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HARPO - P2IO - R & D

This report is our contribution to the P2IO Scientific committee, Ecole Polytechnique, 17 – 18 december 2014. Only the R & D funding is reported here, the post-doc funding is not.

1 Project goals

Two bleeding issues in gamma-ray astronomy are:

- The strong degradation of the angular resolution of pair telescopes at low energy which, together with the absence of Compton telescopes in space sensitive above 1 MeV [1], make the [1 – 100 MeV] gamma-ray sky very badly known.
- The polarimetry diagnostic, which proves to be a very powerful tool to understand cosmic sources at lower energy (micro-waves to X-rays), is missing for gamma-rays, as no polarimeter sensitive above 1 MeV has ever been flown to space.

Our goal is to develop the concept of "thin" homogeneous detectors, such as a gas time projection chamber (TPC), as:

- a high-performance (angular resolution, sensitivity) gamma-ray telescope,
- for the first time, a cosmic source gamma-ray polarimeter.

Besides a series of "theoretical" performance studies, part of which have been published [1, 2], the main part of the present phase of the project is to:

- design, build, validate a demonstrator, which has been done [9];
- to expose it to a beam of monochromatic polarized gamma beam, which will be done from 20 Oct. to 20 Nov. 2014 at NewSUBARU, Hyôgo, Japan;
- to analyze the data so obtained, extract a precise characterization, and publish.

[1] Since Comptel who took data at the end of the last millenium.

2 Description of work achieved

2.1 Pre-P2IO

After some time spent in performance studies of various approaches, detector design, and unsuccessful funding applications, the project "truly" began with a funding by the interdisciplinary PEU (particules-and-universe) program by CNRS (INSU-IN2P3, 2010, 30 k€, that is one third of the requested amount), and IN2P3 (2011, 11 k€).

Despite the project was officially a development of LLR only, we benefited from a huge transfer of competence from Irfu concerning gas detectors, specifically TPC, micromegas amplification, front-end (FEC) electronics for gaseous detectors, including the use of spare FEC cards from the T2K experiment and of the related firmware.

We were able to build, commission and operate the core of a demonstrator, with which we could make our first steps and we learnt a lot[2]. The results of our understanding of the behaviour of the prototype, in particular as a single-track tracker from analysis of cosmic-ray events, has been presented to the Pisa2012 conference the following year [3].

We finalized our earlier performance studies, establishing the power laws describing the contributions to the angular resolution of multiple scattering – under the hypothesis that tracking is performed with an "optimal" fit such as implemented with a Kalman filter – and of the recoil of the nucleus on which the conversion has taken place, the momentum of which goes undetected. This has allowed us to demonstrate the possibility to close the sensitivity gap between the Compton telescopes and the former "thick" pair-telescopes in the [MeV - GeV] energy range [4, 1].

2.2 P2IO Era

The funding situation at CNRS being what we know, the PEU program was "postponed" (means: cancelled) and the DAS (deputy scientific director) for astroparticle at IN2P3 gave up funding instrumentation for astroparticle science (we received .. 2 k€.. from the DAT in 2014). HARPO was at the verge of death.

Funding by P2IO allowed us to:

- Formalize the collaboration between LLR and Irfu (SEDI, SAp, SPP). The full member list of the collaboration can be found at our recent SPIE paper [9].
- Design a set of GEM (Gas Electron Multiplier) foils to complement the already existing micromegas, so that the TPC can be operated at the same overall gain as before, but well within the safety range of the operation parameters. Have them made. After we characterized the performances of these GEM+micromegas combinations with a ^{55}Fe X-ray source [7, 10, 8], we (re)commissioned the TPC and (re)validated it's properties with cosmic rays (Fig. 2 and [9]).
- In parallel, we developed a trigger based on the signals provided by the 12 photomultipliers reading 6 scintillator plates that surround the cubic TPC, and the

[2] In particular we understood that with the narrow (0.5 mm) collecting strips that we are using, with a small average collected charge per track segment, the overall amplification gain of our configuration (micromegas + electronics) was at the limit of a safe routine operation.

signal from the micromegas mesh. The trigger, that includes a veto of the background tracks from conversions upstream the detector, is based on the PMm2 card (courtesy IPNO).

- Prepare a data taking campaign (hardware, transportation / packaging, missions) that is to take place at NewSUBARU (Hyôgo, Japan) next month. To that purpose we organized two collaboration meetings on site (July 2012, Nov. 2013).
- Includes an analysis software with a (Hough transform) pattern recognition, (Kalman filter) tracking, and (Geant4 based) simulation.
- Besides, we developed and validated the first full (5-dimensional) exact (down to threshold, all diagrams) polarized event generator, with which we extended our performance studies of homogeneous detectors to polarimetry. In particular we demonstrated that the single-track angular resolution with a gas detector with optimal tracking is good enough (from our previous [1]) that the induced dilution of the polarisation asymmetry is small. With a full (100 % exposure fraction and efficiency) year of data taking on the Crab pulsar, with a 5 bar argon 1m^3 sensitive-volume detector, a resolution of 1.4% of the polarization fraction can be reached [2].

Figure 1: Préparation de la prise de données au Japon: réunion du 17 juillet 2014.

3 Publications

We have presented HARPO to 10 conferences [3]-[12] and to meetings of the French community [14, 15] on the [2012 - 2014] time range, and we have published two papers as already mentioned [1, 2]. The most relevant paper of ours related to this committee (R&D) is our recent SPIE proceedings [9].

We expect that the forecoming data taking will lead to at least two additional publications:

- First measurement of the polarization asymmetry of gamma rays to e^+e^- pairs in the energy range 2 - 76 MeV. (Phys. Rev. Lett. ??)

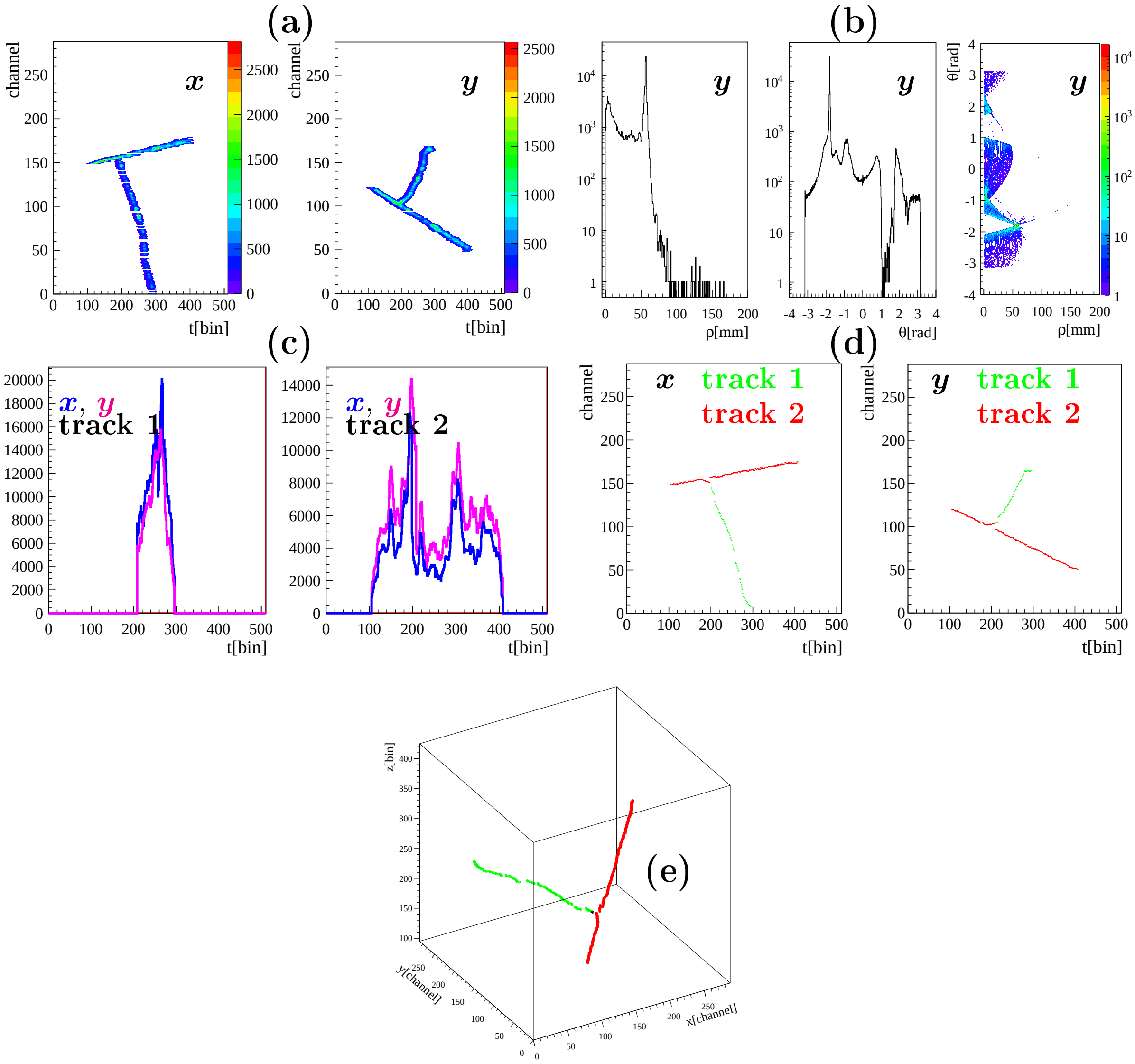

Figure 2: Display of an event in the μM+2 GEM detector configuration with a 2 bar (Ar:95 Isobutane 5 %) gas mixture [9]. The TPC was positioned "vertically", with cosmic rays entering it from above through the amplification system. A cosmic ray crosses through the full TPC thickness (30cm), leaving a lower energy electron (δ ray). The trigger time for this run was $t_0 \approx 100$bin. **(a)** The two event "maps" (x, t) and (y, t) after pedestal subtraction and thresholding (a thin space without any signal is visible due to the presence of a spacer). **(b)** The distributions of the ρ, θ variables that parametrize a track in the combinatorial Hough track pattern recognition[3, 16] and their scatter plot. **(c)** The time spectra for the two tracks, for direction x and y, which are used to perform x, y track matching. **(d)** The maps of the clusters associated with the two matched tracks. **(e)** A 3D view of the reconstructed event, with vertexing (the vertex is indicated by the black dot) [16].

- Beam characterization of a gas TPC as a high performance gamma-ray telescope and polarimeter (Nucl. Instrum. Meth. A ??)

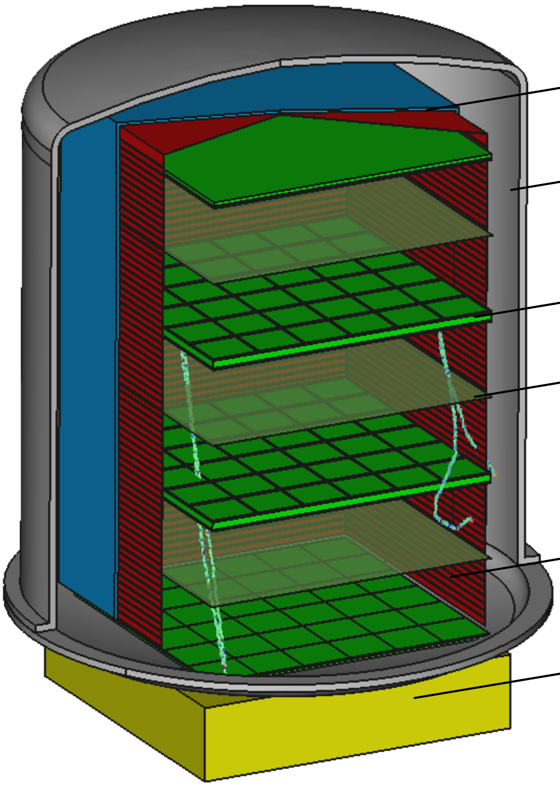

Figure 3: Exploded schematic view of a flight telescope consisting of 3 layers, each layer of 2 back-to-back modules, each module a $(2\ \text{m})^2 \times 0.5$ m TPC with an endplate segmented into $(33\ \text{cm})^2$ micromegas and charge collection blocks. Conversions of a 100 MeV (left) and of a 10 MeV (right) photon in the TPC gas [9].

4 Relevance of the project within P2IO and specific added value for P2IO

In the "scientific document B" that lead to the approval of this Labex, can be read:

The goal of the P2IO LabEx is

- *to create a dynamics of interdisciplinary pioneering researches on the hottest issues in theoretical and experimental physics of the infinitely small and infinitely large aspects of our Universe, pushing the associated questions about the Origins up to the conditions for the appearance of life*
- *to strengthen this dynamics by common researches and developments for innovative instruments to produce, detect and analyse radiations; these new technologies will allow to access new frontiers in probing and observing the Universe*
- *to increase the impact of these sciences and technologies on society by stimulating common applications to nuclear medicine and nuclear energy. The P2IO LABEX is taking advantage of the unique concentration on Paris-Saclay Campus of world leading laboratories covering a broad disciplinary spectrum ranging from particle physics, astroparticle and nuclear physics to astrophysics, experiment and theory, accelerator science, instrumentation and associated interfaces.*

Innovative instruments to [...] detect and analyse radiations; these new

technologies will allow to access new frontiers in probing and observing the Universe

: we're right into it.

More specifically: P2IO has been instrumental in creating a strong collaboration centered on the plateau, with a cross fertilization of competences (Irfu: TPC, gas amplification and electronics for gas detectors, LLR, expertise in high-energy gamma-ray telescopes (the space-flown Fermi LAT and the ground-based HESS, to name only the presently active experiments).

5 Possible valorization of the project

The true valorization of the project will be to have a TPC sent to space by an international collaboration, in which France will have a decisive part.

6 Expenses

The repartition that was decided initially was (€):

	Irfu	LLR	total
2012	25 000	42 230	67 230
2013	5 000	8 770	13 770
Total	30 000	51 000	81 000

The estimated breakdown of the actual expenses is:

	Irfu	LLR	total
small hardware ($\leq$ 4 k€) "fonctionnement"	6 078	7 212	13 290
equipment ($>$ 4 k€)	13 162	11 134	24 296
data taking (personnel travel and stay expenses)	8 987	5 688	14 675
data taking (apparatus transportation)		16 856	16 856
other travels (collaboration meetings, conferences ..)	1 773	10 110	11 883
Total	30 000	51 000	81 000

7 Future of the project after P2IO funding

7.1 In the short term: 2010's

The second part of our scientific program as described in our application to P2IO was related to developments aimed at the spatialization of the technique.

- Development of low outgassing technology for long-term TPC use in space.

  Actually, in contrast with what was feared at the beginning of the project, and despite the present demonstrator includes a lot of "dirty" elements (scintillator, wavelength shifter, PVC structure, O-ring, PCB, epoxy ..) in contact with the gas, we observed that after careful pumping / medium-temperature backing / rincing cycles, the gas quality is preserved after 2 months of operation. Extrapolation from months to years should not be an issue, if needed with a better selection of the building material and .. with a larger budget.

- Development of smaller gap MPGD for optimal use at a larger pressure.
- Characterization of the radiation hardness of the present electronics.

Concerning the last two items, we were not able to do anything (yet). These important points will have to be dealt with in the future (small gap amplification is being studied at Irfu by some of us, but in the framework of an other project).

- We aim at designing a scintillator-free trigger based on the real-time multiplicity signal provided by the digitizing chip AGET recently validated at Irfu, on an ANR funding.

7.2 On a longer term

Ultimately, an international collaboration will fly a TPC to space (Fig. 3).

8 Precise illustration of the added value of P2IO relative to national or international context, even this would not have been possible without P2IO

We are in the process of founding a new way to perform γ-ray astronomy in the energy range above 1 MeV, and the first doable way to perform polarimetry. Or so we think. This would never had been possible without this funding, as already mentioned.

The project has undergone a major transition from infancy to maturity thanks to the supports from the P2IO LabEx, the 3-year R&D funding reported on here, and the post-doc funding that will be reported on request. This "thin" detector γ-ray astronomy polarimetry will keep the P2IO label forever, especially if an international Collaboration, strongly French rooted we hope, does have a detector fly on a space mission in the next future.

A goal for which we will keep on working.

links at http://llr.in2p3.fr/∼dbernard/polar/harpo-t-p.html.

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