verifying the functionality of the angle determination.

Fig. 8. Convertor in a form of a PE bead (ellipsoid 4.4 mm in diameter, 2.4 mm in thickness) placed 4 mm above the detector center.

Fig. 9. A) Integral image: recoiled protons irradiate the whole detector surface, no convertor structure is visible. B) Back projection of impact angles determined from individual clusters – the convertor image is revealed.

The second experiment (Fig. 10) was devoted to verification of the energy measurement. The convertor had shape of PE strip placed 2 mm above the detector surface. The setup was irradiated with fast neutrons at angle of 45°. Among all detected clusters we selected just those with direction perpendicular to the strip (denoted by the red arrow in first frame). All these clusters were sorted according to their energy and sequence of frames was created as displayed in Fig. 11. It is clearly seen that different angles of proton recoil are associated with different energies.

Fig. 10. Convertor shaped as a PE strip (2.5 mm width, 1 mm thickness) placed 2 mm above the detector surface. The whole system was irradiated with neutrons at angle of 45 degrees.

Both these simple experiments demonstrate that information about the direction and energy of recoiled protons is successfully acquired from the measured data.

IV. MONTE-CARLO SIMULATIONS

A series of Monte-Carlo simulations were performed the results are published in a separate article [4]. Here we present just simulation of the energy resolution as a function of neutron energy (see Fig. 12).

Fig. 11. Projection of the convertor shaped as the PE strip. The first image is composed of clusters associated with perpendicular impacts (certain background from Si(n,α) is present). Other images are composed of clusters with direction perpendicular to the strip (direction denoted by red arrow in first frame). Clusters of three energy intervals were selected.

Fig. 12. Neutron energy resolution as a function of neutron energy [4]. The neutron energy resolution depends on the energy resolution of the Timepix, the angular resolution of the proton track reconstruction and on the resolution of the SiPM attached to the plastic scintillator. The last parameter strongly depends on the SiPM used, the scintillator used and the light collection in the scintillator\(^1\). The dependency was therefore calculated for two different values of the resolution.

The detection efficiency of described detector concept is relatively low (about 0.2-0.3 %) but in many cases it is still very sufficient [5].

V. CONCLUSION

The Timepix device can be adapted for detection of fast neutrons using Hydrogen rich convertors such as polyethylene. The spatial resolution of such detection system can be very high (tens of microns). Such a device can be used for fast neutron radiography especially if combined with current high emission D-T and D-D fast neutrons generators. This demonstrates the feasibility of using neutron radiography at laboratories which are not equipped with

\(^1\) As the results published here are very recent the parameters of the SiPM were not yet fully characterized.
costly sources of neutron beams such as nuclear reactors or spallation sources.

We have demonstrated that the plastic scintillator can be used as a neutron converter. If the direction of incoming neutrons is known (i.e., the location of neutron source is known) it is possible to determine also the energy for each detected neutron. The energy resolution is strongly affected by energy resolution of the scintillator and used photomultiplier.

The further experimental results with full data processing will be presented in near future.

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