Calorimeter prototype based on silicon drift detectors coupled to scintillators for Compton telescopes application

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Abstract

The project of a new calorimeter module for Compton telescopes based on an array of silicon drift detectors (SDD) coupled to thallium activated cesium iodide (CsI(Tl)) scintillating crystals is presented. Because of their low output capacitance and the possibility to have the first amplifying stage directly integrated on chip, SDDs show better noise performances than traditional p-intrinsic-n (PIN) photodiodes. For this reason, SDDs coupled to scintillators show a higher energy resolution than similar systems based on PIN photodiodes. The detectors will be integrated in an array with read-out based on custom made ASIC’s built to match with the SDDs electrical properties. Shaped signals are digitally converted by a Digital Front-End Electronic Board which also takes care of ASICs handshaking. The system architecture is based on the PICsIT instrument on board the INTEGRAL satellite, at present fully operative. In this paper an overview of the instrument will be given and the status of the project will be reported.

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1. Introduction

Compton telescopes are suitable instruments to observe the γ-ray sky in the MeV energy range, where Compton effect is the most probable interaction process for γ-rays with matter. Compton telescopes are made of two coupled detectors: the first (D1) should be based on low-Z materials to maximize the Compton interaction probability, while the second (D2) is usually based on high-Z materials to maximize the absorption probability for the scattered γ-ray and thus to allow a good total energy reconstruction. Moreover, D1 and D2 must be position sensitive to reconstruct the scattered photon direction. A state of the art choice for detector D2 could be the use of thallium activated cesium iodide (CsI(Tl)) scintillating crystals coupled to silicon PIN photodiodes. CsI(Tl) is a high-Z scintillator with high light yield (60,000 photons/
MeV) and PIN photodiodes are well known reliable and robust solid state devices suitable for densely packed pixelated arrays. For example, this approach was chosen for the MEGA Compton telescope prototype (Kanbach, 2002; Bloser, 2002).

Energy resolution of both detectors D1 and D2 are important features, as they determine the error on the reconstructed scattering angle of the incidence photon. Typical CsI(Tl)/PIN photodiodes detectors have about 10% FWHM energy resolution at 661 keV. An improvement in energy resolution of detector D2 can be obtained using silicon drift detectors (SDD) (Gatti and Rehak, 1984) as photodetectors coupled to scintillating crystals instead of traditional PIN photodiodes. SDDs allow better noise performances than PIN photodiodes of equivalent surface because of a careful modulation of the electric field inside the active area that concentrates the collected charge in a spot smaller than the entrance window of the device, thus reducing its output capacitance. The electric field modulation is achieved by means of concentric p+ implanted rings suitably polarized by an integrated voltage divider. Moreover SDDs can be realized with the first amplifying FET integrated on the device, further reducing the noise. SDDs have been developed as direct X-ray detectors, but have also been tested as photodetectors coupled to CsI(Tl) scintillators (Fiorini et al., 1998), obtaining an energy resolution as good as 4.34% FWHM at 661 keV, more than a factor 2 compared to a PIN photodiodes system. The drawbacks of SDDs are a higher cost than PIN photodiodes of same area, and the need for a more complex polarization circuit, as up to six different tension values are needed for the operation of integrated FET SDDs.

To exploit the possibilities offered by SDDs, a calorimeter prototype based on such devices coupled to CsI(Tl) scintillators is under development at CNR-IASF, Bologna. The calorimeter is expected to be suitable for application as detector D2 in a Compton telescope. In fact, it is expected to test the performances of the instrument in conjunction with the MEGA prototype with radio-active sources and possibly in a balloon flight (MEGABALL mission). In the following sections the calorimeter prototype will be described and the current status of the project will be reported.

2. The calorimeter prototype

The chosen approach is a pixelated array of independent γ-ray detectors. This is the same approach used in the PICsIT instrument (Labanti et al., 2002) (4096 CsI(Tl)-PIN PD detectors) developed by this team and currently perfectly operative on board the INTEGRAL satellite. Because of the expertise gained during the realization of PICsIT, it has been decided to re-use the instrument concept and as much hardware as possible in order to focus mainly on the feasibility of the SDD based detectors, have a reliable read-out and data handling hardware, already tested and working properly, and speed up the prototype realization.

2.1. System architecture

The calorimeter is composed of 16 independent γ-ray detectors (pixels). Only a small number of detectors will be realized as this instrument is meant as a technological demonstrator to study the performances of the chosen approach. Each pixel will be composed of a 10 mm² active area SDD optically coupled to a 2 cm long CsI(Tl) scintillating crystal. The pixels will be arranged in two columns, eight pixels long each one, in order to face the MEGA prototype silicon tracker in a position not covered by the MEGA calorimeters. The pixels are connected to an analog front-end electronic board (AFEE), which supply polarizations to SDDs and manages detectors read-out by means of custom-built ICARUS-SDD application-specific integrated circuit (ASIC). ICARUS-SDD ASIC (Labanti et al., 2000) contains 16 processing chains and its design is based on that of the ICARUS ASIC developed by a collaboration led by this team.

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1 MEGA web page: http://www.mpe.mpg.de/gamma/MEGA/mega.html

and used in the IBIS/PICsIT instrument on board the INTEGRAL satellite (Labanti et al., 1999). While ICARUS input stage is a charge-sensitive amplifier, for connection to PIN photodiodes, the ICARUS-SDD input stage is a simple voltage amplifier, as the charge to voltage conversion is left outside the chip. This solution is particularly suitable for direct connection to SDDs with integrated first amplifying FET. As this new ASIC is a prototype, eight of the 16 channels (called fast channels) have a shaping time of about 0.6 μs, suitable for use of SDDs as direct X-ray detectors, while the other eight channels (called slow channels) have a shaping time of about 3 μs and are intended for use with SDDs coupled to scintillators. For this calorimeter prototype, two ICARUS-SDD ASICs will be mounted on the AFEE board to read out the 16 detectors by means of their slow channels.

The AFEE board will be connected to a digital front-end electronic board (DFEE), which takes care of handshaking with ASICs, analog to digital conversion, time marking of the data, storing of data in an internal FIFO and data delivery to an external data storage system. The design of the DFEE board is the same as that used in the IBIS/PICsIT instrument. As this board was designed to serve 32 ASICs and 512 detectors, its layout is not optimized for the small number of detectors used in this situation, but the advantage of reusing a reliable and already debugged data-handling hardware is by far more important. Data formatted by the DFEE board will be sent either to a test equipment for stand-alone calibration, or to a VME board to be integrated in the MEGA prototype electronic box for tests in conjunction with the MEGA detector. A schematic drawing of the calorimeter prototype is shown in Fig. 1.

2.2. The SDD detectors

The SDDs used in this project are 33 mm² chips with 10 mm² active area and integrated FET supplied by PNSensors gmbh. The sensitive thickness is 300 μm, allowing more than 90% detection efficiency at 10 keV and more than 50% at 15 keV. The SDDs were originally produced with a thin protective aluminum layer on the entrance window, but this layer was removed by PNSensors to allow optical contact to scintillators. As one contact on the backside (the entrance window) and eight contacts on the electronic side are needed, a custom built ceramic housing has been realized. The ceramic housing is for prototype use only, as it does not allow a dense packaging of the detectors. Figs. 2 and 3 show the spectra obtained with the first available SDD as direct X-ray detector, without a scintillator coupled to it, with ²⁴¹Am and ⁵⁵Fe sources. Spectra were taken at room temperature, respectively with 0.5 and 1 μs shaping time. Energy resolution at 59.54 keV is 1.3%, with 790 eV FWHM. Energy resolution at 5.9 keV is 7.2% with 425 eV FWHM. The high offset and the low
energy background in $^{55}$Fe spectrum is possibly due to incomplete charge collection because of imperfections in the radiation entrance window due to the aluminum layer removal process. This aspect is still under investigation. It must be noted that gain and noise characteristics are strongly dependent upon the six polarization values that must be carefully adjusted to optimize the detector performances. The SDD passivation and optical coupling to scintillators processes have already been developed and tested on dummy devices, and will be applied to working SDDs as soon as the electrical tests of each device will be completed.

2.3. Current status

As concerns the detectors, SDD procurement and bonding is completed. SDD electrical tests and polarization optimization is in progress, as well as passivation and optical coupling to scintillators processes. AFEE board design is in progress, ICARUS-SDD ASIC procurement and test is completed, and SDD coupling to the ASIC has been tested successfully, too. DFEE board is in production, and the definition of the interface between DFEE and the MEGA electronics is in progress, in collaboration with the MEGA staff.

3. Conclusions

A prototype calorimeter based on silicon drift detectors coupled to scintillators is under development at CNR-IASF, Bologna. The calorimeter has been conceived as detector D2 of a Compton telescope and should be able to improve the energy resolution by at least a factor of 2 with respect to a PIN photodiodes system, thus improving the angular resolution of the telescope. The first SDD has already been tested as an X-ray detector showing 1.3% energy resolution at 59.54 keV and 7% at 5.9 keV. The system advancement status is good especially due to the re-use of technology and hardware already developed for the PICsIT instrument on board the INTEGRAL satellite. The calorimeter is expected to be tested with the MEGA prototype on the ground and possibly on a balloon flight (MEGABALL mission).

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References