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Final report on the 2012 - 2014 R&D project of the LabEx P2IO "Development of a Compton gamma-ray telescope"

P2IO's team:

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1. Project goals

Astronomy in the MeV gamma-ray band (0.1 – 10 MeV) holds a rich promise for elucidating many fundamental questions concerning, e.g., nucleosynthesis in stellar explosions (novae and supernovae), the origin of cosmic rays, the laws of physics around neutron stars and black holes, the active sun, as well as the origin of terrestrial gamma-ray flashes. However, once the instruments on-board the ESA's INTEGRAL observatory will be turned off, in a few years from now, this energy range will be inaccessible to astronomers.

One of the most promising concepts for the next generation of gamma-ray space instrument is a Compton telescope made of two main parts: a silicon tracker optimized for Compton scattering of cosmic gamma rays and a calorimeter to absorb the scattered photons. The P2IO project aims at the construction of a small prototype of such an instrument utilizing recent advances in detector technologies and integrated readout electronics. The prototype instrument is realized by combining several thin layers of double-sided silicon strip detectors (DSSSD) with a cerium-doped lanthanum bromide (LaBr3:Ce) scintillator coupled to a multi-anode photomultiplier tube (MAPMT). The DSSSD technology is studied at IPNO, the $LaBr_3$:Ce module is developed at CSNSM, and LAL takes part in the realization of the readout electronics together with the two other P2IO laboratories.

In parallel, a non-P2IO team, which belongs to the LabEx UnivEarthS and involves the laboratories APC (CEA/IRFU, University Paris-Diderot, CNRS/IN2P3 and Paris Observatory) and AIM (Service d'Astrophysique (SAp)/IRFU/DSM/CEA Saclay) develops a detection stage consisting of a DSSSD and its associated electronic readout. This set will be incorporated into the P2IO telescope in 2015.

2. Description of work achieved

2.1. Development of an imaging calorimeter in LaBr3:Ce

We studied a detection module comprising a $LaBr_3$:Ce crystal of 5×5 cm^2 area and 1 cm thickness coupled to a 64-channel MAPMT (Hamamatsu H8500). We used for this a dedicated test bench (Fig. 1) comprising an XY table and a collimator in tantalum and lead for radioactive sources (^{241}Am, ^{133}Ba, ^{137}Cs). The 64 MAPMT channels are read with the latest version of the ASIC MAROC (MultiAnode ReadOut Chip), which was originally developed at LAL for the luminometer of the ATLAS detector (CERN/LHC).

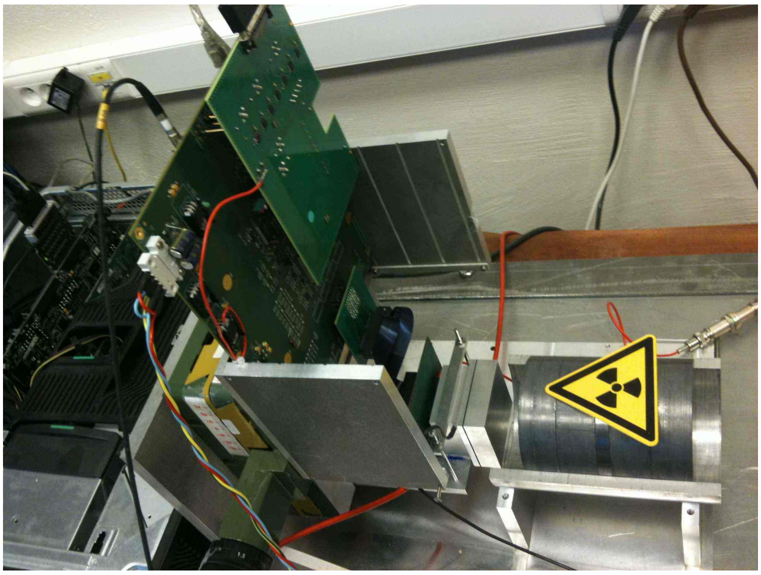

Figure 1: Test bench to characterize the $LaBr_3$:Ce detector

The front-end electronics (FEE) is based on the MAROC test board controlled by LabVIEW, which was originally developed to characterize the ASIC at LAL. But this board has been widely modified within the scope of this project and complemented by an extension for transferring the data into a data merger board based on a Xilinx ML605 evaluation board equipped with a Virtex-6 FPGA. Data are then transferred to a PC via a PCI Express interface (see Sect. 2.3). The online acquisition is based on a trigger-less system controlled via a graphical interface with a dynamic configuration. This system saves, on disk, approximately 50,000 events per second without any loss of information.

Many position measurements were undertaken to study the localization of the gamma-ray interaction site in the $LaBr_3$:Ce scintillator. These measurements were compared with detailed GEANT4 simulations including the tracking of the scintillation photons in the crystal. Once validated, these simulations were used to train an artificial neural network (ANN) for modelling the response function of the detector[1]. The results we obtained show the interest of such a detector for gamma-ray space astronomy. It has indeed a detection threshold of about 10 keV, an energy resolution of 3.4% (full width at half maximum) at 662 keV and a position resolution of about 2.5 mm (standard deviation) in the X-Y plane of the photocathode. All of this work was presented by Aleksandar Gostojic, who is preparing a PhD thesis on this topic, at two international conferences in 2013 and 2014.

[1] The ANN is a multilayer perceptron (with two hidden layers with 10 nodes each) with back propagation of errors from the JETNET 3.0 package. It takes as input the 64 measured charges and returns the three positions X, Y and Z of the gamma-ray interaction site.

2.2. Development of a gamma-ray tracker in DSSSDs

We studied the spectral response of the DSSSD BB7 version 2 of Micron Semiconductor Ltd, which is a detector of 64 × 64 mm^2 area, 1.5 mm thickness, and 32 +32 strips. Initial tests showed that this detector has the ability to detect low energy deposits. To optimize the electromagnetic compatibility of the detection device, we designed and constructed a test bench (Fig. 2) dedicated to the reading of DSSSDs around a conventional analog electronics readout. This task required the realization of electronic cards around the PACI charge preamplifiers previously developed at IPNO. With this device, we measured an energy threshold of 11 keV and an energy resolution of 8 and 10 keV (FWHM) at 59.5 keV (^{241}Am) for the *p* and *n* sides of the BB7 detector, respectively, which validates the choice of this sensor for our application.

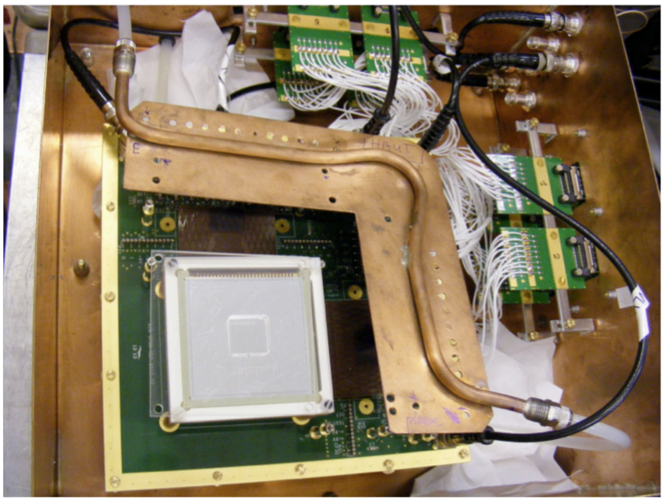

Figure 2: Photograph of the BB7 DSSSD test bench around PACI preamplifiers. The detector is mounted in the lower left corner of the electronic readout card. A copper cooling circuit provides temperature control of the preamplifiers.

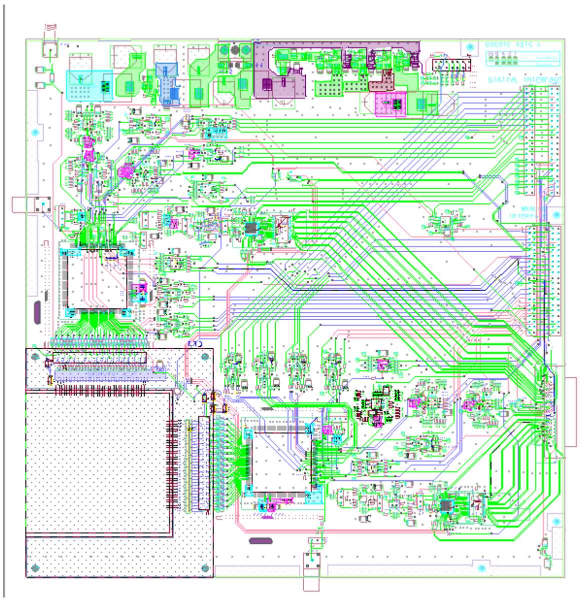

Figure 3 : Computer-aided design of the FEE card of the BB7 detector.

For the Compton telescope, the readout of the DSSSD signals is done with low noise ASICs. We originally intended to use the ASIC ATHED, which was developed for the multi-detector of charged particles MUST2. But after a series of tests, we found that the spectroscopic resolution for the detection of low-energy deposits with this ASIC would be unacceptable for our application. After extensive market research, we selected the chip VA32TA7 from the Ideas Company[2], which incorporates 32 channels of full electronic processing sensor signals. We then designed an electronic board (Fig. 3) carrying a sensor BB7, two ASICs VA32TA7 (one for each sensor face), and an interface to a FPGA development board (ML605, Xilinx). This card, which was delivered in August 2014, is currently in the qualification phase. It will be soon coupled to the detector BB7 for extensive performance testing.

2.3. The data flow architecture

The digitized data from the self-triggered FEE cards VA32TA7 (DSSSDs) and MAROC (detector LaBr3:Ce) are time stamped and merged inside the ML605 evaluation board using the Virtex 6 FPGA. Synchronization of different subsystems is provided by the distribution of a clock signal of about 1 Hz. The data are then transmitted to a PC via a PCI Express interface and processed by the acquisition NARVAL system for identification of events coincidence characteristics of Compton scattering.

2.4. Mechanical integration and tests

The mechanical device of the telescope has just been completed (Fig. 4) and the integration of the $LaBr_3$:Ce module and the first DSSSD will be made before the end of the year. The system comprises supports to accommodate up to three DSSSDs with their associated FEE cards (the two developed at IPNO and the one made by the team of the LabEx UnivEarthS). This entire device will be placed in a special black box, designed at IPNO, ensuring both the light sealing and good electromagnetic compatibility of the apparatus. Moreover, some of the test measurements will be performed in a climatic chamber available at IPNO at temperatures between 0° and 20° C. This will allow us to study the telescope under better operating conditions for the DSSSDs (low leakage current at low temperatures), closer to the expected conditions in space and the upper atmosphere.

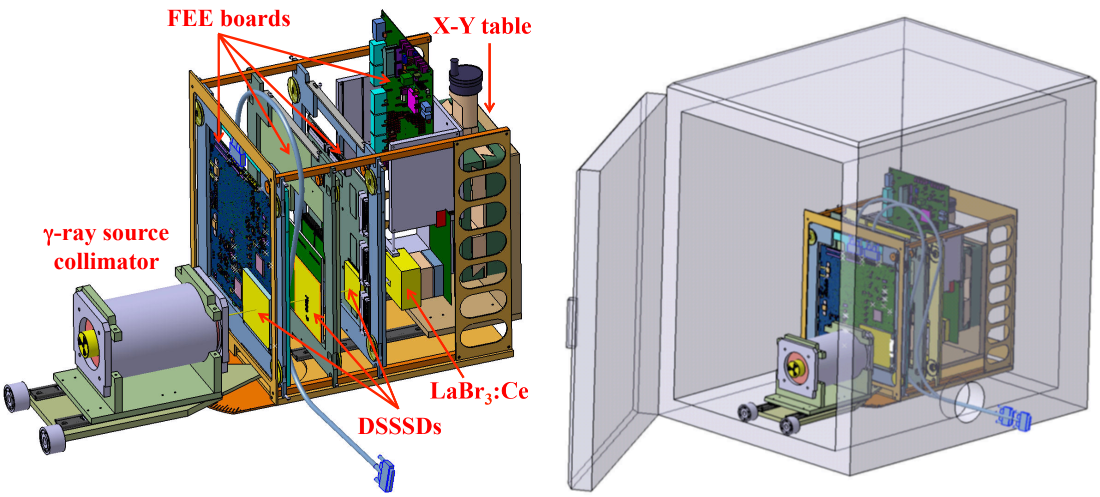

Figure 4: *Left* - Mechanical drawing of the P2IO gamma-ray telescope. *Right* - Presentation of the telescope and the collimator for radioactive gamma-ray sources inside the climatic chamber. The telescope is placed in a black box not shown in this diagram.

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[2] Ideas (http://ideas.no/) specializes in the production of ASICs for medical imaging and X- and gamma-ray astronomy.

3. Publications

We published the results on the $LaBr_3$:Ce module development with 3D imaging based on the use of an artificial neural network in two proceedings papers, one with and the other without peer review. A third publication on the full characterization of this detector is in preparation for Nuclear Instruments and Methods in Physics Research A. Two other publications in peer-reviewed journals are foreseen. The first will show the performance obtained with the DSSSD BB7 and the associated integrated electronics. The second will present the full performance of the gamma-ray telescope.

- Gostojic, A., Tatischeff, V., Kiener, J., Hamadache, C., Karkour, N., Linget, D., Sedes, G., Blin, S. & Barrillon, P. (2013). Development of a 3D Imaging Calorimeter in Lanthanum Bromide for Gamma-Ray Space Astronomy. In Proceedings of the 2013 IEEE Nuclear Science Symposium & Medical Imaging Conference. Seoul, South Korea, October 27 – November 2, 2013. IEEE 2013 NSS-MIC Conference Record (2013) 1- 7.
- Gostojic, A., Tatischeff, V., Kiener, J., Hamadache, C., Karkour, N., Linget, D., Grave, X., Gibelin, L., Blin, S. & Barrillon, P. (2014). Application of Artificial Neural Network in 3D Imaging with Lanthanum Bromide Calorimeter. In Proceedings of the 7th International Conference on New Developments in Photodetection. Tours, France, June 30 – July 4, 2014. Submitted to NIM Phys. Res. A on September 19, 2014.

4. Relevance of the project within P2IO and specific added values for P2IO

The project would not have started without the funding from the LabEx. Some R&D on $LaBr_3$ detectors for a space application had already begun in CSNSM before 2012, with funding from the laboratory's own budget, but it is only through the collaboration between the three P2IO laboratories that our technological developments have started to take an international scale (see Sect. 5).

The project was initially based on skills acquired in IN2P3 laboratories in the development of various detection systems for nuclear and particle physics experiments. In this project, these skills have been applied for the first time in a purpose related to space astronomy. Thus, the project has greatly benefited from the expertise of IPNO in silicon strip detectors, in particular thanks to the development of the multi-detectors of charged particles MUST2 and GASPARD. The CSNSM team has a large experience in high-speed data acquisition systems and online digital signal processing through FPGA programming, with the multi-detectors EUROBALL, EXOGAM, and AGATA and now the realization of the SIRIUS Tunnel detector front- and back-end electronics. Last but not least, the project initially greatly relied on the expertise of LAL and the Omega micro centre for the design of microelectronics readout system.

During the project, a team from the APC and AIM laboratories belonging to the LabEx UnivEarthS joined us (see Introduction). This team has a long experience in space instrumentation, having in particular participated in the making of the low-energy camera of the imager on-board INTEGRAL (IBIS/ISGRI). With this merger, we are now a recognized player in space instrumentation for high-energy astrophysics[3].

[3] Noteworthy, our funding requests to the P2IO LabEx now include the AIM/CEA laboratory; see, e.g., our recent demand for a post-doctoral funding in 2015 – 2017 (project leader: V. Tatischeff).

5. Possible valorisation of the project

Our R&D aims at demonstrating the maturity of some innovative technologies for a future space mission observing the sky in the medium energy gamma-ray domain. The preparation of such a mission is the main goal of the AstroMeV consortium, which already brings together nearly two hundred scientists and engineers from 18 countries (see http://astromev.in2p3.fr/). The two co-PIs of this collaboration are Peter von Ballmoos from the Research Institute in Astrophysics and Planetology (IRAP, Toulouse, France) and Vincent Tatischeff. The immediate objective of AstroMeV is to prepare a high-quality answer to the recent Call of the European Space Agency (ESA) for the 4th Medium-size mission of the Cosmic Vision program (planned launch in 2025)[4].

Within this collaboration, one of the two instrument concepts studied in detail by dedicated working groups is a Pair and Compton Telescope (PACT) of about 300 kg (the recommended payload mass) composed of two main detectors: a gamma-ray tracker made of a stack of DSSSDs and a calorimeter composed of an ensemble of position-sensitive scintillator modules. The prototype telescope developed by P2IO's team is a pathfinder for this concept.

6. Expenses

Development of the imaging calorimeter in LaBr3:Ce

- ASICs MAROC and associated test board: 1600 €
- Electronics cards for MAROC data acquisition: 1394 €
- Calibrated gamma-ray source of ^{133}Ba: 1600 €
- Master 2 internship of Aleksandar Gostojic: 872 €
- Participation in the remuneration of the engineering internship of Rawad Bitar: 622 €
- **Total: 6088 €**

Development of the gamma-ray tracker in DSSSDs:

- Participation in the remuneration of the engineering internship of Olivier Capdevielle: 357 €
- Development of the DSSSD test bench with an analog electronics readout using the PACI preamplifiers: 3690 €
- ASICs VA32TA7 (+support) purchased to the Ideas Company: 2044 €[5]
- Development of the VA32TA7 FEE card: 3273 €
- First BB7 DSSSD purchased to Micron Semiconductor Ltd: 7632 €
- Second BB7 DSSSD and associated FFE board: 7500 €[6]
- **Total: 23996 €**

Data acquisition system and mechanical design of the telescope:

- Development of electronic data acquisition boards: 5584 €
- Computer for the data acquisition: 2231 €
- Mechanical design of the telescope: 1500 €
- **Total: 9815 €**

- **Total expenses: 39899 €**

[4] The AstroMeV Letter of Intend for the submission of a mission concept in response of the M4 Call was sent to ESA on September 16, 2014.

[5] The total cost of the VA32TA7 ASICs amounts to 6830 €. The 4786 € difference was funded in 2013 by a grant from IN2P3 to IPNO.

[6] The total cost of the sensor and associated front-end electronics is estimated at 10,000 €. The difference of 1,500 € will be financed by the project DIAGME "DEFI Instrumentation limits" involving the laboratories CSNSM, IPNO, APC, AIM and IRAP (PI: V. Tatischeff).

7. Future of the project after P2IO funding

From late 2015, the P2IO team will join engineers and researchers from APC, AIM and IRAP to start building a second Compton telescope dedicated to a measurement of gamma-ray polarization at the European Synchrotron facility (ESRF). It is indeed important to evaluate the sensitivity of the proposed instrument concept to polarization, as the latter will certainly become a key observable of the magnetic field structure and the nature of the gamma-ray emission process in astrophysical objects emitting jets (Blazars, gamma-ray bursts, X-ray binaries) or with strong magnetic field (pulsars, magnetars).

The new telescope will include several layers of DSSSDs (the exact number will depend on funding) and a calorimeter made of new scintillation modules. As part of the project DIAGME (Détecteurs Innovants pour l'Astronomie Gamma des Moyennes Energies) funded in 2014 by the CNRS program "DEFI Instrumentation limits" (14 k€), we have just started to study different scintillators, such as $CeBr_3$, which could advantageously replace $LaBr_3$:Ce for a space application. We also plan to replace the multi-anode photomultiplier tubes (MAPMTs) by arrays of silicon PM. Indeed, due to their compactness and robustness, and the fact that they are powered in low voltage (tens of volts), these photodetectors appear to be preferable to the traditional photomultiplier tube (PMT) for a future space telescope.

After the measurement campaign at ESRF, the telescope may later evolve into a bigger instrument dedicated to a stratospheric balloon flight. The main scientific goal of this balloon experiment would be to measure the polarization of bright X-ray sources, such as the Crab nebula and pulsar, in the 100 – 300 keV energy range. With this prospect in mind, specific issues such as the readout electronics of a stratospheric instrument (low consumption, stability of the high voltage at low pressure etc.) will be adressed. Noteworthy, physicists from the High Energy Astrophysics Section of the Naval Research Laboratory (Washington, DC, USA) have expressed interest to participate in the development of the gamma-ray tracker for this project. As for the development of the calorimeter, it could be done in collaboration with scientists from the University College of Dublin (Ireland), who are already funded by ESA to work on new scintillation detectors.

To achieve the instrument dedicated to a measurement campaign at ESRF, we are planning to seek additional support of the two LabEx P2IO and UnivEarthS, as well as from IN2P3 and DIM ACAV of the "Ile de France" area. The development of the telescope for a stratospheric balloon flight will have to be supported by CNES (Centre National d'Etudes Spatiales).