A TPC as high performance gamma-ray telescope and polarimeter: polarisation measurement in a beam between 1.7 and 74MeV with HARPO

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Abstract. We presented in 2014 the very first data from a polarised gamma-ray beam between 1.7 and 74MeV. We now show the results of their analysis, and in particular the polarimetry measurements. With these results, we are establishing a new, high-performance way to do gamma-ray astronomy and, for the first time, polarimetry, in the e+e- pair regime.

1. Introduction
A number of groups are developing pair-conversion detector technologies alternative to the tungsten-converter / thin-sensitive-layer stacks of the COS-B / EGRET / Fermi-LAT series, to improve the single-photon angular resolution. Presently, observers are almost blind in the 1-100MeV energy range, mainly due to the degradation of the angular resolution of e+e- pair telescopes at low energies: to a large extent, the sensitivity-gap problem is an angular-resolution issue.

We have shown that gaseous detectors, such as TPCs (time projection chambers), can enable an improvement of up to one order of magnitude in the single-photon angular resolution (0.5° at 100 MeV) with respect to the Fermi-LAT (5° at 100 MeV), a factor of three better than what can be expected for Silicon detectors (1.0-1.5°@ 100 MeV). With such a good angular resolution, and despite a lower sensitive mass, a TPC can close the sensitivity gap at the level of 10\textsuperscript{-6} MeV/cm\textsuperscript{2}s.

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between 3 and 300 MeV. In addition, the single-track angular resolution is so good that the linear polarisation fraction and angle of the incoming radiation can be measured.

We first describe the fast-gas (low pile-up), cool-gas (low-diffusion), high pressure (0.5-4 bar) HARPO detector prototype, and its test in a polarised photon beam. We quickly describe the full detector simulation developed, and its calibration using cosmic-ray measurements. Finally, we show early polarisation measurement at 11 MeV, and compare it to our simulation.

2. The HARPO Experimental setup

The HARPO (Hermetic ARgon POlarimeter) detector [1] is a demonstrator of the performance of a TPC for measuring polarised $\gamma$ rays. It was designed for a validation on the ground in a photon beam. The most critical constraints related to potential space operation were taken into account, such as the reduced number of electronic channels, and long-term gas-quality preservation.

The HARPO detector is a 30 cm cubic TPC, filled with an Ar:isobutane (95:5) gas mixture at 2.1 bar. It is equipped with a drift cage providing a 220 V/cm drift field. The electrons produced by the ionisation of the gas drift along the electric field toward the readout plane at a constant velocity $v_{\text{drift}} \approx 3.3 \text{ cm/}\mu\text{s}$. The readout plane is equipped with two Gas Electron Multipliers (GEMs) and one Micromesh Gas Structure (Micromegas) to amplify the electrons. The amplified electrons’ signal is collected by two sets of perpendicular strips (regular strips in the $X$-direction, and pads connected together by an underlying strip in the $Y$-direction. The signals from the strips are read out and digitised with a set of AFT$_{\text{ER}}$ chips [2] and associated Front End Cards (FECs).

The HARPO TPC was set up in the NewSUBARU polarised photon beam line [3] in November 2014. The photon beam is produced by Inverse Compton Scattering (ICS) of an optical laser on a high energy (0.6-1.5 GeV) electron beam. Using lasers of various wavelengths and different beam energies (as described in more detail in [4]), we scanned 13 photon energies from 1.74 MeV to 74 MeV. In order to minimise systematic effects due to the geometry of the detector, the detector itself was rotated around the beam axis to 4 different angular positions (-45, 0, 45 and 90°). Finally, for some configurations (in particular at low energy), data were also taken with randomly polarised photons.

3. Simulation of the HARPO detector

The cubic geometry of the detector introduces a systematic bias to the polarisation measurement which cannot be addressed analytically. It is therefore necessary to have an accurate simulation of the TPC. We developed a complete simulation to describe the response of the HARPO detector. It contains three main components:

- an event generator describing the conversion of photons in the gas [6]. It provides the energy momentum of the electron-positron pair.
- a simulation of the interaction of the electron and positron pair with the gas, based on Geant4 [5]. It provides the ionisation electrons in the gas volume.
- a custom description of the processes and geometry of the TPC [8]. It provides a signal map similar to the real data.

The first two components are already independently validated. The last was developed specifically for HARPO, and has to be validated and calibrated. The description of the TPC includes electron drift, diffusion and amplification in the gas, the readout space and time response, and the signal digitisation, including known electronics saturation effects.

This simulation was thoroughly calibrated and validated using a very tight selection of cosmic rays. Figure 1 shows an example of the calibration of the electron diffusion in the gas. This was done with a measurement of the variation of the spatial extent of the signal as a
function of drift distance. We see a perfect agreement between data and simulation. All the simulation parameters were similarly calibrated or validated against data.

![Figure 1.](image)

**Figure 1.** Signal size (RMS) as a function of the drift distance for data (red) and simulation (blue), for a sample of cosmic rays. There is excellent agreement between the data and simulation.

4. Results on polarimetry
A specific reconstruction algorithm was developed to reconstruct vertices in the TPC [8]. This allows us to extract the azimuthal angle $\phi_{+-}$ for the conversion [7],

$$\phi_{+-} = \frac{\phi_+ + \phi_-}{2},$$

where $\phi_{\pm}$ are the azimuthal angles (relative to the beam direction) of the electron and positron. $\phi_{+-}$ is expected to follow a distribution

$$1 + A \cos 2(\phi_{+-} - \phi_0),$$

where $A$ is the polarisation asymmetry, and $\phi_0$ is the polarisation direction.

We cancel the systematic effects by taking the ratio of the polarised and unpolarised distributions of the azimuthal angle $\phi_{+-}$. Figure 2 shows the resulting distributions for data and simulation. We can also correct the systematics in the data using the simulation. The result is also shown in Fig. 2.

5. Conclusions and outlook
The HARPO detector was completed and used successfully in a photon beam in 2014. A full simulation of the detector was developed to describe it, and it was validated and calibrated against cosmic-ray data. We measure the polarisation asymmetry of a 11.8 MeV photon beam with high precision, and with good agreement with simulation.

There is still ongoing efforts to improve these results, and extend them to the full energy range (1.74 to 74 MeV) of the available beam data. The results from the beam data are extremely encouraging and studies are under way to adapt this technology for use as a space telescope.
Figure 2. Polarisation modulation for a beam of 11.8 MeV photons. The plot is obtained by dividing the distribution of the azimuthal angle $\phi_{+\rightarrow}$ for polarised photons, by the distribution for unpolarised photons. Most of the systematic errors are cancelled, only statistical errors are shown. On the top left, both distributions are for real data. On the top right, both distributions are simulated. On the bottom, the polarised distribution comes from real beam data, and the unpolarised one comes from simulation.

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