InGrid Detectors for Rare & Low Energy X-Rays: Application in CAST

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7th Symposium on Large TPCs for Low Energy Rare Event Detection
Paris, 16/12/2014
Micromegas mounted on a pixel chip via photolithographic post-processing pioneered by U Twente & NIKHEF & CEA J. Schmitz, M. Chefdeville et al.

Pixel chip: Timepix
256x256 pixels (55x55 µm²) ~ 2 cm²
Typical threshold: 500 e⁻
InGrids: Wafer-based production

- transferred original single-chip process to a whole 8-inch wafer
- produce up to 107 InGrids at once at reasonable cost
- technologically difficult (e.g. SiN layer homogeneity)

Timepix Wafer

Fraunhofer IZM

universität bonn
InGrids as X-Ray detectors

- almost 100% single-electron efficiency
- diffusion in drift region → 1 primary electron per pixel →
  - electron-counting to measure energy
- no gain fluctuations
- optimal topological suppression of charged background
- alternative energy measure: total charge in all pixels

Optimization for E-resolution:

<table>
<thead>
<tr>
<th>Ar/iC₄H₁₀</th>
<th>U_grid / V</th>
<th>Gain</th>
<th>E_grid/E_drift</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>90/10</td>
<td>380</td>
<td>6346.1 ± 5.1</td>
<td>368</td>
<td>3.85% ± 0.06%</td>
</tr>
<tr>
<td>95/5</td>
<td>335</td>
<td>6069.8 ± 3.4</td>
<td>134</td>
<td>4.38% ± 0.05%</td>
</tr>
<tr>
<td>96/4</td>
<td>320</td>
<td>6122.0 ± 3.3</td>
<td>163</td>
<td>4.76% ± 0.06%</td>
</tr>
<tr>
<td>97/3</td>
<td>300</td>
<td>3735.5 ± 2.3</td>
<td>257</td>
<td>4.60% ± 0.05%</td>
</tr>
<tr>
<td>97.7/2.3</td>
<td>280</td>
<td>2381.5 ± 1.4</td>
<td>96</td>
<td>5.33% ± 0.04%</td>
</tr>
<tr>
<td>98/2</td>
<td>290</td>
<td>3493.8 ± 2.1</td>
<td>133</td>
<td>5.40% ± 0.06%</td>
</tr>
<tr>
<td>99/1</td>
<td>275</td>
<td>2053.7 ± 1.5</td>
<td>169</td>
<td>9.02% ± 0.10%</td>
</tr>
</tbody>
</table>

@5.9 keV

Table 9.1: Overview on the smallest energy resolutions achieved in the different gas mixtures with corresponding grid voltage and ratio of amplification and drift field.

Ar/Iso 90/10 \( \sigma_E/E = 3.9\% \) from pixel-counting

\[ \chi^2 / \text{ndf} = 171 / 30 \]

constant \( 1105 \pm 11 \)

mean \( 219.80 \pm 0.09 \)

sigma \( 8.67 \pm 0.10 \)
Motivation for InGrids at CAST

- axions
  - very low energy threshold $\ll 1$ keV
  - topological background suppression $\rightarrow$ replace CCD behind MPE X-ray telescope
  - potentially very low background

- chameleons
  - $E_{\text{m.p.}} \approx 3$ keV
  - $E_{\text{m.p.}} \approx 0.7$ keV
The CAST InGrid Detector
The CAST InGrid Detector

X-ray photon
The CAST InGrid Detector

X-ray photon
Gas atom
The CAST InGrid Detector

Gas atom
Photo electron
The CAST InGrid Detector

Primary electrons

$\sim 1 \text{ e}^-/26 \text{eV}$
The CAST InGrid Detector

Primary electrons
The CAST InGrid Detector

Diffused electron cloud
Setup in CAST

InGrid is here!
Setup in CAST
Setup in CAST
Noise? No

Out of 2379029 frames (0.98s) 1988773 frames look like this:
Noise? No

Out of 2379029 frames (0.98s) 1988773 frames look like this:

suitable for rare event searches...
Topological Background Rejection

Distinguish between signal (left) and background (right) using the shape of the pixel hit pattern

X-Ray (E=5.9 keV)

Cosmic track
Currently: 2 \( \mu \)m Mylar (aluminized) + Cu strong-back (copied from CAST MMs)
X-ray calibration at CAST detector lab
Calibration

Number of entries

0 50 100 150 200 250 300 350

Number of pixels

Copper K$_\alpha$ line (8048 eV)

preliminary
Calibration

Manganese Kα line (5898 eV)

Number of entries

Number of pixels

preliminary
Silver L$_{\alpha}$ line (2984 eV)
Calibration

Aluminium K$_\alpha$ line (1486 eV)

Number of entries

Number of pixels

preliminary
Calibration

Preliminary

Oxygen $K_{\alpha}$ line (525 eV)
Calibration

Carbon $K_{\alpha}$ line (277 eV)

Number of entries vs. Number of pixels

Preliminary
Ag (3 keV) photons
C (277 eV) photons
First data taking 2014

- Successful running in CAST in Oct/Nov 2014
- Detector operated without intermission for 27 days
- 2,379,029 frames of 0.98 s each have been recorded
- 27 sun trackings (data still blinded)

- Analysis of data is ongoing
- Preliminary background spectrum based on full data set (tuned for ~90% software efficiency)

- Using simple 3-variable likelihood with real X-rays as reference
Background events
Topological variables

reference (2.1 – 3.2 keV)

reference (<0.4 keV)

background
Location of BG events

fiducial cut on position of center corresponding to aperture of magnet focused by telescope
Background spectrum: 27 days

~ 27 days of data (excl 27 sun trackings)

Full lead shielding

preliminary
Background spectrum: 27 days

![Graph showing the background spectrum with rates in keV/cm²/s and energies in keV. The graph has a logarithmic scale for both axes. The data points are marked with error bars. The phrase "preliminary" is noted on the graph.]

Rate [keV/cm²/s]

Energy [keV]
Outlook: Grid signal readout

5.9 keV photon:

Perpendicular cosmic track:

Run0 Event 19

Event No 83

ConvertedFADCulses-19-3

FADC Pulse No. 83

Timepix signal

Induced pulse on the grid
Outlook: TimePix-3

Timepix-3 chip available not equipped with InGrid

- fully data-driven readout
- 640 MHz timing clock
- simultaneous readout of charge (TOT) and time per pixel (TIME)
  → full 3D reconstruction of charge cloud possible
  → improved background rejection for $\perp$ cosmics
Outlook: Larger Areas

8-chip InGrid boards existing (Octopuce/Saclay, Octoboard/Bonn) Challenge (for X-ray detector):
- dead areas between chips
- field distortions

promising but better procedure needed...
Summary & Conclusion

- InGrid as low-energy X-Ray detector employed in CAST experiment
- first data taking successful
- sensitivity down to ~200 eV
- perfect stability over many weeks
- data analysis ongoing, sun trackings still blinded
- background rates look promising (optimization still possible)
- several ideas for further improvement towards
  - CAST run in 2015 (short term)
  - IAXO (longer term)
The group in Bonn

Christoph Krieger
Jochen Kaminski
Yevgen Bilevych
Michael Lupberger

Many thanks to the great CAST collaboration for all their support and for accepting us as „late comers“
Photon absorption in 3cm Ar

Absorption vs. Energy [keV]

Energy [keV] 0 1 2 3 4 5 6 7 8 9 10
Absorption 1.0 0.8 0.6 0.4 0.2 0.0
Backup

Detector operational parameters:

$U_{\text{grid}} = 295 \, \text{V}$
$E_{\text{drift}} = 500 \, \text{V/cm}$
$l_{\text{drift}} = 3 \, \text{cm}$
Gas Ar/Isobutane 97.7/2.3
gas gain $\sim 2400$
threshold: $1000 \, \text{e}^-$
$\sigma_E/E \approx 6\% \, @ \, 5.9 \, \text{keV}$
Energy bins for likelihood

<table>
<thead>
<tr>
<th>low [keV]</th>
<th>high [keV]</th>
<th>line</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.4</td>
<td>C K-alpha</td>
</tr>
<tr>
<td>0.4</td>
<td>0.7</td>
<td>O K-alpha</td>
</tr>
<tr>
<td>0.7</td>
<td>1.2</td>
<td>Cu L-alpha</td>
</tr>
<tr>
<td>1.2</td>
<td>2.1</td>
<td>Al K-alpha</td>
</tr>
<tr>
<td>2.1</td>
<td>3.2</td>
<td>Ag L-alpha</td>
</tr>
<tr>
<td>3.2</td>
<td>4.9</td>
<td>Ti K-alpha</td>
</tr>
<tr>
<td>4.9</td>
<td>6.9</td>
<td>Mn K-alpha</td>
</tr>
<tr>
<td>6.9</td>
<td></td>
<td>Cu K-alpha</td>
</tr>
</tbody>
</table>
InGrids: Photon feedback and cross talk

Figure 9.2: Dependence of the number of pixels over threshold in the photo peak on the grid voltage $U_{\text{grid}}$ (a) and the gas gain (b) for different Ar/iC$_4$H$_{10}$ mixtures. All error bars are inflated by a factor of 100.
Background spectrum: 27 days

Rate \left[10^4 / \text{keV/cm}^2/\text{s}\right] vs. Energy \left[\text{keV}\right]

preliminary
Background spectrum: 27 days

horizontal lines: bins for reference distributions