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First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera

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Abstract:
ARIADNE is a research project for the development of innovative two-phase optical LAr TPC readouts. Optical readout presents several considerable advantages when compared to traditional segmented THGEM (THick Gaseous Electron Multiplier) charge readout technologies, such as ease of scalability, upgrade, installation and maintenance, cost effectiveness and simplicity. This paper presents the first demonstration of 3D particle tracking in a TPC using purely optical readout. By combining an optically sensitive Timepix3 (TPX3) sensor with an image intensifier a single photon sensitive camera has been developed. TPX3, operated in data driven mode, provides both arrival time (ToA) information and charge deposit information (ToT) together with the coordinates of the active pixel when light is received. Since charge produced in a TPC is drifted over time it is possible to perform full 3D reconstruction by combining the (x,y) pixel information with ToA information. ToT information provides a measure of intensity in each pixel and enables calorimetry. Both an Americium-241 alpha source and cosmic rays have been imaged in 100mbar CF4.

Keywords: Time projection Chambers (TPC), Noble liquid detectors, Micropattern gaseous detectors, Photon detectors for UV, visible and IR photons (solid-state).

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Contents

1 Introduction and motivation

Colossal LAr TPCs are considered by many to be the future for long baseline neutrino oscillation physics. Realisation of these colossal-scale LAr TPCs is underway, with international efforts such as the DUNE collaboration bringing together the single and two-phase LAr TPC technologies [1–4]. This paper presents the development of a novel and alternative photographic readout technology. Optical readout presents several advantages when compared to currently accepted segmented THGEM (THick Gaseous Electron Multiplier) charge readout technologies, such as ease of scalability, upgrade, installation and maintenance, cost effectiveness and elegant simplicity without the need for many thousands of charge readout channels that are currently required for the colossal-scale two-phase detectors.

Whilst THGEMs provide excellent gain resulting in good signal-to-noise ratios, the current THGEM charge readout approach has challenges with respect to scale-up: separate readout channels are required for every anode strip, which can easily number in the hundreds of thousands for future colossal scale detectors. This proposed alternative readout method involves the exploitation of the secondary scintillation light produced in THGEM holes [5–9] during the charge amplification process. We have already demonstrated for the first time the imaging of cosmic muons with the Liverpool 40 litre LAr TPC utilizing a THGEM and Electron Multiplying CCD (EMCCD) camera [10, 11]. Subsequently ARIADNE, a one ton two phase LAr TPC with optical readout capabilities has been constructed and has been placed at a charged particle beam at CERN [12–15]. This paper presents an exciting new development of this work which allows for full 3D tracking using purely optical readout.

2 Detection principle and experimental setup

The Liverpool 40 litre LAr TPC assembly consists of an 8-inch Hamamatsu cryogenic PMT coated with TBP wavelength shifter directed upwards towards the fiducial volume, which has a cylindrical 20 cm long drift length with 178 mm diameter. Above the extraction region there is the facility to mount various charge multiplication devices, such as THGEMs and MicroMegas. For this paper dual stacked THGEMs were placed above the TPC and a novel intensified Tpx3Cam camera [16] is mounted outside the detector, looking through a viewport at a distance of 1 m from the THGEMs. When an incoming particle passes through the detector prompt scintillation light is produced and the detector medium is ionised. The free electrons are drifted to the THGEMs by an applied drift field. When electrons enter the 500 μm holes of the THGEM an avalanche occurs due to the high field applied across the THGEM, producing secondary scintillation light. This light is captured by the external camera. Each pixel in the camera that detects light above a threshold records the x and y coordinate as well as simultaneous time over threshold (ToT) and time of arrival (ToA) information. Full 3D reconstruction is possible by combining the pixel x,y position with ToA information. Since there is a known drift velocity in the TPC it is possible to infer z position information from ToA information. ToT information in the pixel gives a measure of pixel intensity and enables calorimetry. The detection principle for this detector is shown in Figure 1. For all results presented in this paper the TPC was filled with 100 mbar CF4. The cathode was biased to -3000 V and the anode to -1000 V producing a drift field of 100 V/cm. The bottom plane of the first THGEM was connected to negative polarity bias voltage. The top plane of the first THGEM and the bottom plane of the second THGEM were both grounded. The top plane of the second THGEM was connected to positive polarity bias voltage. An Americium-241 alpha source was placed inside the TPC in order to produce the alpha tracks that were imaged in this paper. This source is connected to a rotation motion feedthrough which allows it to be moved out of the TPC volume when imaging cosmic rays.

The Timepix3 chip [17] has a minimum operating threshold of $500e^{-}$ and therefore is not capable of directly imaging single photons. In order to achieve single photon sensitivity the camera was coupled with a Photonis intensifier [18]. This intensifier amplifies incoming light signals by first converting light to charge using a photocathode, multiplying the resulting charge in dual (chevron) MCP and then converting this multiplied charge back to an amplified light signal using a fast scintillating screen, P47. The amplified light is then collected using a light sensitive sensor which is bump bonded onto a TPX3 chip [19, 20]. The secondary light produced in the THGEMs in CF4 has a wavelength of approximately 620 nm. The QE of the photocathode of the intensifier at this wavelength is $\approx$20 %. The TPX3 chip has 256 x 256 pixels, each 55 μm x 55 μm in size. When combined with the 50 mm lens used in this setup the camera has a field of view covering roughly 18 cm x 18 cm. The 256 x 256 pixel of TPX3 spread over this area gives a (x,y) position resolution of less than 1 mm. ToA information is time-stamped to an accuracy of 1.6 ns which when considering the observed drift velocity of $\approx$ 10 cm/μs in the TPC yields a theoretical z position resolution of much better than 1 mm. The timing resolution of TPX3 is easily good enough to allow for 3D tracking even in gas TPCs with very fast drift times. When considering the slower drift velocities of liquid Argon/Xenon TPCs the z position resolution is expected to be well below the limits imposed by electron diffusion during drift. If the camera is placed at a suitable distance from the THGEM it should be possible to realise tracking which is diffusion limited in all x, y and z. Figure 2 shows the camera and Figure 3 shows the camera mounted to the TPC.

The non-intensified version of Tpx3Cam has been used before for the ion imaging [21] while the intensified version of camera has previously been used in the single photon regime for spatial characterization of photonic polarization entanglement [22].

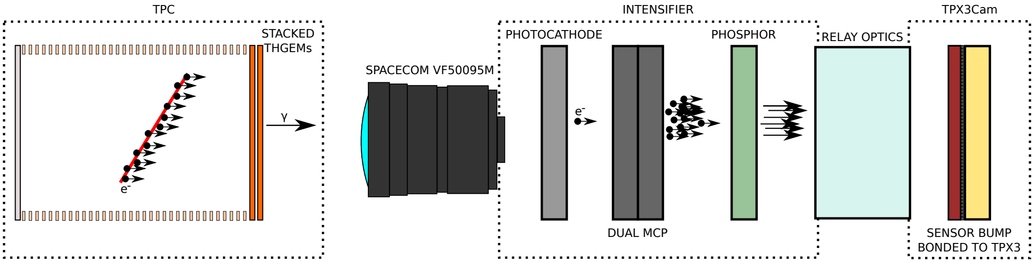

Figure 1: Detection principle. Light produced during the charge multiplication process in the THGEM holes is captured using a lens and focused onto a photocathode inside an image intensifier. The intensifier amplifies this low intensity incident light signal and relays the amplified light signal to Tpx3Cam.

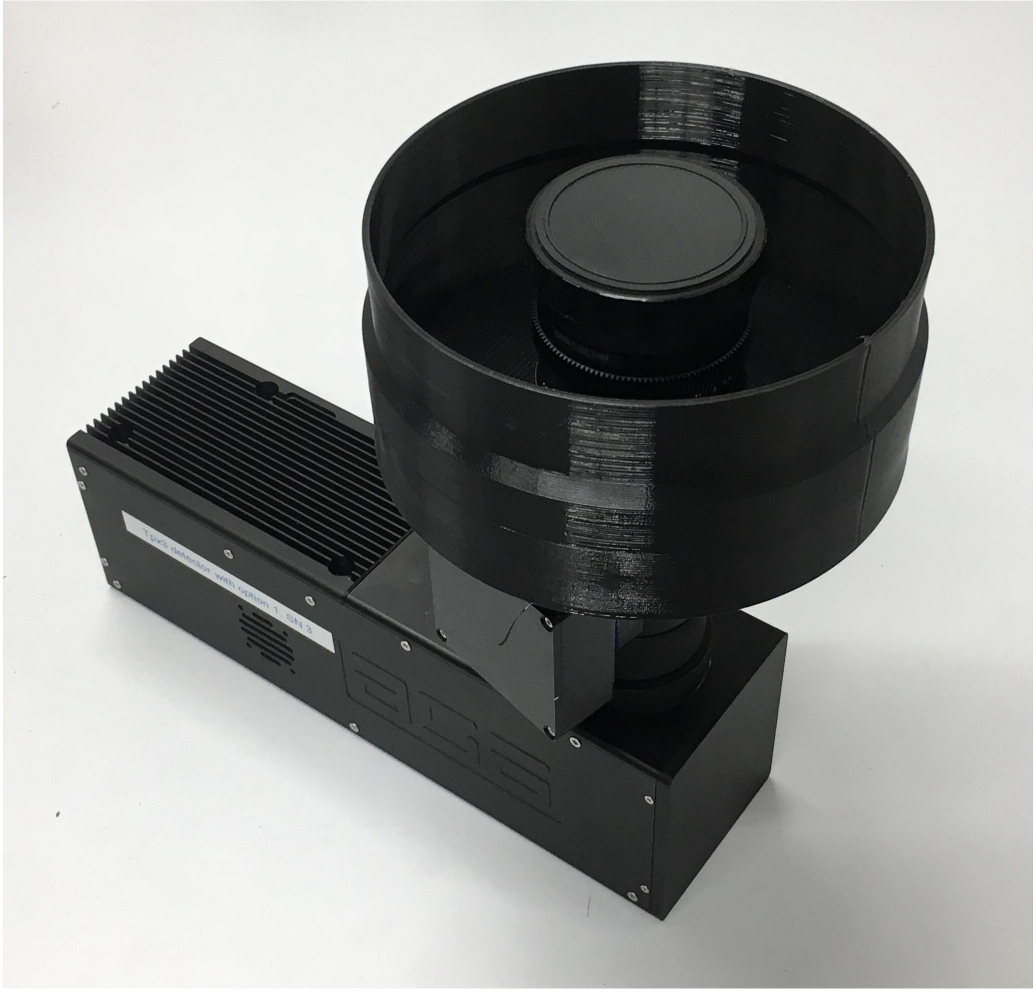

Figure 2: Intensified TPX3 camera. The bellows used to create a light tight connection to the detector can be seen around the lens which has a cap installed to protect the photocathode of the intensifier.

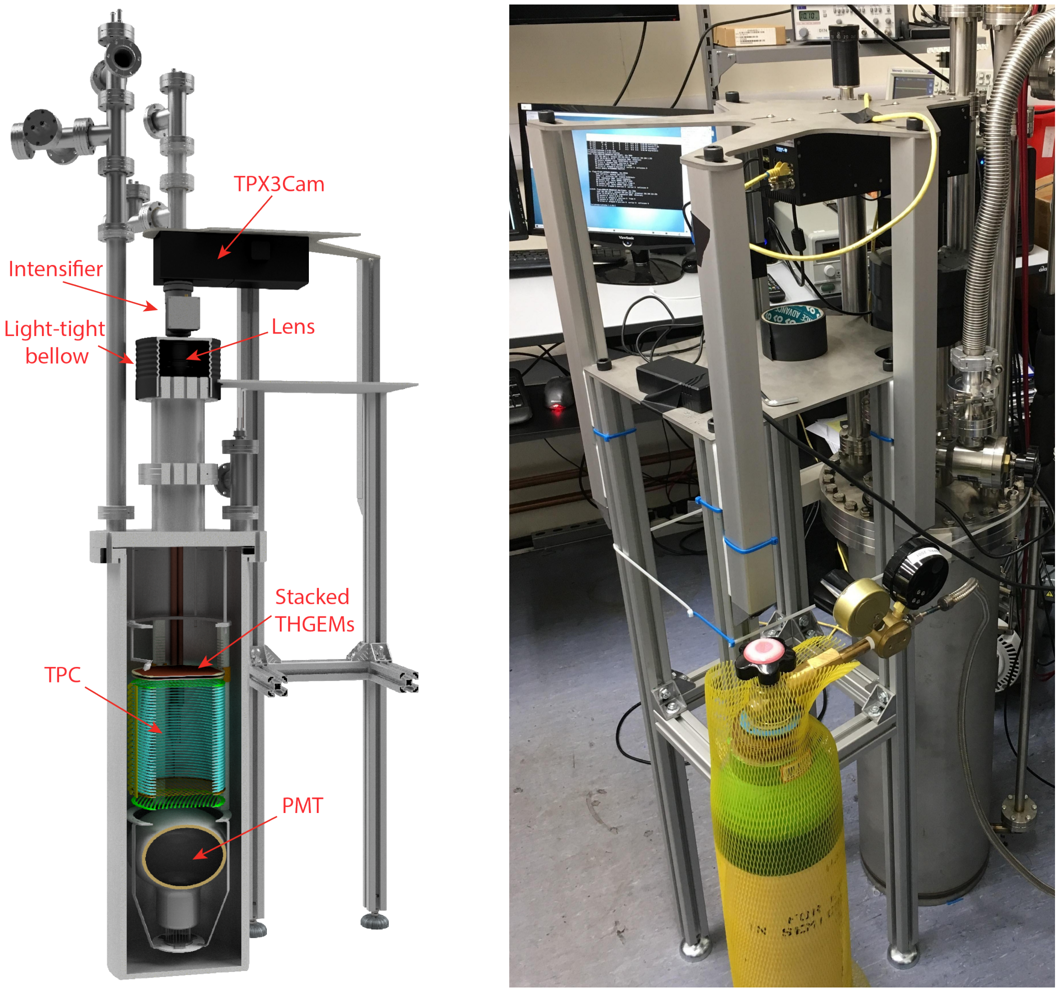

Figure 3: Experimental setup. The intensified TPX3 Camera looks down through a viewport at the THGEMs in the detector. A spacecom VF50095M lens captures the light that is produced during the charge multiplication process in the THGEM holes.

3 Results

It is possible to visualise the data captured by the camera in two different ways. Firstly it is possible to present the data as a traditional CCD image with a simulated fixed exposure time. This way of presenting data may be more suitable for diagnostic or maintenance tasks such as lens focusing which are easier performed using full frame images. SoPhy software provided with TPX3Cam enables this with a simple GUI and live video output. Figure 4 shows an image of several alpha tracks imaged using this approach.

The native mode of operation of TPX3 is data driven. In this mode each pixel is read out individually. If a light signal is received which passes over a preset threshold the pixel's (x,y) position is recorded as well as simultaneous ToT and ToA information. All of this data is sent off camera as a packet over an Ethernet connection. Each pixel operating in this way allows for sparse

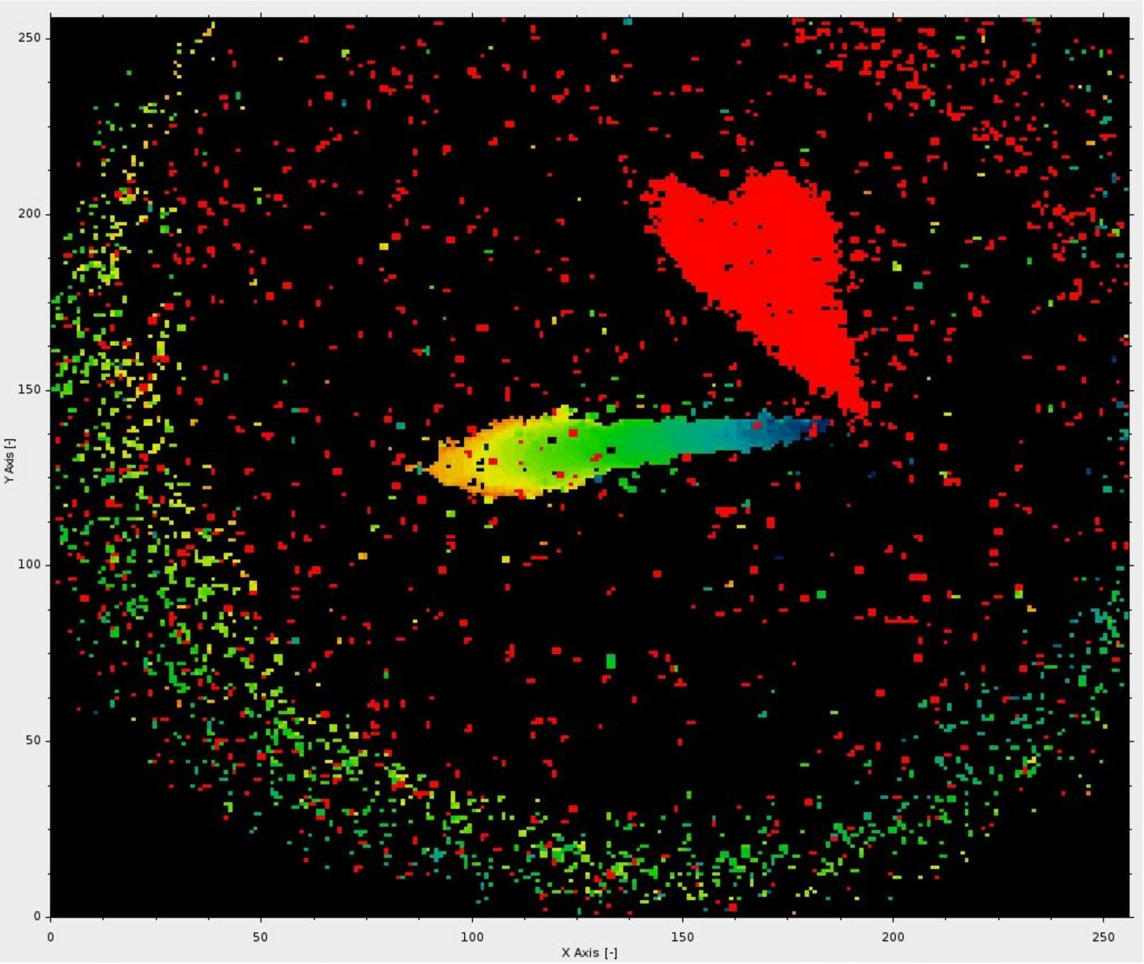

Figure 4: Exposure of 1ms duration captured using diagnostic software. Colour shows ToA. The changing colour scale over the length of the alpha track implies that the ionised track had an angle inside of the TPC. Reflections from the viewport are visible around the edge arriving at the same time as the light from the alpha track. Two additional merged tracks are visible as well. They are in the overflow bin (red colour) of the ToA colour scale.

readout of the sensor and for much higher effective frame rates compared to traditional frame based readout as long as total pixel occupancy is modest. This mode opens up to the potential for a continuous readout TPC which requires no dedicated trigger. Any events in the TPC that are over the pixel threshold will be read out and otherwise regions of the TPC which contain no interactions will be zero suppressed. This is a very efficient and simple way to read a large TPC volume where the dimensions of interactions are expected to be small compared to the total TPC volume. The camera is however still able to accept a trigger signal which places a timestamp into the data stream coming from the camera, marking the time at which the trigger was received with time accuracy of 260ps. These trigger timestamps can be later located in an analysis if the user wishes to search within the data stream for a specific time or event which was marked by this trigger.

Figure 5 demonstrates the key benefit this type of camera has over traditional 2D CCD or CMOS based cameras. On the left hand side of Figure 5 we have visualised the data stream in such a way as to mimic the image that would be produced by a CCD camera set to a fixed 8ms exposure. Multiple alpha tracks can be seen in the image overlapping each other. The right hand side of Figure 5 is rotated to show the additional data dimension gained with the simultaneous ToA information. With simultaneous timestamping of the pixel hit it is possible to distinctly resolve each of these individual alpha tracks in time. These two plots show the raw data stream from the camera with no cuts applied. As well as the alpha tracks we can also see reflections from the viewport. It was possible to confirm that these were reflections by observing that these hits arrive correlated in time with light produced by the alpha tracks. Random low intensity hits are visible in the data which are a result of photocathode dark count. A hot pixel is visible at approximately (30,180) which looks like a single pixel receiving hits more frequently in time than its surrounding neighbours since the pixel deadtime is only about 1μs. The raw data stream from the camera requires minimal to zero manipulation before it is analysis ready. Figure 6 shows this data following a simple ToT threshold cut which is already enough to produce very clean events.

Figure 7 shows a individual alpha track imaged by the camera. The angle of this track is clearly visible as a changing ToA with pixel hits in the camera. After combining ToA information with TPC drift velocity information this data is capable of producing a fully reconstructed 3D track. Clean 3D reconstruction is possible with only simple threshold cuts plus multiplicative factors applied to the ToA timestamp and (x,y) pixel values to convert them to physical coordinates.

Figure 8 shows a long exposure image captured of the TPC with the alpha source removed. Light produced from Cosmic particles passing through the TPC volume illuminates the octagonal active area of the THGEM. Mapping of the ϕ18mm photocathode of the intensifier onto 14mm×14mm optical sensor is also apparent there. Figure 9 shows a gallery of individual cosmic events imaged in the TPC. For these events the THGEM bias was increased to 860V in order to achieve enough gain to image the low intensity tracks of the cosmic rays relative to those of the alpha particles.

Figure 10 plots the counting rate of the camera compared to PMT S2 area with changing bias on the THGEMs. As the bias of the THGEM is increased the gain of the avalanche process and therefore light production increase exponentially. It can be seen that both the counting rate of the camera as well as S2 area are well described by an exponential of the form ae^{bx}. Parameter b in the fit is a measure of the linearity of the device response as the THGEM bias is varied. Parameter b is consistent for both PMT and TPX3Cam which implies the camera has linearity comparable to the PMT. This suggests that good calorimetry performance can be expected over a wide range of incident signal intensities. Figure 11 shows the distribution of total alpha energy deposition in the TPC. Individual pixels were clustered together and a cut was placed which selected clusters containing more than 500 hits which provided a clean selection of alpha tracks. Summed ToT from all pixels in the alpha track gives a measure of total energy deposition of the alpha. A clear peak can be seen which corresponds to the alpha energy of ≈ 5.5 MeV. An upcoming analysis is in preparation which hopes to further demonstrate the calorimetric capability of the camera.

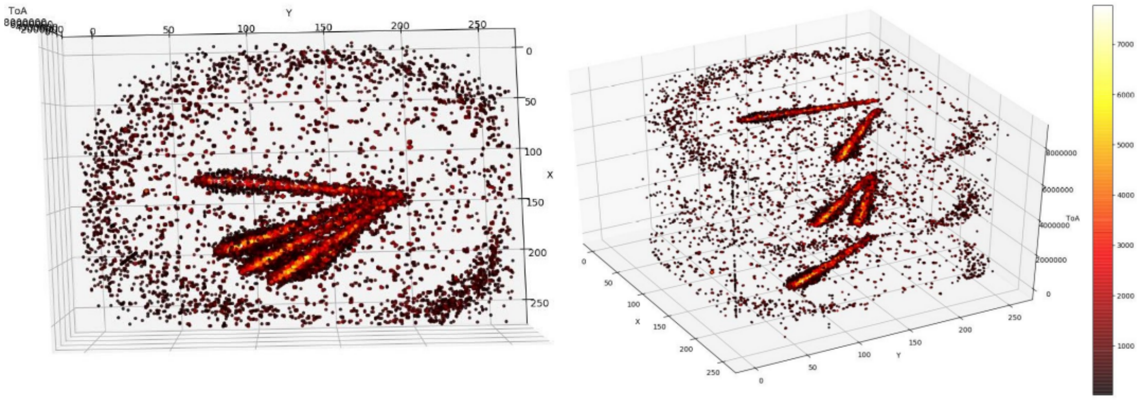

Figure 5: Raw data captured by the intensified TPX3 camera. Left: Data arranged to show a 'traditional' CCD image containing just (x,y) plus pixel intensity information. Right: Data rotated to show the additional simultaneous ToA information dimension given by TPX3. Viewport reflections can be seen as clusters of pixel hits arriving simultaneously with light from the alpha tracks. Photocathode dark count is visible as the remaining individual low intensity pixel hits arriving randomly in time.

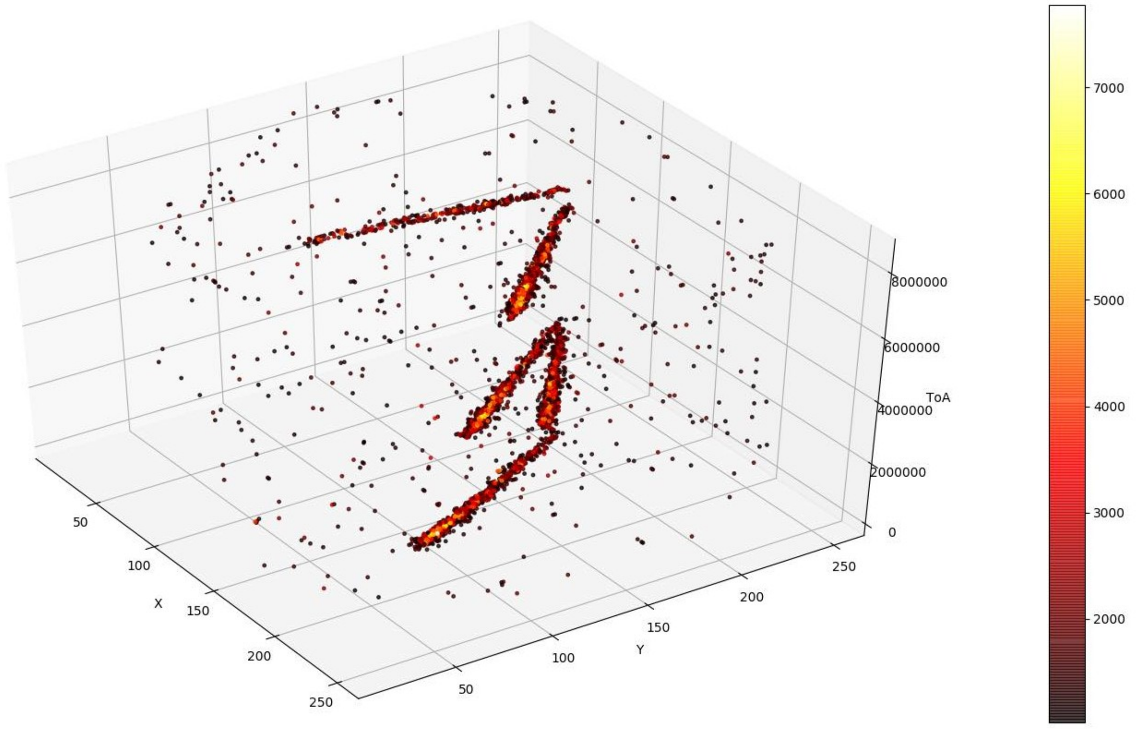

Figure 6: 3D reconstruction of a 8ms time slice of recorded pixel hits where colour represents ToT. A simple ToT threshold cut has been performed to remove a substantial amount dark count and the viewport reflections. Five alpha tracks were visible during this time which is roughly in agreement with the expected source rate of 1 kHz. A Bragg peak is visible at the end of the alpha tracks.

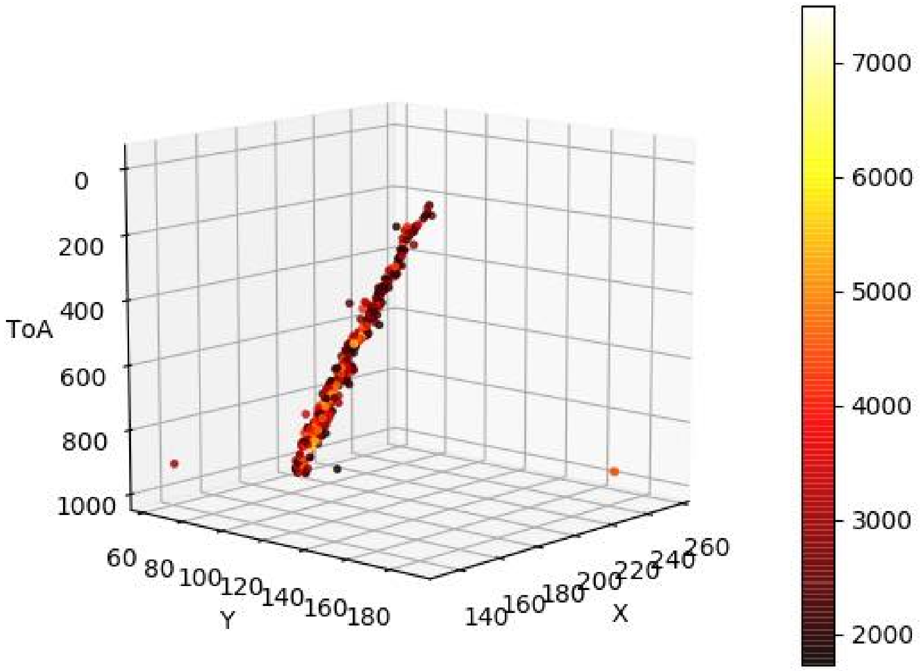

Figure 7: 3D reconstruction of a 1000ns time slice of recorded pixel hits showing a single alpha track. Colour represents ToT. Photocathode dark count is seen as the few individual low intensity pixel hits arriving randomly in time and position.

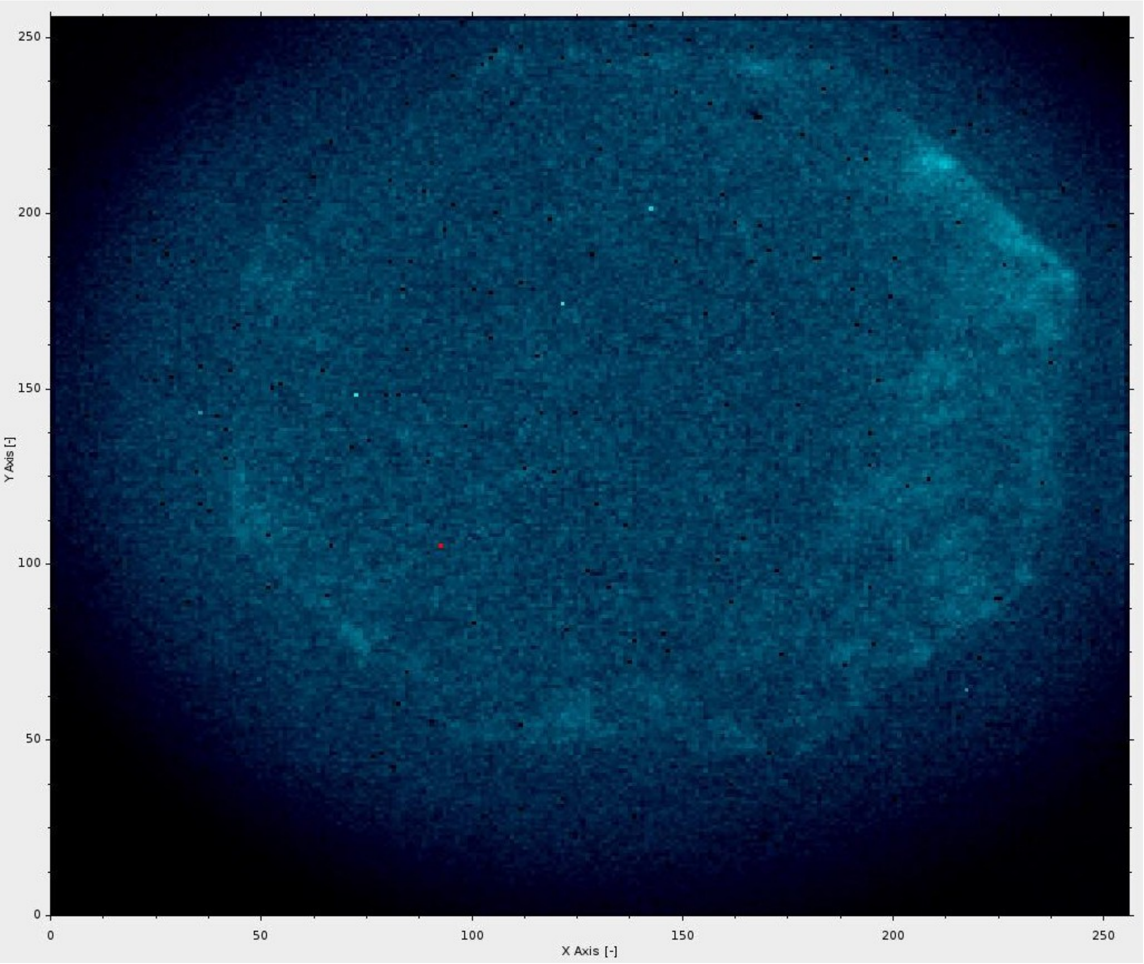

Figure 8: Long exposure image of the THGEMs with alpha source removed. Colour represents ToT. The octagonal THGEM active area is illuminated by cosmics passing through the TPC.

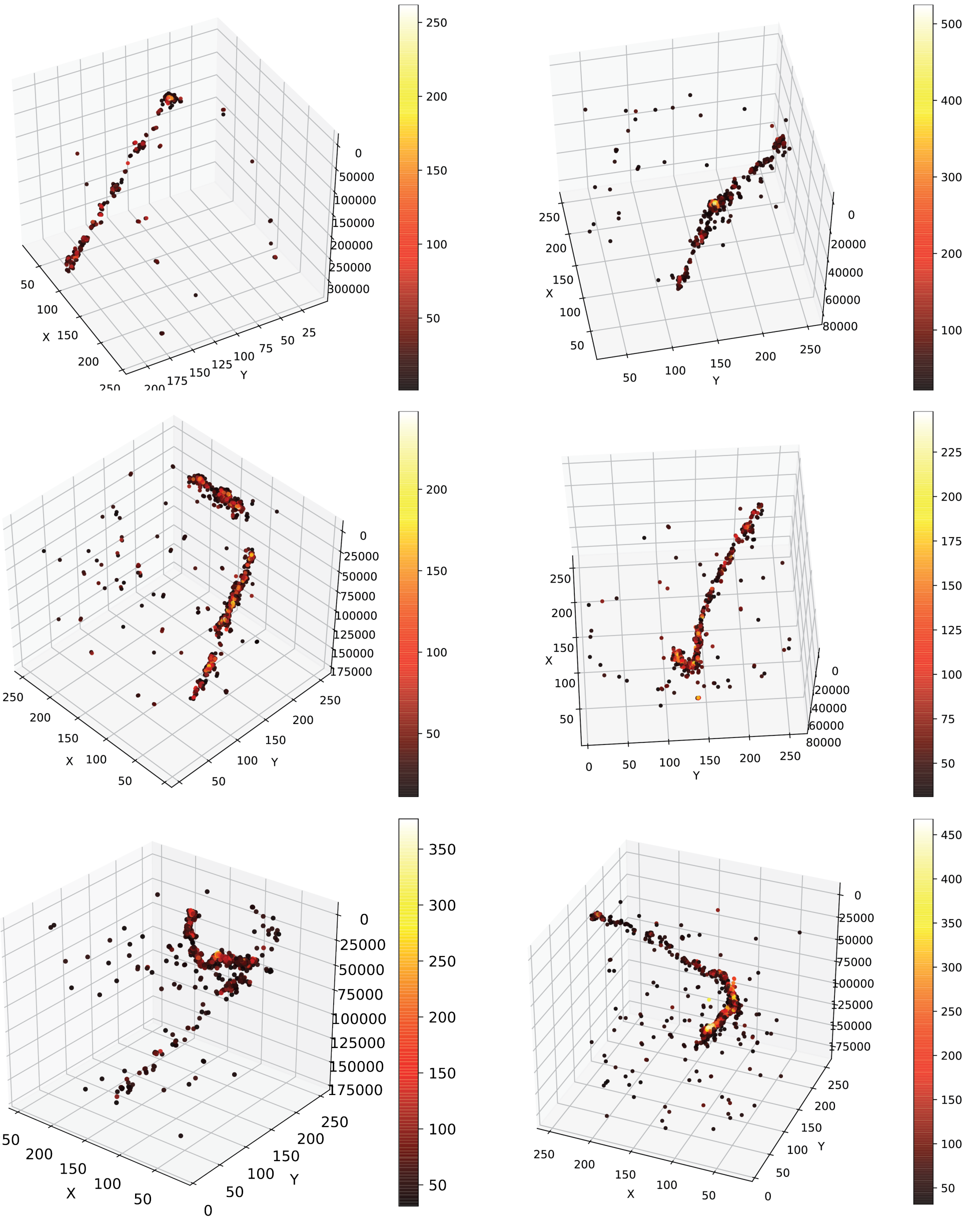

Figure 9: A selection of cosmic events observed in the TPC. The THGEMs were both biased to 860V in order to achieve enough gain to image the low energy deposition of cosmics compared to alpha tracks.

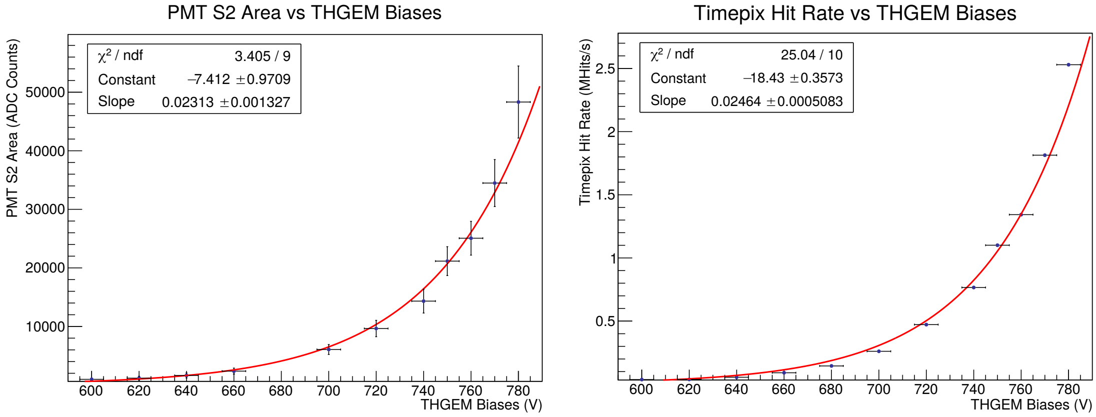

Figure 10: Left: PMT S2 area vs applied THGEM bias. Right: Camera pixel hit rate vs applied THGEM bias. The bottom plane of the first THGEM was connected to negative polarity bias voltage. The top plane of the first THGEM and the bottom plane of the second THGEM were both grounded. The top plane of the second THGEM was connected to positive polarity bias voltage. This plot effectively uses the camera as a photon counter and the expected exponential increase in light production with increasing THGEM bias is well described. The fit is of the form ae^{bx} where a and b are given by constant and slope respectively. Fit parameter b is a measure of the devices response to the exponentially increasing light production in the THGEM. It can be seen that fit parameter b is consistent between both devices, demonstrating that the camera is comparable to that of the PMT.

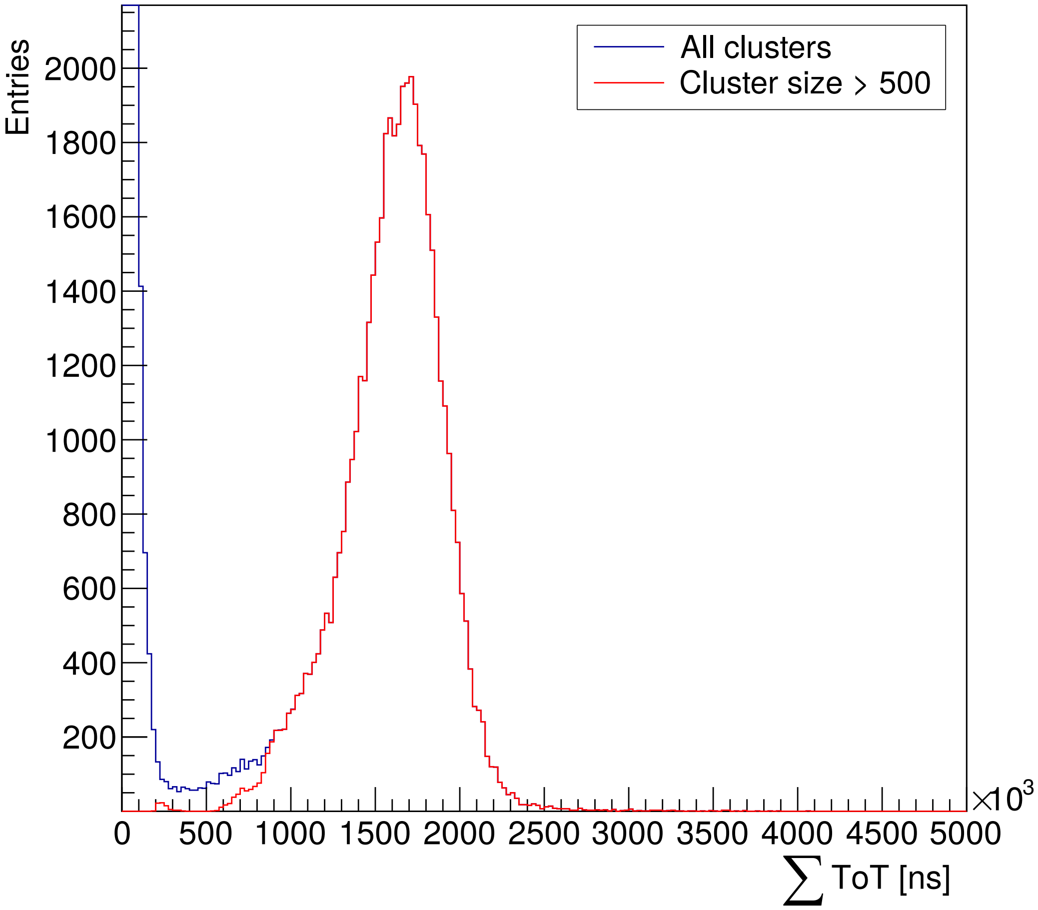

Figure 11: Histogram of summed ToT values for pixel hits combined using a clustering algorithm. When cutting on cluster size > 500 hits to select only alpha tracks a peak is visible corresponding to the alpha energy of ≈ 5.5 MeV.

4 Outlook and future developments

The intensifier used for this demonstration was not ideally configured for our application. Further optimisation of the intensifier can yield substantial improvements in signal intensities and dark counts. Image intensifiers are available with photocathode quantum efficiencies of up to 40-45% at our wavelengths of interest [23]. Further to this it is possible to install MCPs with etched 'funnel type' entrances into the intensifier which improves the collection efficiency of electrons emitted by the photocathode from 60% up to over 90%. Folding these two factors together allows for an immediate increase of light collection by a factor 3. Proper photocathode selection and/or cooling should also allow for significant reductions in dark count rate compared to the photocathode that was available for this study. Combining both higher quantum efficiency and lower dark count should allow for significant increases in signal-to-noise.

It is intended to pursue the application of this technology to the optical readout of LAr TPCs. The EMCCD cameras of ARIADNE are easily interchangeable with the presented TPX3 based camera. When compared to the gas TPC setup presented in this paper, LAr TPCs have much slower drift velocities which translates to expected diffusion limited z position resolution as well as improved detection thresholds due to the increased light production of LAr as a TPC medium. This technology presents a serious potential for fully optical 3D tracking in a diffusion limited regime with good signal-to-noise ratios and low detection thresholds.

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