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# Energy dependent features of X-ray signals in a GridPix detector

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ABSTRACT

We report on the calibration of an argon/isobutane (97.7%/2.3%)-filled GridPix detector with soft X-rays (277 eV to 8 keV) using the variable energy X-ray source of the CAST Detector Lab at CERN. We study the linearity and energy resolution of the detector using both the number of pixels hit and the total measured charge as energy measures. For the latter, the energy resolution $\sigma_E/E$ is better than 10% (20%) for energies above 2 keV (0.5 keV). Several characteristics of the recorded events are studied.

## 1. Introduction and description of setup

Gaseous X-ray detectors with a high granularity readout have advantages over other detector types, such as silicon detectors, if additional information based on the event shape is required to suppress non-X-ray background. One application is the search for axions and chameleons, where a main background stems from cosmic rays passing through the detector. The CAST experiment at CERN uses the helioscope technique by pointing a strong magnet towards the Sun and searching with various detectors for new particles, which convert into X-ray photons inside the magnetic field. CAST is currently setting stringent limits on both axion [1] and solar chameleon searches [2]. To further improve the sensitivity, we have shown that exploiting topological features of a signal is a very powerful technique and can be performed with a GridPix detector [3]. We have, therefore, studied the features of X-ray events of various energies with the help of an X-ray gun setup at the CAST Detector Lab at CERN [4].

### 1.1. X-ray generation

The CAST Detector Lab provides a dedicated setup where X-ray photons of various energies can be generated. For this, an electron beam is directed on a target creating an X-ray spectrum containing the well known characteristic X-ray fluorescence lines of the target material on top of a broad Bremsstrahlung continuum. A dedicated filter is then used to isolate the selected characteristic lines or suppress unwanted parts of the spectrum as well as possible. By adjusting the electron beam energy, the target and filter material, quite clean spectra can be created. For some settings listed in Table 1 more than one fluorescence line is listed, in these cases there was no adequate filter material available to suppress the unwanted line, e.g. the $K_\beta$ lines of several target elements. The filter material EPIC used for the low energetic X-ray photons is a composite filter composed of a 330 nm thick polypropylene carrier sandwiched by two 90 nm aluminum layers with a 35 nm tin layer on top of one side, also known as *Thick filter* and developed as UV filter for the European Photon Imaging Cameras utilized in the XMM-Newton satellite [6].

The photons are guided through a vacuum pipe to the detector. The maximum rate of X-ray photons entering the detector is limited by the filters, windows and by the maximum beam current tolerable for the passively cooled target. Since the data acquisition is frame based, one has to compromise between a low probability of double photon events and acceptable rate of single photon events. At low X-ray energies the logical shutter was set to 600 µs and then the detector is read out which takes about 25 ms resulting in a duty cycle of about 2.4%. Therefore, collecting about 10 000 photons took more than one hour for each energy setting.

### 1.2. Detector

The detector is described in detail in Ref. [7]. A short summary of the important features is given here. The readout is based on a GridPix, which consists of a Timepix ASIC [8] on top of which a Micromegas gas amplification stage (InGrid) is built by photolithographic post-processing techniques [9,10]. The ASIC has $256 \times 256$ readout channels with a pitch of $55 \times 55\,\mu m^2$ giving a sensitive area of about 2 $cm^2$. The good alignment of each mesh hole with one readout pixel of the ASIC and the low charge threshold of the pixels are key features of the setup; if a primary electron enters in one mesh hole, the electron avalanche of the gas amplification is collected by a single readout pixel with a typical

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**Table 1**
Beam energies, target and filter materials chosen to produce photons of the listed fluorescence lines by an X-ray generator. A letter is assigned to each setup for reference throughout this document. The energies of the lines were taken from the X-ray data booklet [5].

| Setup | Beam energy | Target material | Filter | Fluorescence line(s) |
|---|---|---|---|---|
| A | 15 keV | Copper | Nickel | Cu $K_\alpha$ (8.048 keV) |
| B | 12 keV | Manganese | Chromium | Mn $K_\alpha$ (5.899 keV) |
| C | 9 keV | Titanium | Titanium | Ti $K_\alpha$ (4.511 keV)<br>Ti $K_\beta$ (4.932 keV) |
| D | 6 keV | Silver | Silver | Ag $L_\alpha$ (2.984 keV)<br>Ag $L_\beta$ (3.151 keV) |
| E | 4 keV | Aluminum | Aluminum | Al $K_\alpha$ (1.487 keV) |
| F | 2 keV | Copper | EPIC | Cu $L_\alpha$ (0.930 keV)<br>Cu $L_\beta$ (0.950 keV) |
| G | 0.9 keV | Oxidized copper | EPIC | O $K_\alpha$ (0.525 keV) |
| H | 0.6 keV | Carbon | EPIC | C $K_\alpha$ (0.277 keV) |

threshold of about 700 electrons. Thus, at gas gains of about 2500 a primary electron can be detected with an efficiency of about 92%, if primary electrons do not end up on the grid and diffusion spreads the charge cloud sufficiently, so that multiple electrons do not enter the same mesh hole.

The drift volume has a maximum drift distance of 3 cm and a constant pressure of an argon based mixture containing 2.3% isobutane as quencher was maintained at 1050 mbar. This mixture has Penning properties allowing for lower voltages at the gas amplification stage to reach the nominal gas gain. Higher percentages were not allowed for safety considerations (flammability). A drift field of 500 V/cm was chosen to minimize effects of field distortions and to reach sufficiently wide diffusion, but still to guarantee safe and stable operation. The cathode is made of a solid 3 mm copper plate, where $5 \times 5$ windows of $3 \times 3\,\mathrm{mm}^2$ each have been cut out. The optical transparency of this reinforcement is 82.6%. A 2 μm thick Mylar foil with a 40 nm layer of aluminum was glued on the copper to achieve gas tightness between the drift volume and the vacuum of the X-ray generator. A differential pumping is, however, still necessary and requires an additional window consisting of a 0.9 μm thick Mylar foil separating the good vacuum of the X-ray generator $\left(p \approx 2 \times 10^{-6}\,\mathrm{mbar}\right)$ from the bad vacuum $\left(p < 5 \times 10^{-4}\,\mathrm{mbar}\right)$ close to the detector. The transmission probability is shown in Fig. 1 as a function of the X-ray energy for the different parts of the detector incrementally, i.e. for the differential window only (dotted line), then for the differential and the detector window (dashed line) and the transmission through the differential and detector window including the area transparency of the window strong back (dotted and dashed line). Finally, the detection probability of the X-ray photons is shown in a solid line taking also the conversion probability in the gas into account. Transmission and absorption data have been produced by a generator using the semi-empirical approach described in [11].

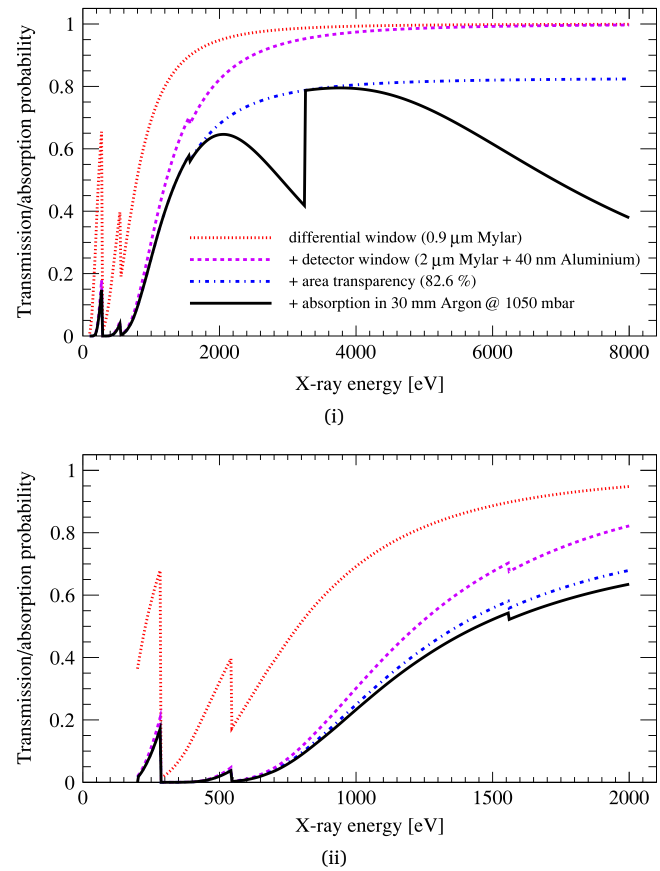


**Fig. 1.** The graph in (i) shows the transmission probability as a function of the X-ray energy through the differential and the detector windows. Also the total detection probability is given. (ii) shows a detailed view of the low energy range.
*Source:* Graphs taken from [7].

### 1.3. Event reconstruction and event parameters

For each pixel hit, the time-over-threshold (ToT) is recorded in a 14-bit pseudo-random counter and used as a measure of the collected charge by applying a charge calibration. A number of offline selection cuts are employed to remove unwanted events such as events having two converted photons, only partially contained charge clouds or cosmic ray tracks. A first cut requires at least three activated pixels in the event to reject empty frames. The remaining events are then analyzed using the MarlinTPC software framework [12]. Here the X-ray photons are reconstructed by searching for a first seed pixel starting at the top left corner. Additional electrons are assigned to the X-ray by searching in a 100 by 100 pixels array around each pixel already found. For every pixel assigned to the X-ray the same search will be performed in its vicinity. In this way all pixels belonging to one X-ray photon are identified and far away noise hits are rejected. Fig. 2 shows the charge clouds of two X-ray photons: one with an energy of 277 eV and one with 8 keV.

Several properties of each charge cloud are determined. The position of the X-ray conversion is determined by calculating the mean of all pixel positions in $x$- and $y$-directions. The mean is required to be less than 4.5 mm from the center of the active area. This ensures a minimal distance of 2.5 mm to the edges, so that even a maximal diffusion after 3 cm of drift gives a charge cloud width of $\sigma(3\,\mathrm{cm}) = D_T \cdot \sqrt{z} = 600\ \mu\mathrm{m}/\sqrt{\mathrm{cm}} \cdot \sqrt{3\,\mathrm{cm}} \approx 1040\,\mu\mathrm{m}$ almost no electrons are lost outside of the sensitive area. Here $D_T$ is the transverse diffusion coefficient at an electric field $E = 500\,\mathrm{V/cm}$ for the argon based gas mixture.

The energy was determined by two different methods. In the first approach the number of activated pixels gives a very good estimate of the number of primary electrons, which multiplied by the average ionization energy $W_I$ yields the energy of the X-ray photon. In the second approach, the total charge $Q$ can be determined by summing over the charge collected by all pixels assigned to the X-ray photon. The total charge $Q$ is then used as a measure of the energy of the X-ray photon times the gas gain $G$ and divided by the ionization energy $W_I$.

The spatial width of the charge clouds is slightly asymmetric. This has two different reasons: for low energy X-rays the low number of electrons gives a larger weight to single electrons fluctuating during the diffusion process further from the center. For higher X-ray energies, also the track length of the photoelectron ejected from the atom contributes to the asymmetry, e.g. a 5 keV electron has a range of about 500 μm in