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Development of the Three-Dimensional Track Imager for 0.3-50 MeV Gamma-Rays Telescopes

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Abstract: An instrument to image medium-energy gamma rays is being designed for future NASA Explorer missions. This instrument, which consists of a gas imaging proportional counter, the 3-DTI, and a segmented calorimeter provides an order of magnitude or more sensitivity over COMPTEL/CGRO. The use of the 3-DTI allows for the detection and tracking of recoil electrons from the Compton interactions and electron-positron pairs from pair production from incident gamma rays in the gas volume. The 3-DTI also allows measurement of the incident gamma-ray energy from the amount of ionization in the fully-active homogeneous gas volume. The segmented calorimeter provides a trajectory and energy measurement of the interaction products from Compton scattering (scattered gamma-ray) and pair-production (positron and electron). The goal is an instrument capable of providing excellent position resolution (4 degrees at 2 MeV) and good energy resolution (<6% at 511 keV). We will discuss the design of a small-scale prototype detector unit as well as future plans for testing and flight.

Introduction

Medium energy (0.4-30 MeV) gamma-ray astrophysics was first studied with the COMPTEL/CGRO instrument [1]. Significant astrophysical research can be done in this regime, particularly with an instrument an order of magnitude greater sensitivity [2]. Our group at GSFC has developed the Three-Dimensional Track Imager (3-DTI) to track the electron and positron pair from gamma-ray pair production or the recoil electron from Compton scattering. The 3-DTI combined with a position-sensitive calorimeter forms a gamma-ray telescope scalable to provide one to two orders of magnitude increase in sensitivity over COMPTEL. In this paper we describe the development of the 3-DTI and segmented calorimeter instrumentation as well as our concept for a MIDEX-scale medium-energy Compton gamma-ray telescope.

The Three-Dimensional Track Imager

The 3-DTI consists of a large volume time projection chamber (TPC) with two-dimensional gas micro-well detector (MWD) readout. The third dimension is obtained by measuring the arrival time of the ionization charge as it drifts into, and is amplified by, the micro-wells. Figure 1 shows a schematic diagram of the detector and how it operates.

The MWD is a two-dimensional array of gas proportional counters. In contrast to multi-wire proportional counter construction, the anodes and cathodes of the MWD are orthogonal electrode strips rigidly affixed to an insulating substrate. This construction allows the anode and cathode electrodes to be longer and have smaller pitch than is possible with multi-wire construction. The micro-wells are defined by holes in the cathode strips and corresponding holes in the insulator that expose the orthogonal anode strips at the

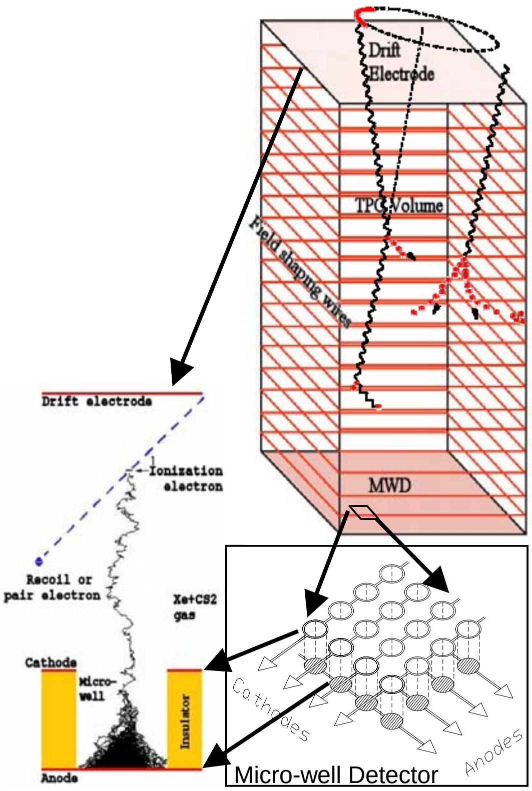

Figure 1: Schematic diagram of the Three-Dimensional Track Imager (3-DTI), time projection chamber (TPC) volume, two-dimensional micro-well detector (MWD), and micro-well operation.

bottom of the well. The micro-wells themselves are 200 μm in diameter with 400 μm center to center pitch and 200 μm depth. An image of one of our microwell detectors taken with a SEM is shown in Figure 2.

The TPC active volume is bounded by a drift electrode on the top and an array of micro-wells on the bottom. A cage of field shaping wires defines the sides of the active volume and establishes a uniform drift field (~500 V/cm). The ionization charge left along the tracks of the energetic electrons resulting from Compton scattering or pair production in the active volume drift away from the drift electrode towards the MWD and into the wells. As the ionization charge enter the wells, where an intense electric field (10^{4-5} V/cm) is set up by the voltage difference between the anodes and cathodes, an ionization avalanche occurs. 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. We use a gas mixture of Xe and CS_2 which provides a drift velocity on the order of ~ 0.1 mm/μs and a low transverse and longitudinal diffusion rate [4].

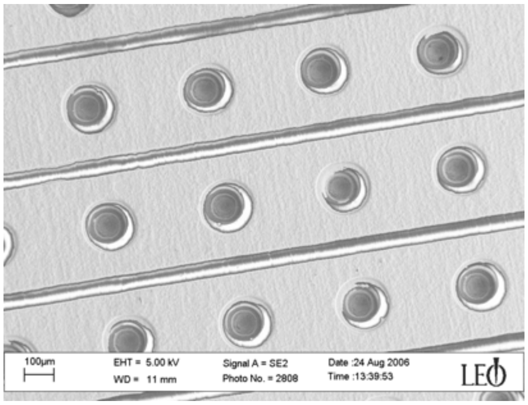

Figure 2: SEM Image of a microwell detector.

The signals from the MWDis sent to a set of charge sensitive amplifiers and pulse shaping electronics (the FEE) and digitized by a transient digitizer system sampling at 2.5 MHz. These electronics and the readout system are described further elsewhere in this conference [5].

Segmented Calorimeter Instrument

The 3-DTI detector can detect gamma-rays interacting by pair production without the need for a calorimeter provided the positron and electron pair stop within the active volume of the 3-DTI. Under these conditions, the energy and trajectory of the incident gamma-ray can be reconstructed as we know the trajectory and energy of both of the electron and positron interaction products.. Gamma rays that interact via Compton scattering require a calorimeter to measure the trajectory and energy of the scattered gamma-ray to compliment the measurement of the recoil electron's trajectory and energy made in the 3-DTI. The calorimeter extends the energy range of the 3-DTI by measuring the energy of positron and electron pairs that may leave the gas volume but stop in the calorimeter. This is particularly important for Compton events with a large scatter angle whose electron will easily traverse the gas volume. We are developing a segmented calorimeter to use in conjunction with the 3-DTI detector. We envision a modular calorimeter similar to the MEGA design [6], covering the entire bottom and ~2/3 of each of the four sides of the 3-DTI. These modules contain a matrix of 5 × 5 mm^2 x 4 cm scintillating crystals such as CsI or LaBr$_3$ read out by a MAPMT or array of photo-detector (e.g. pin diode or SiPMTs). One of the advantages of this design is that the modules can be tiled or stacked in different combinations to compliment the 3-DTI and meet power, space and mass requirements of spaceflight missions.

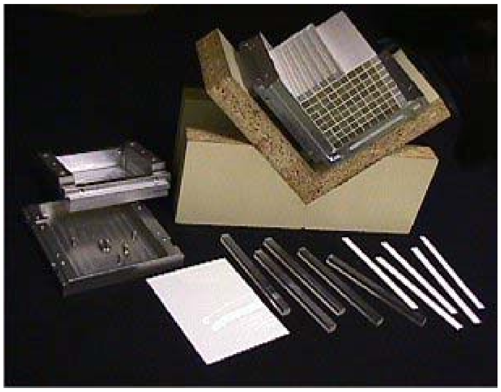

Figure. 3: MEGA Calorimeter module. [6].

10-cm 3-DTI Detector Prototype

We have successfully demonstrated the ability of the 3-DTI to image gamma-ray using a 5 cm x 5 cm prototype MWD. These results are discussed elsewhere in the conference [5]. We are developing a scaled up 3-DTI instrument with a 10 cm x 10 cm MWD and at 30 cm high drift volume. A mechanical drawing of this prototype is shown in Figure 4. The pressure chamber consists of a two piece stainless steel pressure vessel that interfaces to the top and bottom of a large electronic motherboard on a sealing ring built into the board. Traces pass from the inside of the sealing ring to the outside allowing signals from the FEE boards inside the pressure chamber to be digitized by TD boards outside in a electronics rack. Windows on the top and side of the pressure vessel allow gamma-rays to enter the vessel allowing for test-

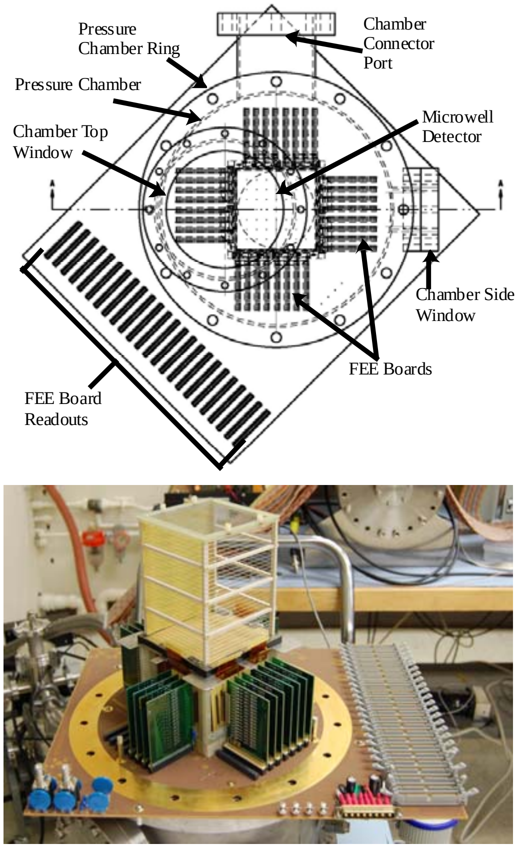

Figure 4: 10 cm x 10 cm 3-DTI prototype. The top figure is an engineering diagram of the 3-DTI in its pressure vessel from a top face on view. The bottom figure is a picture of the built prototype prior to integration in the pressure vessel.

ing with laboratory sources and at accelerator beams.

We will be testing and characterizing our 10 cm 3-DTI prototype this summer and fall at the Positive Ion Accelerator Facility (PIAF) at the Naval Science Warfare Center Carderock. 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.

3-DTI as a NASA Space Instrument

One of the great strengths of our instrumentation described above is that it can be scaled to fit various space mission opportunities and enable new medium energy gamma-ray science. We have completed a preliminary design of a MIDEX scale 60 x 60 cm x 100 cm 3-DTI instrument

Such an instrument could image medium-energy gamma rays from 0.3-50 MeV that interact via pair-production or Compton scattering. Such a spacecraft design would weigh approximately 1000 kg and require about 1000 W of power which is achievable by a medium-scale explorer mission. We have done a calculation of the effective active area of such an instrument compared to EGRET and COMPTEL which is plotted in Figure 5.

Larger versions of the 3-DTI instrument concept with a microwell detector from 1 to 2 m square and a segmented calorimeter on the bottom and going 2/3 of the way up the sides is readily achievable. Simulations of a 1.6 x 1.6 x 1 m sized 3-DTI with calorimeter indicate an energy resolution of <6% at 511 keV and a point spread function resolution of 4 degrees at 2 MeV. This detector is estimated to weigh approximately 1850 kg and draw 1700 W of power. Such an instrument would provide two orders of magnitude more sensitivity than COMPTEL and be compatible with a NASA explorer mission.

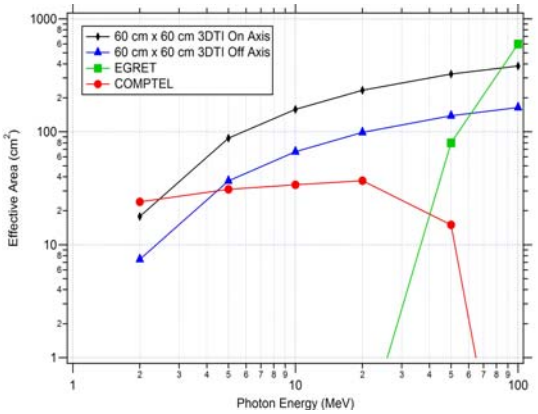

Figure 5: Effective Area of 60 x 60 cm 3DTI versus COMPTEL and EGRET.

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