Measurement of the efficiency of the pattern recognition of tracks generated by ionizing radiation in a TIMEPIX detector

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ABSTRACT: A hybrid silicon pixelated TIMEPIX detector (256 × 256 square pixels with a pitch of 55 µm) operated in Time Over Threshold (TOT) mode was exposed to radioactive sources and protons after Rutherford Backscattering on a thin gold foil of protons beams delivered by the Tandem Accelerator of the Montreal University. Simultaneous exposure of TIMEPIX to radioactive sources and to protons beams on top of the radioactive sources allowed measurements with different mixed radiation fields of protons, alpha-particles, photons and electrons. All measurements were performed in vacuum. The comparison of the experimental activities (determined from the measurement of the number of tracks left in the device by incoming particles) of the radioactive sources with their expected activities allowed the test of the device efficiency for track recognition. The efficiency of track recognition of incident protons of different energies as a function of the incidence angle was measured. The cluster size left by protons in the device was measured as a function of their incident energy at normal and large (75°) incident angles. The operation of TIMEPIX in TOT mode has allowed a 3D mapping of the charge spreading effect in the whole volume of the silicon sensor. The results of the present measurements demonstrate the TIMEPIX capability of differentiating between different types of particles species from mixed radiation fields and measuring their energy deposition. Single track analysis gives a good precision (significantly better than the 55 µm size of one detector pixel) on the coordinates of the impact point of protons with normal incidence interacting in the TIMEPIX silicon layer.

KEYWORDS: Particle identification methods; Particle tracking detectors

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1 Introduction

The TIMEPIX device [1] used in the present experiments (figure 1) consists of a silicon detector chip (300 µm thick) bump-bonded to a readout chip. The detector chip is equipped with a single common backside electrode and a front side matrix of electrodes (256 × 256 square pixels, each of 55 × 55 µm² area). Each pixel is connected to its respective preamplifier, discriminator with an adjustable threshold and digital counter integrated on the readout chip. A globally applied shutter signal determines when all pixels are active. The device was operated in Time Over Threshold (TOT) mode allowing the direct measurement of the energy deposited in each pixel. A particle striking the detector deposits its energy in silicon generating free charge carriers. If the deposited energy exceeds the pre-set threshold, one or several pixels will be activated forming a cluster of adjacent pixels. The data are recorded as images called frames that contain the status of all the pixels (65536) after a given exposure time. Different shapes of clusters of illuminated pixels are visible as tracks in the recorded frames. The lateral spread of the charge carriers from the interaction of an ionizing particle in the silicon layer of TIMEPIX causes a spreading of the charge among adjacent pixels, resulting in different track patterns for different interacting particles [2]. Several experiments were performed in Montreal for measuring the efficiency for pattern recognition of tracks generated in a TIMEPIX detector operated in TOT mode by ionizing particles from radioactive sources and protons of different energies after Rutherford Backscattering on a thin gold foil of protons beams delivered by the van der Graaff Tandem Accelerator of the Montreal University (UMTA). The analysis framework (MAFalda) [3] was used to perform the pattern recognition of tracks in TIMEPIX and associate their shapes to specific types of particles species interacting in silicon. The results of the measurements, regarding the TIMEPIX capability of differentiating between different types of particles species from mixed radiation fields and measuring their energy deposition, are reported in this article together with results on the measurement of the impact coordinates of protons of normal incidence interacting in the TIMEPIX silicon layer as obtained from single cluster analysis. Conclusions and a brief outline of future work follow.
Figure 1: a) The TIMEPIX, located in a vacuum chamber of the University of Montreal Tandem accelerator (UMTA); b) Photography of the TIMEPIX device and Fitpix interface [4] used for the measurements presented in this work. The chip was surrounded by a protective sheet (marbled grey on the picture) to avoid direct contact of the chip surface with materials in the chamber. This sheet has limited the incoming particle incidence angle to values $\leq 75^\circ$. The TIMEPIX detector was exposed to three radioactive sources (on a holder) and proton beams delivered by UMTA (see text).

2 Experimental setup

The measurements were performed at the UMTA. The TIMEPIX device, fully controlled by a Fitpix interface [4] and the Pixelman software [5], was located in a vacuum chamber (pressure of $\sim 10^{-7}$ Torr) of the accelerator. It was struck by protons of different energies from 1.98 MeV up to 9.89 MeV after Rutherford Backscattering (RBS) of 2 MeV up to 10 MeV proton beams delivered by the UMTA on a 0.12 $\mu$m thick gold foil. The TIMEPIX detector was set at a scattering angle of $90^\circ$ after the foil. Rotation of the TIMEPIX detector, supported by a goniometer with a precision of 0.5$^\circ$, allowed the test of tracks recognition at different incidence angles (from 0$^\circ$ up to 75$^\circ$). The gold foil was located in front of the TIMEPIX detector in a contiguous accelerator chamber, at an angle of 45$^\circ$ with respect to the beam direction (figure 1a). The TIMEPIX detector was also exposed to three radioactive sources (a source of alpha particles- $^{241}$Am, a source of electrons- $^{106}$Ru, a sources of photons- $^{137}$Cs), separately and simultaneously (two by two and then altogether, giving mixed radiation fields of photons, electrons and alpha-particles). The sources were mounted on a holder placed inside the chamber at different heights and located at 6.3 cm from the TIMEPIX detector (figure 1b). The average incidence angle of the particles emitted by the $^{241}$Am, $^{106}$Ru and $^{137}$Cs sources was 29$^\circ$, 13$^\circ$ and 22$^\circ$, respectively. For several experiments the TIMEPIX detector was exposed to protons from RBS beams on top of the radioactive sources giving for each proton energy a mixed radiation field of heavy charged particles (protons and alpha-particles), photons and electrons. The operation of the TIMEPIX detector in TOT mode allowed direct energy measurement in each pixel, with a low threshold of 10 keV and usually at a bias voltage of 100 V (the full depletion voltage is 25 V corresponding to a resistivity of 13 k$\Omega$cm). The exposure time was set to values short enough to avoid large tracks overlaps.
Figure 2: Examples of pixel shapes generated by different types of particles in TIMEPIX [2].

![Examples of pixel shapes generated by different types of particles in TIMEPIX](image)

Figure 3: Frames showing the tracks left in TIMEPIX by different particles emitted by the three radioactive sources A)\(^{241}\)Am, B)\(^{106}\)Ru, and C)\(^{137}\)Cs (Threshold = 10 keV, bias voltage = 100 V).

### 3 Pattern recognition of tracks with TIMEPIX

#### 3.1 Reliability

The analysis framework (MAFalda) [2] was used to perform the pattern recognition of tracks at low threshold in TIMEPIX. MAFalda is a set of algorithms written in C++ language and based on the ROOT framework and dedicated to data analysis of any device of the Medipix family. MAFalda uses the cluster shape to recognize the different types of clusters which can be associated to a specific type of particle. Examples of pixel shapes generated by different types of particles in TIMEPIX are shown in figure 2.

Frames showing the tracks left in TIMEPIX by different types of ionizing particles are displayed in figure 3.

The reliability of track recognition was tested by comparing the activities \((A_{\text{reconst}})\) of the \(^{241}\)Am, \(^{106}\)Ru and \(^{137}\)Cs radioactive sources (separate exposure) extracted from the experimental data (eq. (3.1)) with the expected activities \((A_{\text{expected}})\) (table 1). The count of the number of tracks \(N\) left in the detector by particles emitted by a radioactive source, allowed the extraction of its activity from the experimental data. The activity can be calculated using eq. (3.1):

\[
A_{\text{reconst}} = \frac{N}{t\epsilon_{\text{geom}}\epsilon_{\text{det}}} \quad (3.1)
\]
Table 1: Deviation \( \frac{A_{\text{reconst}} - A_{\text{expected}}}{A_{\text{expected}}} \% \) of the measured activities of the \(^{241}\text{Am}, ^{106}\text{Ru}\) and \(^{137}\text{Cs}\) radioactive sources from their expected activities.

| Sources  | \(^{241}\text{Am}\)      | \(^{106}\text{Ru}\)   | \(^{137}\text{Cs}\)     |
|----------|--------------------------|-----------------------|--------------------------|
| Reconstructed activity \( [\mu \text{Ci}] \) | 0.102 ± 0.002            | 0.125 ± 0.002          | 1.809 ± 0.017            |
| Expected activity \( [\mu \text{Ci}] \)  | 0.100                    | 0.128                  | 1.738                    |
| Deviation \( [%] \)                    | 2.0                      | 2.3                    | 4.1                      |

where \( A_{\text{reconst}} \) is the activity of the radioactive source from the experimental data, \( t \) the exposure time, \( \varepsilon_{\text{geom}} \) the geometric efficiency and \( \varepsilon_{\text{det}} \) the particle detection efficiency. The detection efficiency is practically 100% for charged particles with energies above the pre-set threshold of 10 keV. For the 661 keV photons emitted by \(^{137}\text{Cs}\), the detection efficiency is 0.54% \[6\]. Table 1 shows the deviation - defined as \( \frac{A_{\text{reconst}} - A_{\text{expected}}}{A_{\text{expected}}} \% \) - of reconstructed activity with the data of tracks measurements from expected activity. This reconstruction error is 2.0% and 2.3% for \(^{241}\text{Am}\) and \(^{106}\text{Ru}\), respectively. The larger error (4.1%) observed for \(^{137}\text{Cs}\) is possibly due to photons originated in the chamber wall. The results reported in table 1 show that the pattern recognition software used can recognize tracks efficiently.

3.2 Heavy tracks recognition

Figure 4 shows the device response to a mixed field of particles emitted by \(^{241}\text{Am}, ^{106}\text{Ru}, ^{137}\text{Cs}\) sources and 9.89 MeV protons incident at 75° on the TIMEPIX sensor plane. Figure 4a shows the measurement of the position \( X \) and position \( Y \) [pixel units] coordinates in the TIMEPIX active (pixels) plane of tracks left by the particles of the mixed field. The corresponding generated signal with the vertical axis representing the number of clock periods over threshold expressed in TOT [count] for each pixel is shown in figure 4b. Charge spreading among adjacent pixels is clearly observed in both figures. The threshold was set at 10 keV and the applied bias voltage was 100 V. The 9.89 MeV proton tracks are characterized with the asymmetric Bragg peak energy deposition of protons incident at large angle at the end of their range in silicon that gives also the entry position of the particle. The Bragg curve of energy deposition of 9.89 MeV protons can be clearly distinguished from the tracks left by electrons, photons and alpha-particles at the incidence of 75°. An example of single track of 9.89 MeV protons (threshold of 10 keV and bias voltage of 100 V) with incidence angle of 0° and 75° on the TIMEPIX sensor plane is shown in figures 5a and 5b, respectively. In both figures, the vertical axis represents the number of clock periods over threshold TOT [counts] expressed in energy [keV] for each pixel. Figure 5b clearly shows the lateral charge diffusion generated with the typical comet-like Bragg energy deposition (position \( X \) and positon \( Y \) [pixel units] coordinates in the pixel plane). Charge spreading among adjacent pixels is observed.

Figure 6 shows track recognition of incident protons of different energies (2.97 MeV, 4.95 MeV, 6.93 MeV and 9.89 MeV) as a function of the incidence angle. The proportion of heavy tracks is expressed by the ratio: 100 × heavy tracks/(heavy tracks+heavy blobs). Protons with energy higher than 6.93 MeV, beyond the incident angle of 35°, are recognized as heavy tracks at the level of 90% as these protons have a large incidence to the sensor surface. For protons of energy lower than 6.93 MeV the contribution of heavy tracks decreases while the contribution of heavy blobs increases and is dominant for protons of energy lower than 4.95 MeV. At lower energy,
Figure 4: Response of TIMEPIX to a mixed field of particles from the three radioactive sources and 9.89 MeV protons of 75° incidence on the TIMEPIX sensor plane: a) frame showing the lateral charge diffusion generated with the typical comet-like Bragg energy deposition (position X and position Y [pixel units] coordinates in the pixel plane); b) corresponding generated signal: the vertical axis represents the number of clock periods over threshold TOT [counts] expressed in energy [keV] for each pixel. Charge spreading among adjacent pixels is clearly observed (threshold = 10 keV, bias voltage = 100 V).

ranges in matter are small and the sensitivity to distinguish incidence angle is small as it is difficult to distinguish heavy blobs from heavy tracks.

Figure 7 shows the cluster size as a function of the incident energy (from 1.98 MeV up to 9.89 MeV) for protons striking TIMEPIX at 0° and 75° incident angles. Protons with perpendicular incidence (0°) on the sensor with kinetic energy above 6.93 MeV have a range in silicon larger than the detector thickness of 300 µm and can traverse the detector thickness. They cannot deposit all of their energy in the sensor, then, the cluster size has to decrease. Conversely, protons above 4.95 MeV have a range in silicon exceeding 300 µm and with an incidence of 75° remain inside the detector. They can deposit their kinetic energy completely in the sensor. Then, the cluster size largely increases.

4 Single track analysis

Due to charge spreading effects, a 2D Gaussian can be fitted to each energy deposition point left by a track in the sensor plane. Thus, for 0° incidence angle, a Gaussian can be fitted to a track left by a highly ionizing particle to determine the exact position of impact of the interacting particle in silicon. An example is shown in figure 8 for a 9.89 MeV proton hitting the sensor plane at 0° incidence with TIMEPIX operated at a bias of 50 V (figure 8a) and 100 V (figure 8b). The precision on the position (X and Y) coordinates of impact point is better than the size of one pixel (see caption...
Figure 5: Example of a single track generated by a 9.89 MeV proton of 0° incidence as shown in (a) and 75° incidence as shown in (b) on the TIMEPIX sensor plane: the vertical axis represents the number of clock periods over threshold TOT [counts] expressed in energy [keV] for each pixel. Charge spreading among adjacent pixels is clearly observed (threshold = 10 keV, bias voltage = 100 V).

Figure 6: Heavy track recognition of incident protons of 2.97 MeV, 4.95 MeV, 6.93 MeV and 9.89 MeV energy on TIMEPIX as a function of the incidence angle. The proportion of heavy tracks is expressed by the ratio: 100 × heavy tracks/(heavy tracks+heavy blobs) (threshold = 10 keV, bias voltage = 100 V). This single cluster analysis is currently under development to be extended to incoming particles with any incidence angle.
Figure 7: The cluster size as a function of the incident energy (from 1.98 up to 9.89 MeV) for protons striking TIMEPIX at 0° and 75° incident angles (threshold = 10 keV, bias voltage = 100 V).

Figure 8: Impact position of a 9.89 MeV proton striking the sensor plane with a incidence of 0°. The coordinates of the reconstructed position of impact are: a) bias of 50 V, \( X = 118.04 \pm 0.13 \) [pixel], \( Y = 72.21 \pm 0.13 \) [pixel]; b) bias of 100 V, \( X = 46.45 \pm 0.04 \) [pixel], \( Y = 8.41 \pm 0.07 \) [pixel] (threshold = 10 keV).

5 Conclusion and future work

The results of the present measurements demonstrate the TIMEPIX capability, based on efficient track pattern recognition, of differentiating between different types of particles species from mixed radiation fields and measuring their energy deposition. The deviation \( (A_{\text{reconst}} - A_{\text{expected}})/A_{\text{expected}} \) [%] of the activities \( A_{\text{reconst}} \) reconstructed from the count of the number of tracks left in the detector by particles emitted by individual radioactive sources (\(^{241}\)Am, \(^{137}\)Cs, and \(^{106}\)Ru) from their expected activities \( A_{\text{expected}} \) is below 5%. Distinction is achieved at \( \sim 90\% \) between heavy tracks and heavy blobs for protons with a large incidence angle (\( \geq 35^\circ \)) and with energy larger
than 6.93 MeV. The use of TOT has allowed a 3D mapping (position $X$, position $Y$ in the pixels plane and the number of clock periods over threshold TOT [count] for each pixel along the normal axis to the pixels plane) of the charge spreading effect in the whole volume of the silicon sensor. Single cluster analysis currently under development already gives a good precision (significantly better than the 55 $\mu$m size of one pixel) on the position of impact point of a proton with normal incidence interacting in silicon. The single cluster analysis is currently being developed to account for incoming particles with any incidence angle. Further studies (higher energy protons and neutrons) with TIMEPIX detectors will be done towards their installation in the ATLAS detector at the CERN/LHC. For neutron detection, the TIMEPIX silicon layer will be covered with a mosaic of neutron converters ($^6$LiF and polyethylene for a position sensitive detection of slow and fast neutrons, respectively).

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