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Performance of the Three-Dimensional Track Imager (3-DTI) for Gamma-Ray Telescopes

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Abstract: We have been developing the Three-Dimensional Track Imager (3DTI), a gas time projection chamber for the imaging of gamma-rays between 0.3 - 50 MeV. The detector is being designed for use on satellite experiments for the imaging of astrophysical gamma-ray sources. Electrons produced by pair production or Compton scattering ionize the gas and these ionization electrons are detected by the cross-strip micro-well detector at the bottom of the chamber. Front end electronics and time digitization electronics have been developed. We present gamma-ray imaging results of prototype micro-well detector and laboratory set-up in various gas mixtures.

Introduction

The field of medium energy gamma-rays is entering an exciting new era with the advent of state-of-art imaging technology. One of the emerging new technologies for gamma-ray imaging is the Three-Dimensional Track Imager (3-DTI). 3-DTI has been developed at GSFC to address the technological needs of future medium-energy (0.3 - 50 MeV) and high-energy (30 MeV - 50 GeV). Observation of medium energy gamma-rays are particularly challenging as they can only be detected indirectly via Compton scattering or pair production, in which a recoil electron or electron-positron pair are produced. The significance of 3-DTI technology is the capability to track recoil electrons with high precision, which offers a substantial improvement in sensitivity over that of previous missions. In this paper, we discuss preliminary results of the 3-DTI prototype and its imaging capability. Relavance to gamma-ray astrophysics and the technology required for space missions is addressed in these proceedings [1],[2].

3-DTI Detector and Performance

The 3-DTI prototype incorporates a large volume time projection chamber (TPC) with two-dimensional gas micro-well detector (MWD) readout. Electromagnetic interactions such as Compton and Pair, which occur within the TPC, leave an ionization trail produced by recoil electrons. These electrons (and if applicable positrons) drift into the MWD, in which an avalanche of secondary electrons significantly amplifies the signal. For details instrumentation of 3-DTI, see this proceeding [2]. The electrons from the avalanche are collected on the anode, while an equal but opposite image charge is measured on the orthogonal cathode. In this way, the MWD provides 2-D imaging. To accomplish 3-D reconstruction of a track, the z-coordinate of the ionization charge is determined by recording the time structure of the avalanche charge signals on each anode and cathode. The drift velocity of the ionization charge in the gas determines the translation from time to spatial coordinate.

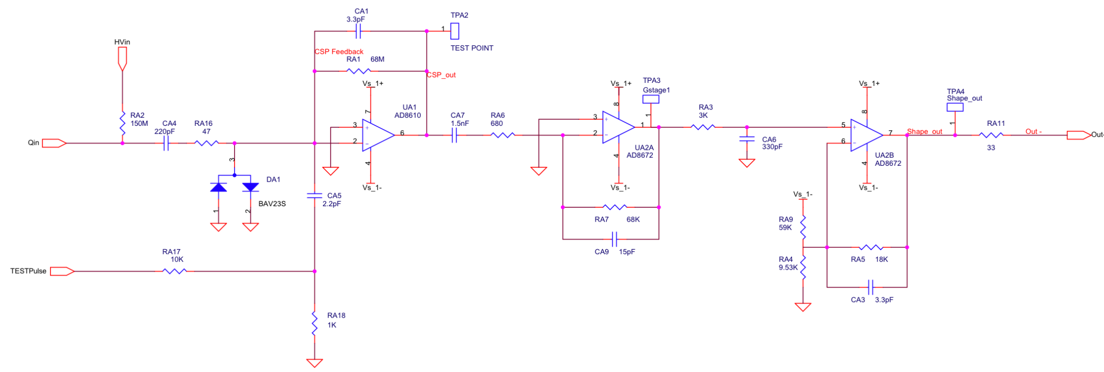

Figure 1: The schematic of a front end electronics channel. It shows a charge sensitive preamplifier and CR-RC pulse shaper.

The drift velocity of the ionization charge (free electrons) in xenon is on the order of 30 mm/μs, but depends strongly on additive gases (CH_4, CO_2, etc.) and drift field [3]. In addition, because this velocity is significantly higher than the thermal velocity of the gas, this electron drift has significant longitudinal and transverse diffusion that smears out the spatial structure of the ionization charge (track structure) after only a few centimeters of drift. The drift velocity of the ionization charge can be substantially reduced by the addition of gaseous CS_2, a molecule with moderate electron affinity that quickly scavenges the ionization electrons forming negative anions. The anions drift in thermal equilibrium with a drift velocity of $\sim$0.1 mm/μs. Drifting in thermal equilibrium also substantially reduces the transverse and longitudinal diffusion [4] greatly increasing, the maximum drift distance. These anions drift towards the anodes where, in the strong electric field of the micro-well, the electrons are stripped off and an electron cascade is produced in the well.

In addition, the slow drift velocity reduces the required sampling rate of the transient digitizers that record the arrival time of the ionization charge. Each anode and cathode electrode of the MWD requires a channel of front-end (FEE) and transient digitizer (TD) electronics. Figure 1 shows a schematic of the front-end electronic for one channel. Each FEE channel consists of a charge sensitive preamplifier, a pulse shaper with gain and a resistor divider with a 2.2 pF test input pulse. The overall gain of FEE is about 23 mV/fC. The

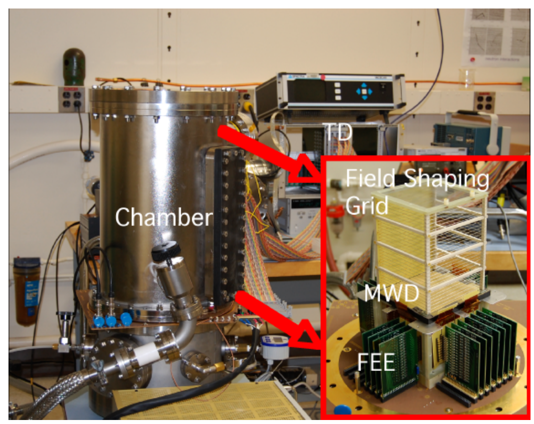

Figure 2: Prototype 3-DTI detector for characterization of 10×10 cm^2 MWD performance. Shown here is a MWD, drift electrode, 15 cm field-shaping grid, and 16-channel FEE cards.

TD system consists of one controller board, which provides the 2.5 MHz sample clock and USB computer interface, and can support up to 32 TD boards. Each TD board contains 48 channels of differential receiver and 12-bit ADC, and FPGA controller and flash memory. The common sample clock insures that all the ADCs in the system sample synchronously. After each sample clock cycle (400 ns), the TD board FPGA collects the 48 samples, compares them to a threshold value, and stores them in a circular buffer with 32,000 samples per channel. A trigger is generated if a preset number of channels on any one of the TD boards exceed the threshold at which point a preset number of post-trigger samples are recorded.

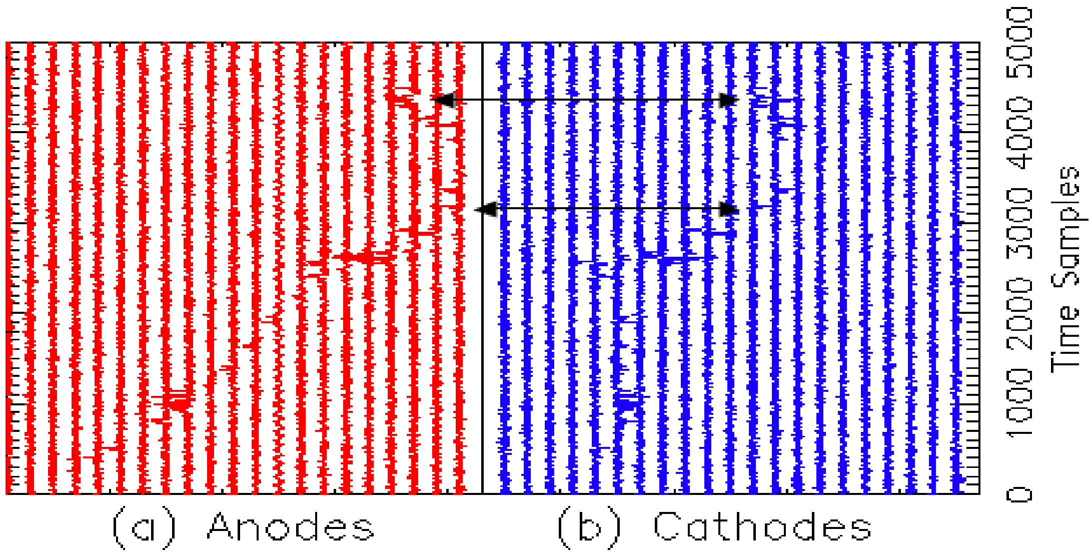

Figure 3: The raw TD output of the ionization charge recorded from a pair production event for (a) the anode strips and (b) the cathode strips versus sampling time. Only a portion of the active MWD anodes and cathodes are shown here for clarity.

The circular buffer insures that pre-trigger samples are available. The pre- and post-trigger samples, which make up the event, are sent to data acquisition computer via the USB interface. Dynamic range of the electronics is about 48 fC for the maximum ADC output 2024 counts, which corresponds to equivalent noise of 0.5 fC.

We have been working with several commercial vendors to develop viable fabrication processes for MWDs that can be scaled to 50×50 cm^2 areas [5], appropriate for gamma-ray astrophysics experiments. Currently, the MWDs are characterized with a 10×10 cm^2 "**Proof of Principle**" 3-DTI detector. Figure 2 shows the proof-of-principle 3-DTI detector, including MWDs, a drift electrode, a field shaping grid, and 16-channel FEE cards. This detector configuration, sized to fit in a 14″ (36 cm) diameter vacuum chamber, supports the MWD and drift electrode with 15 or 30 cm drift distance, and the interface to 448 channels of FEE. A Vacuum pump and multi-gas manifold allows this chamber to be easily evacuated and filled with a variety of gas mixtures up to 3 atm. We have measured energy resolution (△E/E) of ∼20% at 5.9 keV in P-10/CS_2 at a gas gain of 10^3.

3-D Electron Track Imaging

Using the proof-of-principle 3-DTI detector, Fig 2, we demonstrate three-dimensional track imaging of electrons from gamma-ray interactions in a variety of gas mixtures: P-10, helium, and xenon, with CS_2. Figure 3 shows the raw TD data of the electron-positron pair recorded from a 6.12 MeV gamma ray (^{16}O excited state) interaction in P-10 80%/CS_2 20% at a total pressure of 0.55 atm. The field within the MWD was 880 V/cm and MWD field was 4×10^4 V/cm. The structure visible in the raw TD data, corresponding to the MWD avalanche signals of groups of ionization electrons, illustrates that the 3-DTI is capable of recording the track with high resolution including the statistics of the ionization process, energy loss mechanism, and Molière scattering. The apparent truncation of the tracks is due to the particles leaving the active volume.

When a charge is multiplied in a well, the same and opposite polarity of signal will be readout through an anode and a cathode respectively. The temporal coincidence of the anode and cathode signals allows the raw TD data to be translated into three spatial coordinates and energy deposition. The x-

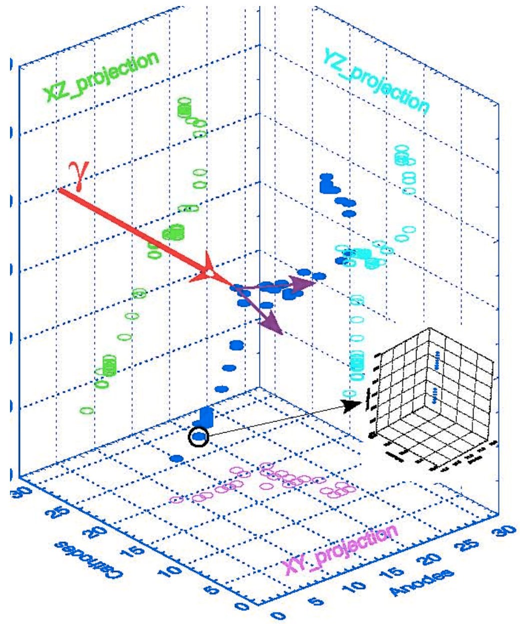

Figure 4: Reconstruction of the raw data (Fig 3). The arrows indicate our best estimate of the electron-positron directions (purple) and incident gamma ray direction (red). The inset figure shows the individual ionization charges at the full time resolution of the TD.

and y- coordinates of each coincidence TD pulse are determined by the anode and cathode strip locations. The z-coordinate is derived from the sample time and the negative-ion drift velocity. The energy loss, dE/dx, is proportional to the signal amplitude. We refer to the spatial and energy deposition as the voxel data, (x, y, z, $\triangle$E).

The 3-D reconstruction of the raw pair image data (Fig. 3) into voxel data is shown in Fig. 4. Complete reconstruction of this event is not possible because the electron and position escaped from the limited active volume. Nevertheless, arrows indicate our best estimate of the electron-positron directions and incident gamma ray direction. Preliminary analysis, based on a drift velocity of $\sim$50 m/s , indicates an opening angle of $\sim 40°$ for the electron-positron pair, consistent with the opening angle of a 6.1 MeV gamma ray [6]. This demonstration of 3-D gamma-ray imaging is a major milestone for our track imaging technology and future development of high angular resolution gamma-ray telescopes.

We will be testing a scaled-up 10×10 cm^2 3-DTI prototype this summer at the Positive Ion Accelerator Facility (PIAF) at the Naval Science Warfare Center in Carderock, MD. This accelerator can produce a monoenergetic beam of gamma-rays with energies up to 15 MeV as well as positive ions of MeV energies and neutrons up to 8 MeV. Accelerator tests will help to characterize the angular and energy response of 3-DTI technology.

Summary

With a 3-DTI prototype proof-of-principle detector, we have demonstrated the capability of imaging gamma-ray interactions within a fully active gas volume. Such imaging is essential for future space missions. Our upcoming accelerator tests will help to further characterize the angular and energy resolution in addition to refine our imaging software.

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