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Measurement of an accelerator based mixed field with a Timepix detector

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ABSTRACT: We present an analysis of a high energy mixed field taken with a Timepix chip at the CERF facility at CERN. The Timepix is an active array of 65K energy measuring pixels which allows visualization and energy measurement of the tracks created by individual particles. This allows characteristics of interest such as the LET and angular distributions of the incoming tracks to be calculated, as well as broad morphological track categories based on pattern recognition techniques. We compute and compare LET-like and angular information for different morphological track categories. Morphological track categories are found to possess overlapping LET and energy spectra, however the approaches are found to be complementary with morphological clustering yielding information which is indistinguishable on the basis of LET alone. The use of the Timepix as an indirect monitoring device outside of the primary beam at CERF is briefly discussed.

KEYWORDS: Dosimetry concepts and apparatus; Particle tracking detectors (Solid-state detectors); Pattern recognition, cluster finding, calibration and fitting methods

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1 Introduction

The radiation environment around high-energy proton accelerators is similar to that produced by the cosmic radiation field at commercial flight altitudes. This field is composed of charged hadrons, neutrons, leptons and photons of widely varying energies. Particle accelerators are most well known for their use in fundamental research, but they are also widely employed in industry and medicine. Monitoring of the ionising radiation around these facilities is an important radiation protection task, and characterising these fields requires discrimination of their various components. Hybrid pixel detectors have functionality that may be useful in the characterisation of mixed radiation fields. The Timepix detector [1] is in principle well suited to discrimination in mixed fields as impinging particles leave a distinctive track in the detector which is somewhat characteristic of the impinging radiation. A prototype dosimeter based on Timepix is being tested on the International Space Station [2, 3] and a series of Medipix are used to characterize the radiation field present in the ATLAS experiment at CERN [4, 5]. The use of Timepix devices to track high-energy particles has also been studied [6, 7].

In this paper the performance and utility of Timepix in a mixed field environment is explored through measurements at the CERF (CERN-EU high-energy Reference Field) facility at CERN [8]. This facility provides a radiation field with particle composition and spectral fluences similar to those found in the cosmic radiation field at commercial flight altitudes.

2 Experimental set-up and measurements

CERF is a reference radiation facility installed in one of the secondary beam lines from the Super Proton Synchrotron (SPS), in the North Experimental Area of the Prévessin (French) site at CERN. CERF produces a field similar to that produced by the interactions of cosmic rays with the atmosphere at commercial flight altitudes. The stray radiation field is created by colliding a beam of 1/3 protons and 2/3 positive pions at 120 GeV/c with a 50 cm long copper target, which is equivalent...
to three interaction lengths for the impinging beam. The intensity of the beam is measured with an Ionization Chamber (IC) [9]. CERF produces a field consisting mostly of protons, electrons, photons, neutrons and muons (plus some pions and kaons) with a wide range of energies, which makes it interesting for the evaluation of detector performance in mixed fields.

The Timepix is a pixelated hybrid semiconductor detector developed by the Medipix 2 collaboration. It is based on a read-out chip consisting of a $256 \times 256$ pixel ASIC to which different pixellated semiconductor sensors can be bump-bonded. Each pixel measures $55 \times 55 \mu m^2$ for a total sensitive area of $1.96 \text{ cm}^2$. The salient feature of the chip is that the processing electronics for each pixel, including a preamplifier, discriminator threshold and counter fit inside the footprint of the overlying semiconductor pixel. The Timepix ASIC contains a global clock, which normally operates at 10 MHz. This allows each pixel to act as a Wilkinson type ADC measuring the discharge time of the preamplifier (the time over threshold). This quantity can be calibrated to the energy deposited in the pixel following the procedure of Jakubek [10]. In this work the Timepix was coupled with a layer of silicon $300 \mu m$ thick, biased to over depletion at 100 V. The Timepix chip is read out using the FITPix system and Pixelman software developed at the Czech Technical University in Prague [11, 12]. Data analysis was carried out with the aid of the MAfalda framework [13].

A single, interacting particle impinging on a pixellated sensor will deposit charge along the track of its interaction in the sensor, allowing the Timepix to act as a kind of digital nuclear emulsion. The resultant signal is formed by the electronic transport of charge through the sensor to the pixel preamplifier pads. We define a cluster as a group of contiguous reading pixels. Providing care is taken to limit the acquisition time of the detector in order to avoid overlapping tracks, a cluster represents the track left by a single particle.

Cluster morphology can often be characteristic of the radiation field [14], and assignment of particles into broad morphological categories can provide a measure of discrimination between particle types. To separate our data into different morphological categories several primary characteristics were computed for each cluster such as total deposited energy, length and width of a bounding box [15], cluster occupancy (which we define as the fraction of occupied pixels within the bounding box), azimuthal angle and polar angle [16, 17]. The clusters were then sorted into different morphological categories following a methodology similar to that described in ref. [18]. Sample clusters are shown in figure 1. Table 1 summarises the six cluster categories used and their selection criteria.

During the measurements the Timepix was placed in a reference irradiation position 100 cm downstream of the copper target (figure 2(a)), shifted 50 cm horizontally and 20 cm vertically. The Timepix was placed at a 90 degree angle of incidence (i.e. side on) with respect to the target. This is important because it allows a first broad separation of particle types based on track angle. We define the azimuthal angle in the sensor as $\phi$ and the altitude angle as $\theta$ following figure 2(d), a picture of the Timepix sensor is shown in figure 2(c) for comparison. Particles coming from the target should leave tracks at an approximate angle of $\phi = 70^\circ$ and $\theta = 15^\circ$. Figure 2(a) and 2(b) also show the expected angular widths of these distributions from geometrical considerations, they are $\Delta \theta = 8.1^\circ$ and $\Delta \phi = 11.8^\circ$.

Particles not coming from the target leave tracks going in other directions. Our clustering algorithm discriminates medium and heavy “Blobs” as clusters which are highly circular. These clusters are produced by particles moving at a near vertical $\phi$ angle through the chip or by slow
Figure 1. Sample data acquisition measured with the Timepix. The sensor was oriented at an angle of approximately 62 degrees with respect to the incoming particles, the experimental setup is fully described in the next section.

Table 1. Different types of clusters and selection criteria.

| TYPE          | Inner Pixels | Length/Width Ratio | Other Criteria                              | Example Clusters |
|---------------|--------------|--------------------|---------------------------------------------|------------------|
| Small Blob    | 0            | -                  | - 1 or 2 pixels                              | ![Example Clusters](image1) |
|               |              |                    | - 3 pixels if L shape                        |                  |
|               |              |                    | - 4 pixels if square                         |                  |
| Heavy Track   | > 4          | > 1.25             | - Occupancy > 0.3                            | ![Example Clusters](image2) |
| Heavy Blob    | > 4          | < 1.25             | - Not Heavy Track                            | ![Example Clusters](image3) |
|               |              |                    | - Occupancy > 0.5                            |                  |
| Medium Blob   | > 1          | < 1.25             | - Not Heavy Blob                             | ![Example Clusters](image4) |
|               |              |                    | - Occupancy > 0.5                            |                  |
| Straight Track| 0            | > 8                | - Minor Axis < 3 pixels                      | ![Example Clusters](image5) |
| Light Track   | -            | -                  | - Not Straight Track                         | ![Example Clusters](image6) |
particles moving at other angles which stop in the first few microns of silicon. From the geometry of our setup the only major source of fast particles is from the target. These particles pass through the timepix at a low angle of incidence with respect to the sensor projecting a track in silicon several pixels long. As there are no major sources of fast particles at high angles of incidence blobs are to first order restricted to slow particles (which may come from the target, or anywhere else).

3 Results and discussion

3.1 Tracking measurements

For radiation protection purposes an important quantity to calculate is the linear energy transfer, LET, the restricted collision stopping power of particles traversing the sensor, usually expressed in keV/µm [19]. LET is a differential quantity, dE/dx, but for simplicity we here call LET in silicon (LET\textsubscript{Si}) the energy divided by the track length ΔE/ΔL measured by Timepix, following the method of Hoang [17].

Figure 3(a) shows a heat map of cluster length and deposited energy (defined as the sum over all the hit pixels in the cluster) for light track clusters. Within the light track cluster category there appear to be two distinct branches of clusters with different LET\textsubscript{Si} values. The tracks in groups (1) have a range of several pixels and follow curved paths with many changes of direction in the sensor. The tracks in group (2) are straighter and more ionizing than those in group (1) as illustrated by the sample clusters shown in figure 3(b).
Figure 3. Measured light track properties, (a) Track length distribution on sensor versus the deposited energy. Two different branches are visible, likely due to electrons (1) which have a low LET$_{\text{Si}}$ (the gradient of the graph) and energetic protons which have a higher LET$_{\text{Si}}$ (2). Sample tracks from (1) and (2) are shown in (b).

We computed LET$_{\text{Si}}$ distributions for light (high LET$_{\text{Si}}$ and low LET$_{\text{Si}}$ branches), heavy and straight tracks (the different morphological categories defined in table 1). These LET$_{\text{Si}}$ distributions are shown in figure 4. The LET$_{\text{Si}}$ distributions overlap, showing how broadly our morphological clustering algorithm separates clusters by LET$_{\text{Si}}$. Interestingly the LET$_{\text{Si}}$ distribution of the straight track category fits entirely within the LET$_{\text{Si}}$ of the light track category. This implies that these track categories would not be separable on the basis of LET$_{\text{Si}}$ characterisation alone. This capability to distinguish electrons from other low-LET charge 1 particles on the basis of their morphology (and hence scattering physics) is important for dosimetry. This is because electrons largely contribute to skin dose and not to doses for more shielded organs [20], while other charge 1 low LET particles are highly penetrating. Most existing dosimeters that measure LET are monolithic and cannot make this distinction.

We also computed the $\theta$ and $\phi$ angles for track like particles. Heat maps of these distributions are shown in figure 5. Both branches of the light tracks and heavy tracks have an extended distribution centred around $\phi = 70^\circ$ and $\theta = -10^\circ$. The absolute limits of this bounding box from the geometrical constraints shown in figure 2(a) and 2(b) are also shown overlaid on the track distributions, which in the case of light and heavy tracks fit inside this box. Straight tracks are offset from this distribution by approximately 5 degrees in theta and phi, which lies outside the bounded region from the target geometry. The distribution of straight tracks is also much more point like than for other tracks. This suggests a single separate source for these tracks, one explanation for which is energetic muons. These are produced by pion decay and primary beam interactions with the collimators in the beam line (which is several hundred metres long) upstream of the CERF copper target.
Figure 3. LET$_{Si}$ distributions for light (high and low energy deposition branches, regions (1) and (2) from figure 2), heavy and straight tracks (as defined in table 1).

3.2 Blobs

As discussed in section 2, due to the geometric constraints of our setup, blob-like clusters could only correspond to either slow particles coming from the target, or fast particles coming from somewhere else, at a high angle of incidence. As we have excluded to first order fast incident particles from this category we can compute the spectrum of deposited energy, but not the LET$_{Si}$. This is shown for small, medium and heavy blobs in figure 6(a). As with the LET$_{Si}$ distributions for tracks these spectra for blobs are broad and overlap.

We also note that there is a qualitative similarity between the so called ‘medium’ blob population, shown in figure 6(b), and the spectrum of (n,Si) background events measured with an AmBe source in the Calibration Laboratory at CERN shown in figure 6(c). These medium blobs are interesting because they contain some events which deposit a relatively large amount of energy in only a few pixels, which one would expect to be spread over more pixels if the charge was deposited in the top of the sensor. (n,Si) interactions deep in the sensor provide a possible explanation for this distribution.

3.3 Time distribution of clusters

Figure 7 shows the number of measured clusters as a function of time with the Timepix placed outside of the beam in the reference position. It also shows the beam intensity measured with the reference IC. There is a good correlation between the two data sets, which raises the possibility of using a Timepix like device as an indirect monitor of beam intensity at CERN and other energetic mixed fields.
Figure 5. Heat maps of altitude and azimuthal angles of tracks. Both light tracks and heavy tracks have an extended distribution centred around $\phi = 70^\circ$ and $\theta = -10^\circ$, with a width corresponding to the geometrical width of the target (figure 2). Straight tracks originate outside of this distribution and probably are muons from primary beam pion decay and interactions with collimators upstream of the target. The distribution of light tracks in region 1 is shown in both a logarithmic and linear scale due to the much higher number of tracks in this region in comparison to the others.

4 Conclusions

The properties of different morphological cluster categories in the Timepix have been investigated. Clusters in the CERF mixed field sorted by morphology have widely overlapping $\text{LET}_\text{Si}$ distributions. However, this does not mean that this information is not useful. One category of clusters identified at CERF ("Straight Light” tracks which probably correspond to muons) originates from
Figure 6. Blob energy spectrum at CERF (a), medium blob energy/pixel distribution at CERF (b) and for comparison at the CERN calibration laboratory (c). These blobs are interesting because they deposit a large amount of energy (1–2 MeV) in a comparatively small number of pixels (5–10).

Figure 7. Number of measured clusters and beam monitor (IC) counts as a function of time.
a different point in space to the others, but would not be identifiable on the basis of LET\textsubscript{Si} alone. Angular information provides an additional degree of freedom for mixed field disentanglement, especially if one expects the field to be highly anisotropic. This is the case for many accelerator-based measurements.

The information in ‘blob’ like clusters is hard to extract useful quantities from, because the range of the particles is unknown. Like track LET\textsubscript{Si} distributions blob energy distributions produced by our clustering algorithm also overlap considerably. Separation of (n,Si) interactions from charged particle interactions remains an open question in fields with a substantial neutron component.

Finally, it was demonstrated that the number of detected secondary particles produced by collision of energetic protons and pions with the copper target is proportional to the beam intensity.

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