Particle tracking with a Timepix based triple GEM detector

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2015 JINST 10 P11003
(http://iopscience.iop.org/1748-0221/10/11/P11003)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 131.169.4.70
This content was downloaded on 13/01/2016 at 22:20

Please note that terms and conditions apply.
Particle tracking with a Timepix based triple GEM detector

S.P. George,¹ a,F. Murtas, a J. Alozy, a A. Curioni, a A.B. Rosenfeld b and M. Silari a

a CERN,
1211 Geneva 23, Switzerland
b University of Wollongong Centre for Medical Radiation Physics,
Northfields Avenue, Wollongong NSW 2522, Australia

E-mail: stuart.george@cern.ch

ABSTRACT: This paper details the response of a triple GEM detector with a 55 µm pitch pixelated ASIC for readout. The detector is operated as a micro TPC with 9.5 cm³ sensitive volume and characterized with a mixed beam of 120 GeV protons and positive pions. A process for reconstruction of incident particle tracks from individual ionization clusters is described and scans of the gain and drift fields are performed. The angular resolution of the measured tracks is characterized. Also, the readout was operated in a mixed mode where some pixels measure drift time and others charge. This was used to measure the energy deposition in the detector and the charge cloud size as a function of interaction depth. The future uses of the device, including in microdosimetry are discussed.

KEYWORDS: CMOS readout of gaseous detectors; Particle tracking detectors (Gaseous detectors); Time projection chambers; Microdosimetry and nanodosimetry

¹Corresponding author.
1 Introduction

In this paper we present characterization measurements performed on a triple Gas Electron Multiplier (GEM) detector [1] coupled to a highly pixelated ASIC (the Timepix [2]) for readout. This offers a total of 262,144 individual readout channels over $2.8 \times 2.8 \text{ cm}^2$. We have dubbed this detector the ‘GEMPix’ [3].

The concept for gas pixel detectors has been around for several years [4] and was first developed by Bellazzini et al. [5] as an X-Ray polarimeter using a custom ASIC [6] for x-ray astronomy [7, 8]. Other examples include the GRIDPIX detector designed for high energy physics applications [9], however sparks and discharges have proven to be persistent problems for these devices. Thanks to a specially designed High Voltage power supply (HVGEM, [10]) and a carefully designed GEM electrode layout, the GEMPix demonstrates good reliability and discharge resistance.

Such a detector can be operated as a highly granular compact Time Projection Chamber (TPC). One of the possible applications is a tracking detector where the amount of material over the track is the same as that in a biologically relevant site, such as a cell nucleus, as a sort of ‘tracking microdosimeter’ [11]. Other advantages of such a device include the direct access to the statistics of the gas avalanches produced by the GEM foils, and the radiation hardness of the device.

We characterize the detector’s performance in a minimum ionizing particle field to validate its tracking capabilities. The device is also operated in a hybrid mode where some pixels measure deposited charge and others measure the drift time of the charge in order to gain a complete construction of the track.
1.1 GEM detectors and the GEMPix

The GEMPix is based on coupling a small triple GEM detector \((3 \times 3 \times 1.2 \text{ cm}^3)\) to a quad Timepix ASIC with 262,144 pixels of \(55\mu\text{m} \times 55\mu\text{m}\) area for readout. A photograph of the detector is shown in figure 1(a) and a diagram of the principal dimensions, components and electrical fields used in the detector are shown in figures 1(b) and 1(c).

GEM detectors are a relatively recent innovation in detector technology first invented at CERN by F. Sauli in 1996 [1]. The basic element of a GEM detector is a GEM foil. This consists of a thin insulating layer which is electroplated with a conductive metal on both sides. Small holes are then etched in this foil and a voltage applied across it as shown in figure 1(b). This produces electrical fields as high as \(100\text{kV cm}^{-1}\) inside the holes. When an electron traverses the hole this allows for the formation of a localized electronic avalanche typically producing of the order of 20 electrons for each input electron. The exact gain depends on the gas used and the voltage applied. The triple GEM configuration used in the GEMPix has gains on the order of \(10^2 - 10^4\).

In the GEMPix the GEM foils are held rigid by gluing them to a frame, and the electrodes supplying the high voltage are arranged in such a way as to avoid discharges onto the wire bonds of the Timepix readout. On top of the GEM/Timepix region is a 12 mm thick drift volume, topped with a mylar cathode metallized with a thin aluminium layer. A continuous flow of a Ar:CO\(_2\):CF\(_4\) (45:15:40 ratio) gas mixture is supplied externally at a rate of 2-3lh\(^{-1}\). The whole system is made relatively gas tight with a thin layer of epoxy resin. Seven electrical fields (one per GEM foil, two charge transfer fields, an induction field and a drift field, shown schematically in figure 1(c)) are controlled externally by an HVGEM unit. Except where otherwise noted the chamber is operated at a gain of \(G = 2.10^4\) corresponding to a total applied voltage to the GEM foils of 1.35kV (450 V per foil) [12] and a drift field of 0.66kV cm\(^{-1}\).

The quad Timepix is mounted on a bespoke quad PCB, and read out using the FITPix system [13] and accompanying Pixelman [14] software developed by CTU Prague.

More details on the design of the device and the discharge protection features will be detailed in a future publication.

1.2 The Timepix ASIC

The Timepix [2] is a pixelated silicon detector developed by the Medipix 2 Collaboration. It is based on a read-out chip consisting of a 256 \(\times\) 256 pixel CMOS ASIC to which different pixelated semiconductor sensors are normally bump-bonded. It has seen wide application in particle tracking [15, 16], as an educational tool [17, 18] and in dosimetry [19, 20] and is currently commercially available from various companies. In this application however, we use a \(2 \times 2\) array of chips (for a total of 512 \(\times\) 512 pixels) without sensor as the readout for a triple GEM detector. Each pixel measures \(55 \times 55\mu\text{m}^2\). The salient feature of the Timepix is that the processing electronics for each pixel, including a preamplifier, discriminator threshold (set at a minimum value of about 1000 electrons for noise free operation) and 13.5 bit pseudo-random counter (counts up to 11818) fit inside the footprint of the overlying semiconductor pixel. The Timepix contains a global clock which was operated at 48 MHz.

One of three modes can be used for each pixel: counting (Medipix), Time Of Arrival (TOA) and Time Over Threshold (TOT). In TOA mode the chip measures the particle arrival time by...
counting from when the preamplifier goes high on the discriminator to the end of the acquisition (which can be triggered in hardware, or in software). In TOT mode whenever the pulse is high against the discriminator the pixel counts until the pulse is low again. This allows each pixel to act as a Wilkinson type ADC measuring the discharge time of the preamplifier (i.e. the time spent over the threshold). Figure 2 shows schematically how the TOA and TOT modes of operation work. As each pixel is individually programmable, it is possible to operate different pixels in different modes during the same acquisition. We exploit this feature to operate the detector in a so called ‘mixed mode’ where 1 in every 16 pixels measures TOA while the rest measure TOT.

The Timepix operates with a frame based readout. This means that the chip possesses a digital shutter, and the pixels only count when the shutter is open. After the shutter closes the Timepix
Figure 2. The TOT mode in the Timepix ASIC measures the time elapsed while the preamp output is high against the threshold discriminator. TOA mode measures the time from when the preamp goes high against the threshold until the end of the acquisition frame.

is then read out before acquiring a new frame. The FITPix system and accompanying Pixelman software are used to readout the Timepix. This allows us to read out the $2 \times 2$ array at approximately 10 Frames Per Second (FPS). One significant limitation of our system is that to operate the pixels in TOA mode we are inherently limited in our frame length by the time of one clock cycle multiplied by the counter size in order to prevent the clock overflowing. At 10MHz this limits the frame length to 1.2 ms, at 48MHz to 246 µs. At 10 FPS this leads to a significant dead time of 98.8% at 9.8 MHz and 99.75% at 48 MHz.

2 Experimental characterisation

The GEMPix was used to measure a beam of $\frac{2}{3}$ protons and $\frac{1}{3}$ positive pions with momenta of 120 GeV at the CERF facility at CERN [21]. The detector was placed approximately 10 m away from the beam aperture, where it is spread out. The impinging particle beam was nearly plane parallel. A sample frame 250 µs long is shown in figure 3, where the color scale denotes the counts of the detector running in TOA mode with a 48 MHz clock (1 count = 20.8 ns).

2.1 Track object reconstruction

There are clearly well separated track-like objects in figure 3, consisting of several contiguous clusters of pixel hits [22]. In order to construct tracks the pixels are first grouped into clusters by performing a flood-fill search on a hit pixel for neighboring pixels with a TOA value within 2 counts ($\pm 41$ ns). Single pixel hits are probably readout noise and hence ignored. Once all the clusters in the frame have been constructed they are then grouped into tracks. To do this a search in TOA
Figure 3. Sample frame taken with 120GeV proton/pion tracks. The beam was incident at 30 degrees and the chip operated in TOA mode. The color of a track denotes its time of arrival (as per the counting scheme in figure 2 higher counts arrive earlier). Individual particle tracks are clearly visible.

is performed with some wider bin (in this case 10 counts, or 200ns) and a minimum proximity requirement for the centroid of the cluster (within 50 pixels). Finally the completed track can be analyzed for useful information. Figure 4 shows examples of reconstructed tracks at 0, 20 and 40 degrees. The color scale denotes the TOA value. We use custom code to find clusters and construct tracks, and use the ROOT [23] based MAfalda framework to interface with the Timepix data [24].

2.2 Results of gain and drift scans

An important parameter to characterize in a GEM detector is the chamber gain [25]. This determines the number of electrons created by each primary ionization. A signal is only measured if the number of electrons reaching a pixel exceeds the threshold, so changing the gain in turn changes the minimum energy sensitivity of the detector.

Figure 5 shows the result of a scan in GEM foil voltage measured with the impinging particles at a 30 degree angle of incidence. Figure 5(a) shows the number of objects as a function of total GEM voltage (summed voltage over all GEM foils) for all clusters and tracks while figure 5(b)
shows only candidate tracks with a length of over 100 pixels, or 13.2 mm if the particle is assumed to fully penetrate the drift volume. A track incident at 30 degrees (angle $\phi$ in figure 7 below) should have a length of 125 pixels. This length is determined by computing the distance between the two intersection points of a least squares best fit line through the hit pixels of track with its minimum bounding box which is found using a rotating calipers procedure [26].

Both figures 5(a) and 5(b) show a characteristic S shape with a knee at 1300 V and both curves reach a plateau value which implies that the track detection efficiency is 100%. Interestingly at an applied voltage of 1380 V there is a sudden increase in the number of clusters (and hence tracks) which is associated with a large number of small, randomly placed clusters. This effect has been observed to be modulated with the amount of ambient light and we speculate that it is associated with single photoelectron emission off the aluminium on the 12$\mu$m mylar cathode of the detector. As these clusters are small and randomly distributed, they have no effect on the measured number of tracks shown in figure 5(b).

Figure 6(a) shows the results of varying the chamber drift field on the time of arrival difference between the top and the bottom of candidate tracks incident at 30 degrees (the same track selection as figure 5(b)). As these tracks should pass through both the bottom and top of the drift volume this time is equal to the drift time of the electrons over the 12 mm drift gap. From a Gaussian fit to these distributions the drift velocity of ArCO$_2$CF$_4$ can be measured which is shown in figure 6(b). If the track is assumed to enter at the top of the drift volume and exit through its bottom then this calibration can be used to provide an absolute track position in 3D space. Shown for comparison is a Magboltz [27] simulation of the drift velocity in the used gas mixture. In general the simulation matches the results well, with a small systematic shift.
Figure 5. Gain voltage scan for the GEMPix at a 30 degree angle of incidence (a) shows the total number of clusters and tracks, (b) Shows only constructed tracks with a length > 100 pixels, most of which should be primary beam particles (fit with a cubic spline).

Figure 6. (a) track time difference distributions for different incident drift fields, (b) drift velocity measurement formed by plotting the centroid of a Gaussian fit of the distributions in (a) against the drift field, compared to a Magboltz simulation of the gas mixture used for reference.

2.3 3D track reconstruction and measurement of angular resolution

The drift velocity at 0.66 kV cm$^{-1}$ was measured to be 2.97 cm µs$^{-1}$. With this result the 3D positions of the pixel hits and hence the path of the track can be reconstructed as shown in figure 7. The track is fit with 3D least squares to all of the pixel hits in 3D space. Two quantities are computed from this fit, the azimuthal angle $\theta$ and the altitude angle $\phi$. Distributions of $\theta$ and $\phi$ can be computed as a function of the incident beam angle. These are shown in figure 8(a) and figure 8(b). The moving centroid of the $\theta$ distributions can be attributed to slight changes in the orientation of the GEMPix as the detector was repositioned for new measurements.
Figure 7. 3D least squares fit through of a track constructing the $\theta$ and $\phi$ angles.

Figure 8(c) shows the angular resolution of these profiles which we define as the Full Width Half Maximum of the distributions in figure 8(a) and figure 8(b). The $\theta$ resolution improves with increasing beam angle (longer tracks provide more sampling points) to a minimum value of 1.2 degrees at 40 degree $\phi$ angle, while the $\phi$ resolution decreases. The $\theta$ resolution is in general better than the $\phi$ resolution. The reason for this is that the intrinsic drift resolution of the GEMPix is inferior to the lateral resolution of the pixel pad (electrons drift approximately 0.5 mm, or 10 pixel lengths in one clock count).

2.4 Track fitting parameters and spatial resolution

The spatial resolution of tracks was investigated for 40 degree tracks. Unlike the fits computed in the preceding section, this was investigated by separating the track into individual ionization clusters and fitting the identified 3 dimensional centroids of these clusters. Identification of the individual ionization clusters is clearly a more physically motivated approach than a fit to all of the pixel hits as used in the previous section. However for angles lower than 40 degrees it is clear from figure 4 that a substantial number of individual ionization clusters would overlap.

Individual cluster hit positions were defined as the pixel hit centroid in x and y directions, and their average TOA count value in the z direction. Future work with the detector may motivate selecting a different TOA value (for example, the maximum TOA value, or fitting a distribution to the extended charge cloud), but for simplicity we choose the average.

Figure 9 shows the relevant fitting parameter distributions. The average number of clusters per track is 8.32 (6.02 per cm) and well fit with a Poissonian distribution. The individual track residuals in the $x$, $y$ and $z$ directions are also shown. The width of the residual in $y$ ($\sigma = 45.9 \mu m$) is much smaller than that in $x$ ($\sigma = 331.9 \mu m$) or $z$ ($\sigma = 292.9 \mu m$). This is because the particle beam is aligned along the $y$ axis, so the $y$ residuals are angled perpendicular to the fit and so insensitive to changes in the fit parameters in the $x$ and $z$ direction. The correlation between the $x$ and $y$ variables
Figure 8. (a) $\theta$ distribution as a function of incident beam angle, the distribution slightly changes as the detector was repositioned by hand (b) $\phi$ distribution as a function of incident beam angle, (c) angular resolution of $\theta$ and $\phi$ as a function of beam angle, defined as the FWHM of Gaussian fits to (a) and (b).

is also shown in figure 9. The $x$ and $z$ residuals are highly correlated as they both lie angled (40 and 50 degrees respectively) to the fit and so are subject to the considerably larger error in $z$ axis measurement.

Defining an estimate of the resolution as $\frac{\sigma}{\sqrt{n}}$ the resolution along the pixel pad can be estimated using only the $y$ residuals as 19$\mu$m. The total spatial resolution of the detector is 170$\mu$m which is mostly limited by the time resolution of the detector.

3 Mixed mode operation

The Timepix ASIC cannot simultaneously measure deposited charge (via the TOT measurement scheme) and time of arrival. However, as our clusters are typically extended over many pixels, we can operate our detector in a so called mixed mode where 1 in every 16 pixels measure TOA while the rest measure TOT. Figure 10 shows a sample track at 30 degrees measured using this dual mode scheme.
Figure 9. Fit parameters using individual clusters for tracks at 40 degrees. The $x$ and $z$ residuals are much larger than the $y$ residual as they are highly correlated due to the path of the particles (roughly perpendicular to the $y$ axis, at 50 and 40 degrees to the $x$ and $z$ axes respectively).

Figure 10. Example of a track incident at 30 degrees measured in mixed mode operation. 15 out of 16 pixels measure TOT (left) and 1 out of 16 measure TOA (right). The TOA pixels are drawn at twice lateral size for illustrative effect.
Figure 11. Energy deposition curve in the GEMPix fitted with a Landau distribution convolved with a Gaussian. The high energy part of the distribution nicely matches the Geant4 photo-absorption ionization (PAI) model, but additional Fano like Gaussian smearing where the sigma follows the square root of the energy is required to fit the low energy part of the curve.

3.1 Charge measurement

The charge deposition spectrum for 30 degree tracks is shown in figure 11. The curve is Landau-like but not well described by a Landau function. As the GEMPix is a small and thin detector ($3 \times 3 \times 1.2\text{cm}^3$) the Landau curve is expected to be truncated. This is because energetic delta electrons will exit the detector having only deposited a fraction of their total energy.

The curve is fit with a convolved Gaussian and Landau distribution, and the TOT counts are normalized to energy using a Geant4 [28] simulation of the energy deposition in 13.9 mm (12 mm $\cos 30$) of the ArCO$_2$CF$_4$ gas mixture used in the detector using the Photo Absorption Ionization physics model [29] which is designed to simulate energy loss in thin gaseous absorbers. The range cut for the production of secondary particles was set to 100µm in order to be much less than the 13.9 mm path length. This distribution reproduces the high energy tail of the curve very well, but fails to reproduce the low energy part of the spectrum. In an attempt to physically motivate the shape of this curve we convolved this spectrum with a Gaussian where the sigma of the Gaussian varies as a square root of the energy (a Fano like model). This model was used as the number of electrons produced in a GEM avalanche is highly variable for small (1-2) numbers of incident primary electrons [30]. This modified spectrum fits the described curve well.

Figure 12 shows the $\theta$ and $\phi$ distributions for the mixed mode operation compared to the pure TOA mode validating the tracking capabilities of the mixed mode operation. For both $\theta$ and $\phi$ the TOA distributions are slightly narrower than those measured in mixed mode.

3.2 Diffusion as a function of depth

The highly pixelated readout of the GEMPix makes it highly suitable for the investigation of the electron transport properties of gas detectors. Figure 13 shows the average cluster width as a
Figure 12. Comparison of $\theta$ and $\phi$ reconstruction in mixed and TOA modes at 30 degrees. The mixed mode distributions are slightly wider than the pure TOA mode distributions.

The cluster width is defined as $2\sqrt{a/\pi}$ where $a$ is the area of the cluster (the number of counting pixels multiplied by the area of one pixel). The energy calibration used to normalise figure 11 was used to bin the clusters by energy. Clusters were selected only from a subset of tracks which are highly linear (i.e. with no significant delta electron emission), and which appear to fully penetrate the drift volume in order to ensure that the $z$ position is accurate. It is difficult to account for overlapping clusters as ionization events consisting of only a few electrons may be inherently highly asymmetric given the stochastic nature of electron transport. The charge binning used can only be used to approximate the number of primary ionizations as small numbers of electrons produce an extended, long tailed avalanche distribution in GEM detectors [23].

The plots in figure 13 are fit with a square root curve ($y = a + \sqrt{bx}$) following the classical diffusion relation $\sigma = \sqrt{2Dt}$ where $\sigma$ is the diffusion width of a point like cloud in a gas with diffusion coefficient $D$ and drift time $t$. The $b$ parameter is almost flat for single/double electron clusters, but becomes increasingly larger for multi-electron clusters. At its highest value the $b$ parameter is much less (approximately a factor 5) than the diffusion coefficient for the Ar:CO$_2$;CF$_4$ gas mix used. This is probably because of the high (> 1000 e-) threshold in each pixel. For small charge clouds a relatively large fraction of the cloud may be below threshold and so undetectable.

The $a$ (intercept) parameter as a function of primary cluster energy is shown in figure 14. We interpret this as the measured cluster width for interactions at the bottom of the drift volume.
Figure 13. Cluster width as a function of drift depth for different charge bins. The curves are fit with functions of the form \( y = a + \sqrt{bx} \).

Figure 14. Measured cluster width from interactions at the bottom of the drift volume as a function of energy (intercepts from figure 13). Fit linearly with \( y = p0 + p1x \).
4 Discussion

In the future it should be possible to improve low charge performance of the detector with detailed characterization of the Timepix ASIC, specifically by introducing a charge calibration and compensating for the timewalk effect for low charges.

The charge response of a pixel is nonlinear for low charges (below about 4000 electrons). The standard procedure [31] for determining this function relies on single pixel hits from characteristic photon lines which are impossible to produce in the GEMPix. The Timepix also has a test pulse functionality which injects a fixed amount of charge into the preamplifier but this does not reliably describe the shape of the surrogate function at low charges [32].

The timewalk effect occurs when the rise time of a low charge signal is significantly different than for a high charge one, resulting in a systematic shift of a few counts in the TOA measurement.

Use of the Timepix3 ASIC [33] could considerably improve the performance of the GEMPix. The Timepix3 test pulse functionality has been demonstrated to work well allowing for easy readout calibration. The Timepix3 also measures time and charge simultaneously removing the need for a mixed mode and features a time resolution of 1.5 ns which corresponds to a distance on the order of the pixel pitch (with an equivalent triple GEM setup). Finally the Timepix 3 offers a data driven readout (which sends out the measured information as soon as pixels go low) with maximum data throughput rate of 85 Mhits/second which should improve the dead time, or remove it entirely in low count rate situations.

One of our target applications is to use the GEMPix as a particle tracker that can measure energy deposition/track structure in tissue equivalent gases over biologically relevant site sizes, i.e. as a Microdosimeter. The central principle of such a detector is that the atomic composition and number of atoms in a given path length is the same as that found in a biological site, such as a cell nucleus. This seems eminently achievable with the GEMPix as the length of a HeLa cell nucleus is some 10µm, the equivalent path length in a propane based tissue equivalent gas at STP is some 90 pixels. Future work in this regard will focus on producing appropriate algorithms to extract microdosimetric spectra and validation of the GEMPix against existing devices (typically Tissue Equivalent Proportional Counters, TEPC).

To motivate this application in figure 15, we show some of the more unusual interactions measured using the detector. Figure 15(a) shows a shower probably originating in the wall of the detector, (b) a multiple scattering particle, probably an electron, (c) a dense track (most likely a light ion emitting delta electrons and (d) a primary particle (i.e. a 120 GeV proton or pion) emitting a delta electron.

5 Conclusions

We have demonstrated the particle tracking capability of a novel compact TPC based on a triple GEM detector coupled to a quad Timepix ASIC with minimum ionizing particles.

Scans in chamber gain and drift field were performed, finding the gain plateau value for the detector and measuring the drift time in the detector. The 3D path of the tracks measured by the detector were constructed and the angular resolution of the these tracks measured, in the azimuthal direction this varied from 6.2 degrees at a 10 degree angle of altitude to 1.3 degrees at a 40 degree
Figure 15. Unusual events measured with the GEMPix in TOA mode (a) shows a shower most likely originating in the wall of the detector, (b) shows a particle multiple scattering, (c) appears to be a light ion, with a dense track and delta electron emission (d) appears to be a primary beam particle emitting an energetic delta electron.

<table>
<thead>
<tr>
<th>Pixel (x)</th>
<th>Pixel (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>400</td>
<td>450</td>
</tr>
</tbody>
</table>

altitude. In the altitude direction this varied from 3.8 degrees to 7.1 degrees over the same range. The track spatial resolution of the detector was estimated to be 170µm which is limited by the resolution of the time measurement.

Deposited energy and track path were simultaneously measured by operating the detector in a ‘mixed’ mode where some pixels measured charge and others drift time. The energy deposited in the detector was found to match well to the Geant4 simulation when it was convolved with an additional energy dependent smearing term.

The diffusion of small amounts of charge in the detector was investigated as a function of energy and height, and the intrinsic width of the charge distributions produced by our triple GEM detector measured as a function of input energy.

Potential improvements to the device using the Timepix3 ASIC and the use of such a detector as a microdosimeter were briefly discussed.
Acknowledgments

The authors would like to thank Erik Bosne for electronics support, John Idarraga for his help with the MAfalda framework, Filippo Resnati for help with Magboltz simulations, Nersine Dinar for experimental support as well as Erik Frojdh and Stefano Agosteo for useful discussions.

This research project has been supported by the Marie Curie Initial Training Network Fellowship of the European Community’s Seventh Framework Programme under Grant Agreement PITN-GA-4 2011-289198-ARDENT.

References


[33] T. Poikela et al., Timepix3: a 65k channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout, 2014 JINST 9 C05013.