Imaging of 0.3-50 MeV Gamma-Rays with the Three-Dimensional Track Imager

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Abstract: An instrument to image medium-energy gamma rays is being designed for future NASA Explorer missions and the Advanced Compton Telescope (ACT). 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 scattered gamma. 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 and performance of a small-scale prototype detector unit as well as future plans for testing and flight.

Introduction

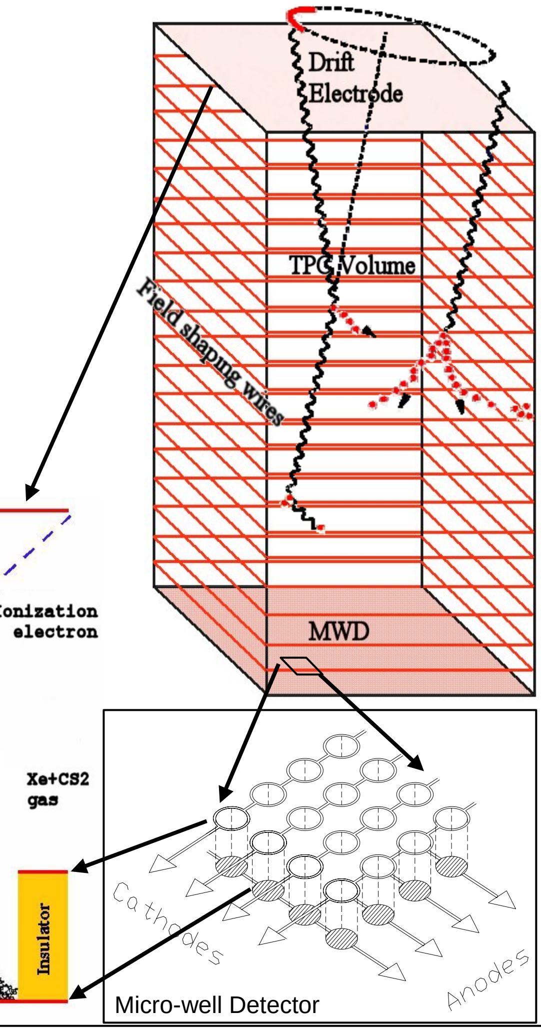
Medium energy (0.4-30 MeV) gamma-ray astrophysics was first studied with the COMPTEL/CGRO instrument [1]. Significant astrophysical research can be done in this regime, particularly with an instrument an order of magnitude greater sensitivity [2]. Our group at GSFC the Three-Dimensional Track Imager (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 segmented 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 3-DTI and segmented calorimeter instrumentation as well as our concept for a medium-energy Compton gamma-ray imager suitable for future space missions (such as the Advanced Compton Telescope [3]). In the proceeding sections we will describe the 3-DTI and our segmented calorimeter concept as well as discuss a prototype 10 cm x 10 cm 3-DTI system we are developing and future plans for an even larger imager to fly on future space missions.

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 bottom of the well.

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].



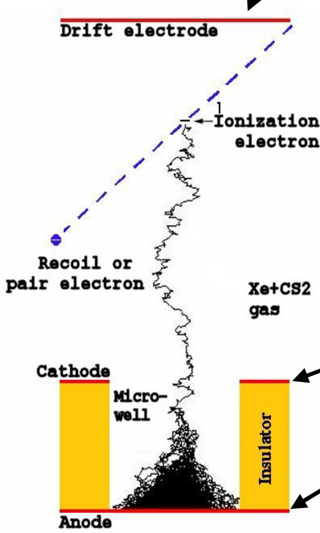


Fig. 1 – Schematic diagram of the Three-Dimensional Track Imager (3-DTI), time projection chamber (TPC) volume, two-dimensional micro-well detector (MWD), and micro-well operation.

The signals from the MWD is 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. The electronic readout system is 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 their energy is less than about 30 MeV so that the interaction products can be contained in the gas volume. 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 can also help extend 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. 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.

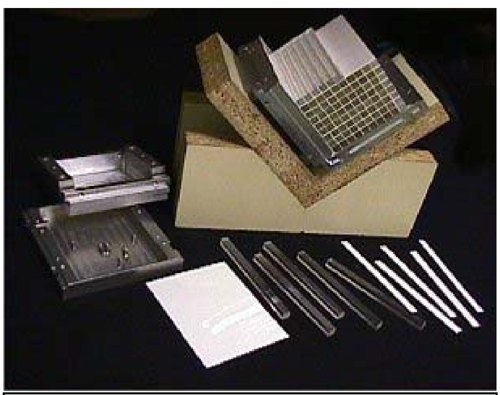


Fig. 2: MEGA Calorimeter module. [6]

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 3. The pressure chamber consists of a two piece stainless steel pressure vessel that interfaces to the top and bottom of a large electronic

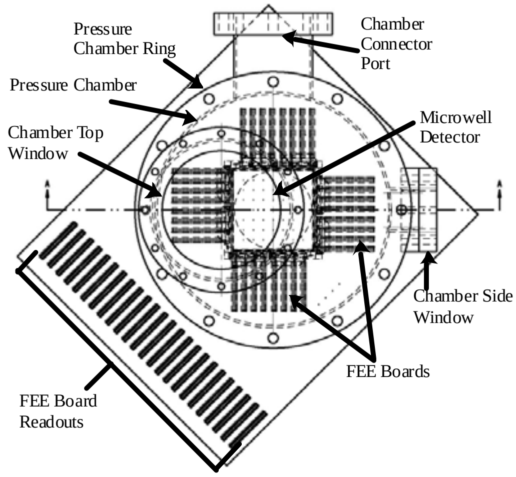


Figure 3: Face on view of the 10 cm x 10 cm 3-DTI prototype. The pressure chamber, main electronics motherboard, readout electronics and microwell detector are all shown.

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. The pressure vessel has a 1.2 cm thick PYREX window on the top which is transparent to incident gamma-rays from a source or an accelerator beam. There is also a 1.9 cm thick Ultem window on the side of the pressure vessel to allow scattered Compton gamma-rays to exit the vessel. This allows us to use an existing Anger Camera calorimeter or to test the segmented calorimeter modules we're developing in conjunction with the 10 cm 3-DTI detector.

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 analysis of a 60 x 60 cm x 100 cm 3-DTI instrument without a calorimeter. Such an instrument would only be effective over an energy range of about 1.1-30 MeV where one has pair-producing gamma-rays whose interaction products can be stopped in the gas volume of the detector. Based on our analysis our initial estimate is that this instrument plus spacecraft would weigh approximately 800 kg and require about 800 W of power. These requirements would be realizable on both a small and medium class space mission and the instrument size can of course be scaled up or down depending on the specific mission requirements. We have also done a calculation of the effective active area of such an instrument compared to EGRET and COMPTEL which is plotted in Figure 4.

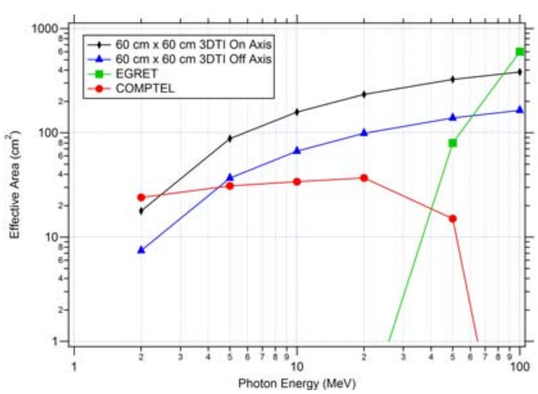


Figure 4: Effective Area of 60 x 60 cm 3DTI versus COMPTEL and EGRET.

The addition of a segmented calorimeter to the 3-DTI instrument above would add another 200 kg of mass and at least 200 watts of power. Such an addition would almost certainly require a medium class mission. As we continue our development of both the 3-DTI and segmented calorimeter we are working on ways to reduce the mass and power for both instruments.

A larger version of the 3-DTI instrument measuring 1.6m x 1.6m x 1m with a segmented calorimeter on the bottom and going 2/3 of the way up the sides has been proposed as a mission concept for the ACT [3]. This detector would provide two orders of magnitude more sensitive than COMPTEL. Simulations of such a detector indicate that we would expect 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 which is within the ACT mission requirements.

References

[1] Schonfelder, V. et al., ApJ, **86,** 657, 1993.
[2] Hunter, S.D. et al. ICRC, 2007.
[3] Boggs, S. et. al. ACT NASA Vision Mission Proposal, 2004.
[4] Martoff, C.J. et al. NIM-A, **440**, 355, 2000.
[5] Son, S. et al. ICRC 2007.
[6] Kanbach, G. New Astron. Rev.**, 48**, 275, 2004.