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A GridPix-based X-ray detector for the CAST experiment

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ABSTRACT

The CAST experiment has been searching for axions and axion-like particles for more than 10 years. The continuous improvements in the detector designs have increased the physics reach of the experiment far beyond what was originally conceived. As part of this development, a new detector based on a GridPix readout had been developed in 2014 and was mounted on the CAST experiment during the end of the data taking period of 2014 and the complete period in 2015. We report on the detector design, its advantages and the performance during both periods.

1. Introduction

The helioscope technique for searches of axions, axion-like particles, chameleons and similar particles is based on the idea of pointing a strong magnet towards the Sun. In the case of CAST [1,2] a prototype LHC dipole magnet with a length of 10 m and a magnetic field strength of $B = 9$ T is directed towards the Sun for 1.5 h during sunrise and 1.5 h during sunset. Background data is recorded during the rest of the day. If the aforementioned particles exist and are emitted by the Sun, a fraction of these would be converted into X-ray photons via the inverse Primakoff effect while traversing the magnetic field. X-ray detectors such as described in Refs. [3,4] at the end of the magnet record the energy spectrum of the photons during solar tracking and background measurements. By comparing the two spectra, an excess in the solar tracking data could be interpreted as discovery of a new particle.

Since the conversion probability is very low, the most important requirements on the detector are both a high detection efficiency and a good background suppression. Because of its composition and working principle a GridPix detector fulfills both requirements better than most other gaseous detectors: It consists of a pixelized readout chip, like the Timepix ASIC, in combination with a Micromegas stage (InGrid). The production of pillars and the mesh by photolithographic processes allows for a very good alignment of one mesh hole with each readout pixel. Each primary electron created in the X-ray conversion drifts towards the readout and enters in one mesh hole. The electron avalanche created subsequently in the gas amplification stage is collected mostly by a single pixel. Gas amplifications of $G_{\mathrm{MPV}} \approx 2200$ are generally chosen and have to be compared to readout thresholds of about 700 e. This allows for a close to 100 % detection efficiency of single primary electrons and thus of photon detection in general if more than three primary electrons are created in the X-ray conversion, i.e. for $E_\gamma > 100\,eV$. Background suppression can easily be done by comparing the topological features such as maximum length, eccentricity and kurtosis of each signal with a pure sample of X-ray signals created by a radioactive source or X-ray source [5]. The high granularity of the readout gives sufficient information for a high discrimination power. An example event of a 5.9 keV X-ray photon of a ^{55}Fe source is shown in Fig. 1.

An X-ray detector with a GridPix readout has been operated for one month in 2014 and a complete data taking period of 6 months in 2015. This detector is described in the following and its performance is reported.

2. The GridPix based X-ray detector

The detector developed for the CAST experiment uses a Timepix ASIC as readout and an InGrid structure as gas amplification.

2.1. The Timepix ASIC

The Timepix ASIC [6] is a pixelized readout chip. It features 256 × 256 pixels with a pitch of 55 μm, giving an active area of

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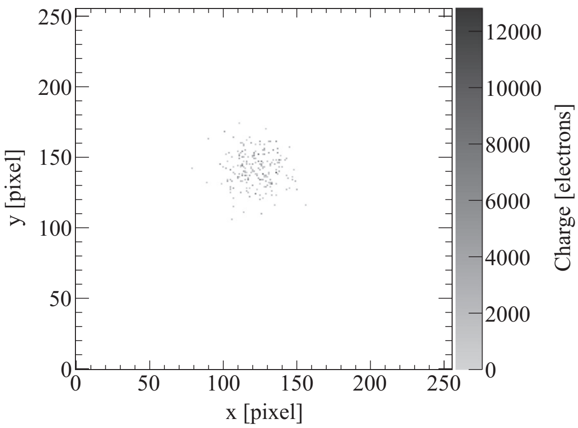

Fig. 1. Single 5.9 keV photon from an ^{55}Fe recorded with the GridPix-based X-ray detector. Each activated pixel represents a single primary electron, the circular shape is typical for X-ray photons and allows to discriminate other type of events like tracks originating for example from cosmic particles. Z-axis depicts charge collected on each pixel fluctuating according to the gas gain.

about 2 cm^2. Each of the pixels features a charge sensitive amplifier and a single-threshold discriminator connected to a counting logic. This allows for measuring either the charge collected on the pixel (time over threshold, TOT) or the arrival time of the charge (time of arrival, TOA) with respect to an external trigger signal.

When combined with a gas amplification structure the chip's pixels (bump bond pads) act as charge collecting anodes. The equivalent noise charge of each pixel is about 90 electrons, resulting in an effective threshold of 700–1000 electrons if the chip is to be operated quasi noise-free. The readout mode of the Timepix ASIC is not continuous but frame based.

2.2. InGrid – an integrated Micromegas stage

To make full use of the high granularity of a pixelized readout the gas amplification structure has to match the pixel size. A photolithographic production technique was pioneered in a collaboration of the University of Twente and Nikhef [7]. Meanwhile full eight-inch Timepix wafers can be equipped with InGrids in a single procedure at the Fraunhofer IZM in Berlin.

In order to protect the underlying electronics from discharges, a 4 μm thick resistive layer made of a mixture of silicon and nitrogen [8] is deposited on the chip's surface first. The Micromegas structure consists of a 1 μm thick metal grid resting on 50 μm high pillars made from a photoresist. Fig. 2 shows an SEM image of a GridPix where part of the grid has been removed revealing the underlying pillars and pixels of the Timepix ASIC.

2.3. Detector design

The design of the GridPix based X-ray detector for the CAST experiment is based on the design of the Micromegas detectors [3] which were already used in the CAST experiment. This decision was taken to avoid integration issues and to allow testing of the detector at already existing facilities of CAST. The detector mainly consists of a body made of acrylic glass which houses the readout module. It is closed by a copper cathode plate also holding the entrance window for the X-ray photons. Fig. 3 shows an exploded CAD view of the detector with main parts labeled.

2.3.1. Readout module

The GridPix is glued onto a small carrier board and electrically connected via wire bonds. The carrier board plugs onto the intermediate board connecting it to the readout system (see Section 3) via a VHDCI cable. Intermediate board, carrier board, some

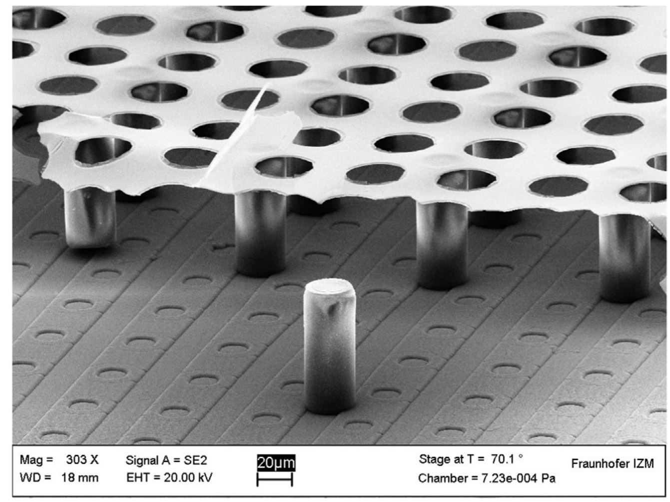

Fig. 2. SEM image [9] of an InGrid structure on top of a Timepix ASIC, produced at the Fraunhofer IZM at Berlin. A part of the aluminum grid has been removed to reveal the underlying pillars and ASIC. The surface of the ASIC is covered by a resistive layer of a few μm thickness.

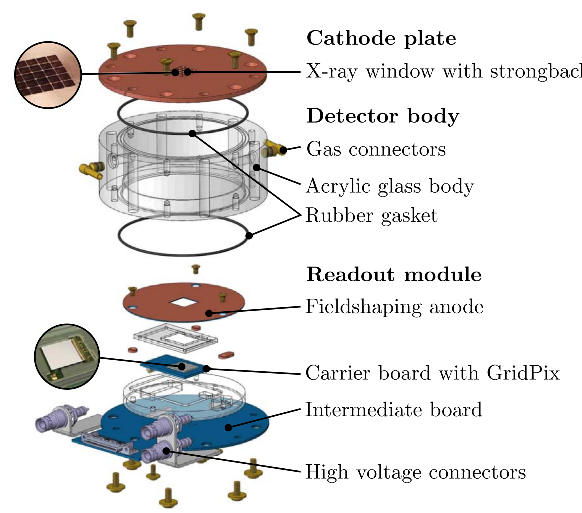

Fig. 3. CAD drawing showing an exploded view of the GridPix based X-ray detector. Embedded detail images show the strongback of the X-ray entrance window and the GridPix on the carrier board.

acrylic framing components and a field shaping anode form the readout module. The anode is made of a copper-clad glass fiber reinforced plate with a cutout above the active area of the GridPix. A high voltage potential applied to this electrode is determined by minimizing the field distortions at the transition between drift volume and GridPix.

2.3.2. Detector body

The acrylic glass detector body defines the drift length of 3 cm. It has an inner diameter of 7.8 cm and holds the gas connectors used to flush the detector with an Argon-based mixture using isobutane as quencher. For CAST, a mixture of Argon and 2.3 % isobutane is used. Due to safety considerations regarding flammability no higher isobutane fractions were allowed. The gas pressure in the detector is set to 1050 mbar and kept constant by a pressure regulator.

2.3.3. Cathode plate and X-ray entrance window

The 3 mm thick copper cathode plate is used to close the detector and to set the electric drift field of 500 V cm^{-1} . The entrance window for X-ray photons was realized by removing copper