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Characterisation of Timepix3 with 3D sensor

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ABSTRACT: Tests were performed at the SPS facilities at CERN using a 40 GeV/c pion beam with prototype 3D-Timepix3 detectors (3D detector). A planar-Timepix3 (planar detector) was placed along the beam axis together with the 3D detectors in a telescope arrangement for comparison and reference. We demonstrate that the combination of 3D-geometry silicon sensors and Timepix3 module can reduce the effect of charge sharing and lowers the carrier drift-time, while giving the same spectroscopy performance without sacrificing the timing or any performance advantages of the Timepix3 module.

KEYWORDS: Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases); Performance of High Energy Physics Detectors;

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1 Introduction

The combination of a Timepix3 readout chip with a solid state sensor as a hybrid active pixel detector [1, 2] (Timepix3 detector), over its past three iterations have been applied in a large number of applications, such as particles tracking, identification, and trajectory mapping [3]. The readout chips were developed within the Medipix Collaboration at CERN. A Timepix3 detector (shown in figure 1) enables simultaneous measurement of Time-over-Threshold (ToT) and Time-of-Arrival (ToA) in every pixel with a time resolution of 1.5625 ns. The chip has a dead time per pixel of approximately 475 ns. It consists of 65,536 pixels in a 2 cm² area. The module can be operated with a data-driven readout scheme.

Current Timepix detectors are used in conjunction with planar geometry sensors using materials such as silicon, gallium arsenide, cadmium telluride, and other substrates. In conventional planar geometry, the electrodes are at the top and bottom of the detector, with electric fields perpendicular to the plate surface. 3D silicon sensors [4] have arrays of columnar electrodes penetrating through the bulk, with electric fields parallel to the surface (shown in figure 2). 3D geometry decouples the inter-electrode spacing with the sensor thickness which gives this new breed of sensors many advantages over the traditional planar sensor, such as greater radiation tolerance, reduced depletion voltage, and lower carrier collection time. The four electrodes that form a single pixel also act as a “cage” for the induced charge cloud which significantly reduces the charge sharing effect.

With the emergence and usage in particle detection applications of 3D sensors, we decided to investigate the performance of 3D sensors with Timepix3 modules. Specifically charge sharing, minimum ionising particle charge collection, and charge carrier drift-time. A planar Timepix3 detector was used as the benchmark for comparison.

Figure 1: Front and back photos of the Timepix3 module with 3D sensor mounted. The 3D silicon sensor visible at the top-centre of the two pictures is about 2 cm^2 . In the picture one can also see the bias voltage lemo-connector and the multi-pin readout connector at the opposite side of the sensor.

2 Experimental setup

For this experiment we used Timepix3 from the Medipix3 collaboration. The silicon sensor is bump-bonded onto the readout ASIC. This ASIC reads out the induced current from the silicon sensor after a particle penetrates the detector.

The 3D silicon sensor used for this experiment was fabricated at the Institute of Microelectronics of Barcelona IMB-CNM. Its substrate is $300 \mu\text{m}$ thick with $227 \mu\text{m}$ electrode length, and inter-electrode spacing of $55 \mu\text{m}$, as shown in Figure 2. Figure 2a is a microscopic photo showing the cutaway view of the sensor with n-type electrodes partially penetrating the substrate, and figure 2b is a sketch of the electrode geometry. The planar sensor used for comparison is $500 \mu\text{m}$ thick.

The readout interface, Katherine [5], has a bandwidth of 16 Mhit/s or 16 Mpix/s with a Gigabit Ethernet interface. Timepix3 has the capability to work in self-trigger mode with a set threshold low (THL) value. THL for the 3D detector was set to 1515 (energy equivalent of 4.935 keV).

Figure 2: 2a is the microscopic photo (taken by fabricators) of the 3D sensor's structure with electrodes. 2b is the illustration of the partial-3D structure.

3 Method

3D (named G10 and G11) and planar (named F03) Timepix3 detectors were placed in the pion beam ($40 \text{ GeV}/c$) at the Super-Proton-Synchrotron (SPS) facility at CERN. The detectors were mounted

on precision rotation motors to change the angle of individual devices relative to the beam. All devices were energy calibrated as described in [7]. For this analysis, the bias voltage for the 3D sensor G10 was set to 20V, and the bias voltage for the planar sensor F03 was 150V.

Figure 3: 3a is the detector arrangement in the beam line. 3b is the orientation of the detector (grey block) with respect to the beam. Where black, red, and blue lines represent the beams with incident angle of 0° , 45° , and 60° respectively. Same coordinate system is used in figure 8, where x corresponds to the axis “Pixel No. X” and y to “Pixel No. Y”.

The output data from the readout is in text format, which includes the pixel coordinate, ToA, and ToT. The pixel data is clustered as demonstrated in [8] with the time window set to 300 ns for 3D and 50 ns for planar¹. The ToT for this particular track is then summed and scaled according to energy calibration to give the reconstructed particle energy spectroscopy.

4 Radioactive source and X-ray fluorescence

The 3D detector was used to measure radioactive sources and X-ray fluorescence from a metal plate for calibration and linearity checks. Radioactive isotopes used were Fe-55 and Am-241, Cadmium plate was used for X-ray fluorescence. Their nominal energy can be found in Table 1. The fitted energy spectrum is shown in figure 4. In figure 5a we plotted the measured spectrum peaks against the nominal peaks of each sample to show the accuracy of the energy calibration of the 3D sensor. At higher energy the data points deviate slightly from a straight line fit, however this calibration accuracy is sufficient for the scope of this paper. Figure 4c and 4d indirectly shows that a higher bias voltage has a positive effect on the energy resolution, G11 was fabricated from the same wafer as G10, so they are comparable.

¹The activated pixels with a certain ToA which is within the time window and located next to each other are clustered together and reconstructed to represent a track left behind by a single pion particle.

Table 1: Nominal energy peaks used.

Source	Energy(keV)
Fe-55	5.888&5.899
Am-241	59.5412
Cadmium	23.173&26.093

(a) Fe-55 spectrum with G10 at 20 V.

(b) Cd spectrum with G10 at 20 V.

(c) Am-241 spectrum with G10 at 20 V.

(d) Am-241 spectrum with G11 at 40 V.

Figure 4: Fitted plots of Fe-55 and Am-241 radioactive source and Cadmium X-ray fluorescence. The fit functions used are (4.1), (4.2), and (4.3) respectively, where A, B, and C are constants (number of entries), μ is the mean of the distribution, σ is the standard deviation. The fit results are in the figure. G10 bias voltage were set to 20 V and G11 bias voltage was set to 40 V.

$$a = A \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) \quad (4.1)$$

$$b = A \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) + \frac{B}{2} \left(1 - \operatorname{erf}\left(\frac{x - \mu}{\sqrt{2}\sigma}\right)\right) + C \exp\left(-\frac{(x_2 - \mu_2)^2}{2\sigma_2^2}\right) \quad (4.2)$$

$$c/d = A \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) + \frac{B}{2} \left(1 - \operatorname{erf}\left(\frac{x - \mu}{\sqrt{2}\sigma}\right)\right) \quad (4.3)$$

Figure 5: Measured energy peaks of the radioactive and fluorescence samples against their respective nominal energy peaks. The fit function for figure 5a is made to fit through zero. The relative energy resolution shows a clear $1/\sqrt{E}$ relationship.

5 Result and analysis of the 40 GeV/c pion test beam

5.1 Cluster size and charge sharing

The experimental setup was described in Sections 2 and 3. The cluster size is the number of pixels grouped together to form the reconstructed track of the particle. A larger beam incident angle creates longer tracks, due to the pion penetrating more pixels. As expected, the 3D detector has a smaller cluster size compared to the planar as shown in figure 6.

Figure 6: 3D and planar cluster size comparison.

(a) 3D at 0°

(b) Planar at 0°

(c) 3D at 45°

(d) Planar at 45°

(e) 3D at 60°

(f) Planar at 60°

Figure 7: 3D and planar detectors at different beam incident angles, with the energy spectrum for each cluster size superimposed.

The reconstructed energy of each different cluster sizes is overlaid on top of the uncut energy spectrum for each incident angle. Figure 7 shows how, at different incident angles, the 3D and planar cluster size combinations contribute to the particle energy spectrum. The energy deposition of minimum ionising particles in matter follows Landau distribution. The substandard background signals below the Landau peak were eliminated by cutting the cluster size variable, exact methods are discussed later. From figure 6 and 7 one can see that it is possible to use the cluster size to cut for every scenario apart from 3D at 0° incident angle, where the non-Landau part consisting of 1 pixel clusters and the main pion peak have merged². It should be noted that 3D tracks have less energy due to thinner silicon bulk (300 μ m) compared to planar (500 μ m). Planar results were first

²The 0-60 keV energy level can be made up of background radiation, inadequate clustering, scattered pions, and other factors. It should be noted they are not detector noise because as shown in figure 4a, the detector is sensitive to 6 keV.

presented in [9].

5.2 Particle track samples

Figure 8 shows the 2D plots of the pixel array, they give a visual representation of how the cluster size changes relative to the beam incident angle. Particles are moving in the negative x direction.

Figure 8: 3D detector 2D plots. Left is energy (Colour scale in keV) and right is ΔToA (Colour scale in ns). The coordinate system follows figure 3b. Pixel No. X is the pixel number in the x-axis, and same for the y-axis.

At 0° , the pions only activate a single or double pixel footprint on the 3D detector. At 45° and 60° , the pions start to leave a single pixel wide track. Not shown here, planar detectors show 5 pixel clusters in the form of a cross at 0° and noticeably longer and wider tracks at 45° and 60° .

In a single cluster, the ΔToA is the time difference between the ToA of a pixel and the minimum ToA of the cluster. ToA is the sum of the carrier drift-time and the Timepix3 time resolution of the particular event. In the 45° and 60° plots, the first pixel in some of the tracks has abnormally large ΔToA , this phenomenon will be discussed further in Section 5.4.

5.3 Energy spectra

The energy deposited by minimum ionising particles (MIPs) in silicon detector is given by the Landau distribution. We determine the most probable value (MPV) and the full width at half maximum (FWHM) of the Landau for both the 3D and the planar detectors at different angles. The 3D and the planar detectors have different thickness, $300\ \mu\text{m}$ and $500\ \mu\text{m}$ respectively, the FWHM is affected by the thickness of the detector [9].

All cuts were applied to cluster size, except for 3D detector at 0° angle where the cut was applied to energy spectrum.

The cuts used for this analysis are given in Table 2, which were derived from previous sections, especially figures 6 and 7. For 0° , the planar detector gives mainly ≥ 2 pixels sized clusters, thus the cut is chosen to be cluster size > 1 . The 3D detector has both 1 and 2 pixel sized clusters in the energy spectrum, hence we cannot use the cluster size cut. Using a GEANT4 simulation we concluded that cutting at energy of $> 60\ \text{keV}$ matches the expected energy spectrum of the beam.

For 45° , the planar detector with cluster sizes of 1-8 do not contribute to the energy spectrum, as can be seen from figure 7d and 6b, the cut was chosen to be > 8 . For 3D it is clear from figure 7c that almost the entire Landau spectrum is made up of cluster size bigger than 4, hence the cut is chosen to be > 4 .

For 60° , the planar detector has little to no entries in the range of 1-15 cluster size in figure 6c, the cut is chosen to be > 14 . The 3D also has negligible number of entries in the range of 1-7 cluster size and figure 7e further illustrates that all signals lie above cluster size 6, so the cut is chosen to be > 7 .

Table 2: Final cut selected for each detector geometry and detector incident angle to the beam.

Detector Geometry	Incident Angle		
	0°	45°	60°
Planar	> 1 pixels per cluster	> 8 pixels per cluster	> 14 pixels per cluster
3D	$> 60\ \text{keV}$	> 4 pixels per cluster	> 7 pixels per cluster

(a) 3D at 0°

(b) 2D at 0°

(c) 3D at 45°

(d) 2D at 45°

(e) 3D at 60°

(f) 2D at 60°

Figure 9: results from different beam incident angles. 3D on the left and planar on the right. Fitted to Convolved Landau and Gaussian fitting function (Based on a Fortran code by R.Fruehwirth) with FWHM and MPV of the fitted curve displayed.

5.4 Drift-time

Drift-time (or signal collection time) is the time taken by the charge carriers to travel to the electrodes from their original creation position. In traditional planar geometry, depending on the carrier creation location, they could travel the entire thickness of the detector. The drift-time for the planar detector can be found in [8], where at 150 V bias voltage, the maximum drift-time is found to be approximately 30 ns. In 3D geometry, carriers only have to traverse half of the inter-electrode spacing (27.5 μm). As shown in figure 10 the ΔToA for 68% of all pixels (1σ) is less than 3.925

Figure 10: ΔToA spectrum of 3D detector at 60° beam incident angle. Fitted with Gaussian distribution with $\mu = 0$.

ns. Since the Timepix3 time resolution is 1.5625 ns, the actual drift time for 68% of all induced charge carriers is $< 3.925 \pm 1.5625$ ns.

One abnormality is the high drift-time in the 3D detector at the start of long clusters. The particles enter the detector from its backside. In the case of 45° and 60° incident angles, pions induce the charge carriers near the bottom of the first pixel, which is where the electrode does not extend fully through the substrate, as shown in figure 2b.

6 Conclusion

We have demonstrated the 3D detector have considerably less charge sharing compared to traditional planar silicon sensors when used in conjunction with Timepix3 modules. The cluster size for the 3D detector due to minimum ionising pions is typically a factor 2 smaller than for the planar detectors. The 3D detector also has a significantly lower drift-time due to the shorter distance needed for induced charge carriers to travel. The result shows the 3D detector has a better at two-track resolution in high pile-up situations, reducing post-processing workload required in cases where the sub-pixel resolution ($< (55/\sqrt{12})^2 \mu\text{m}^2$) is not needed. These advantages can be looked upon as favourable in applications such as radiation imaging and high energy particle detection.

Acknowledgments

References

- [1] Llopart, X., Ballabriga, R., Campbell, M., Tlustos, L. and Wong, W., 2007. *Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 581(1-2), pp.485-494.
- [2] Poikela, T., Plosila, J., Westerlund, T., Campbell, M., De Gaspari, M., Llopart, X., Gromov, V., Kluit, R., van Beuzekom, M., Zappone, F. and Zivkovic, V., 2014. *Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout*. Journal of instrumentation, 9(05), p.C05013.

- [3] Ballabriga, R., Campbell, M. and Llopart, X., 2018. *Asic developments for radiation imaging applications: The medipix and timepix family*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 878, pp.10-23.
- [4] Da Via, C., Boscardin, M., Dalla Betta, G.F., Darbo, G., Fleta, C., Gemme, C., Grenier, P., Grinstein, S., Hansen, T.E., Hasi, J. and Kenney, C., 2012. *3D silicon sensors: Design, large area production and quality assurance for the ATLAS IBL pixel detector upgrade*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 694, pp.321-330.
- [5] Burian, P., Broulím, P., Jára, M., Georgiev, V. and Bergmann, B., 2017. *Katherine: ethernet embedded readout interface for Timepix3*. Journal of Instrumentation, 12(11), p.C11001.
- [6] Capeans, M., Flick, T., Vuillermet, R., Darbo, G., Pernegger, H., Einsweiler, K., Garcia-Sciveres, M., Elsing, M., Rohne, O. and Gemme, C., 2010. *ATLAS insertable B-layer technical design report (No. CERN-LHCC-2010-013)*. ATLAS-TDR-019.
- [7] Jakubek, J., 2011. *Precise energy calibration of pixel detector working in time-over-threshold mode*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 633, pp.S262-S266.
- [8] Bergmann, B., Pichotka, M., Pospisil, S., Vycpalek, J., Burian, P., Broulim, P. and Jakubek, J., 2017. *3D track reconstruction capability of a silicon hybrid active pixel detector*. The European Physical Journal C, 77(6), p.421.
- [9] Burian, P., Broulím, P., Georgiev, V., Bergmann, B. and Pospíšil, S., 2018. *Particle telescope with Timepix3 pixel detectors*. Journal of Instrumentation, 13(01), p.C01002.
- [10] Groom, D.E. and Klein, S.R., 2000. *Passage of particles through matter*. The European Physical Journal C-Particles and Fields, 15(1-4), pp.163-173.