Tracking Detectors for X-rays

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Abstract

X-rays are normally detected as single-hit energy deposits at their absorption point. A different technique, combining high efficiency photon to charge converters and fine-pitch, highly granular readout matrices of low-noise pixels with integrated smart amplifiers, can effectively track the low energy electrons resulting from the photon interaction, thus revealing details of the Compton scattering or the photo-electric absorption.

Gas Pixel Detectors, which have enabled efficient polarimetry of soft X rays for the IXPE and Polarlight satellite missions are the first class of such devices. They are based on the XPOL custom readout ASIC built in CMOS technology coupled to a Gas Electron Multiplier for amplification of the primary photoelectrons generated in the gas. This talk reviews the concept underlying this method and its most promising implementations, starting from the advances offered by the latest generation of the XPOL chip.
Fermi LAT
16 Tracker modules
2008

~ $7 \times 10^5 \text{cm}^2$ silicon active area
900k digital channels
40cm x 200\text{\textmu}m single channel dimensions
~100 Kg mass
~100 W power

IXPE
3 Detector Units
2021

~ $7 \text{cm}^2$ silicon active area
400k analog channels
50\text{\textmu}m^2 single channel dimensions
~1Kg mass
~1W power
Tracking X-rays with Gas Pixel Detectors

GPD

XPOL ASIC

Single Event Display
Tracking X-ray photons as single events requires:

- A reasonably efficient photon to charge converter
- A sensor (or amplifier) providing $O(10^4)$ electrons
- A highly efficient, asynchronous, auto trigger
- A high density array of charge collecting anodes
- A distributed network of low-noise charge amplifiers
- A fast and configurable digital control readout to transfer data and clear the detector
- Good reconstruction algorithms
Electron multipliers

Gas Electron Multiplier (GEM)
- LCP GEM qualified for space (SciEnergy)
- GEM wet-etched (Techtra, CERN)
- GEM dry-etched (new R&D)

Capillary plates
- Demonstrated to work but far from being qualified

Mostly relevant for amplification of the primary charge in gas - no more info on this topic in this talk
The XPOL ASICs family - a 20+ years development

Four generations of increasing size, reduced pitch, improved functionality

- First VLSI implementations
- XPOL-I, largest scale
  - Operating onboard Polarlight and IXPE
- XPOL-III, ~10x faster readout
  - Ready to fly on eXTP

References
1. ASIC-I, 2004, NIM-A 535
2. ASIC-II 2006, NIM-A 560
3. XPOL-I 2006, NIM-A 566
4. XPOL-III, 2023, NIM-A, 1046
5. PolarLight, 2019, Exp. Astronomy 47
6. IXPE, 2022 JATIS, 8, 2
XPOL chip layout and single pixel front-end chain

CMOS VLSI chip built with 180nm technology

- 16M+ transistors
- 105k hexagonal pixels (300x352)
- 15mm² - 470 pixel/mm² density

Each pixel contains

- Hexagonal metal top layer
- Charge sensitive amplifier
- Shaping circuit
- multiplexer
XPOL - electrical properties and typical S/N

1V dynamic range

Typical noise ~10 ADC counts / ~30 electrons

Typical pixel signal O(1000) ADC counts/pixel

5.9 KeV X-rays tracks at normal operating conditions peak at 20k ADC cts
XPOL-I Trigger and readout primitives

2x2 pixels mini-clusters

- Trade-off between signal (coherent noise sum) and noise (incoherent sum)
- Threshold is defined by the user

Region of Trigger

All triggered mini-clusters

Region of Interest

<Xmin, Ymin> - <Xmax, Ymax> around all triggered mini-clusters + padding

Padding

- +4 mini-clusters in X (400 um)
- +5 mini-clusters in Y (430 um)
XPOL-I Region Of Interest

Typical ROI around triggered mini-clusters requires a relatively large padding to capture initial part of the track.
XPOL - considerations about Padding

ROI dimension drives event readout time

- ~600 pixels evt readout at 5MHz needs 120usec
- ROI should be ideally minimized around track

NOTE: actual deadtime for XPOL-I on IXPE is higher and ~1ms because of

- event-by-event pedestal subtraction (2x)
- System internal delays
  - Most notably Sample & Hold reset to allow pedestal readout (500usec)

But padding (ie no signal) pixels are useful to measure trigger threshold by measuring PH distribution endpoint
Moving to XPOL-III

Project goal was to readout ~10x faster to match eXTP mirrors effective area

XPOL-III ASIC implementation relies upon

- Same design center and production technology to preserve heritage
- 2x faster clock - 10 MHz
- 10x faster recovery from hold - 50 µsec
- Flexible ROI definition to reduce event readout time
- Trigger mask available for single pixel
XPOL-III The role of padding

Lower trigger threshold confines track inside ROT

Flexible padding configuration minimizes readout time
XPOL-III readout time

\[ \approx 150 \mu \text{sec} \] (vs \( \approx 1 \text{ms} \) XPOL-I) from faster clock, smaller padding, minimized delays in the readout
Spectral and polarization performance

Pure Be window eliminates low energy tail

Modulation factor and azimuthal asymmetry as known
New directions - *tracking* X-rays with solid state devices

Basic advantage: a single technology for ASIC and sensor - however

- $W_{\text{gas}} \sim 30\text{eV}$ vs $W_{\text{Si}} \sim 3\text{eV}$ → no need for amplification with Si!
- $\lambda_{\text{gas}} \sim 100\ \mu\text{m}$ vs $\lambda_{\text{Si}} \sim \mu\text{m}$ → ~point interaction

Tracking therefore becomes essentially spectral imaging.

Implementation details critical to determine possible applications - two directions

- Hybrid: replace gas gap with external silicon sensor
- Monolithic: grow sensor directly onto ASIC
Demonstration of monolithic approach with commercial device


- Sony IMX291 CMOS sensor
- 4144x2822 pixels (4.63 $\mu$m)
- 10% efficiency @ 6KeV (after glass removal)

- manufacturing technique induces large dead areas
- optical filters reduce efficiency
Performance of commercial devices

Energy resolution (FWHM) ~2.2% @ 6KeV (comparable to state of the art SDD)

excellent imaging power - Counting mode - no single event tracking concept

Intensity scaled to overcome poor CMOS efficiency and dead areas

Polarized beam through Bragg diffraction
Expected response with hybrid device based on XPOL-III

- Single photon sensitivity
- ~3% energy resolution at 8KeV
- auto-trigger


Realistic simulation assuming 20e noise per pixel, charge sharing and threshold effects
Drivers for a new generation of custom ASIC

Further developments in the work towards:

- larger geometrical acceptance → replace planar wire-bonding with Through-Silicon-Vias connections to allow tiling of hybrid detectors
- faster readout → exploit ROI padding, add internal ADCs for parallel readout, increase readout clock
- Increased compactness → monolithic active pixels

All such developments are the subject of different proposals recently submitted to INFN, MUR and ASI
Final remarks

Tracking single events with high sensitivity detectors, as performed for charged particles, was made possible for KeV photons in gas, enabling X-ray polarimetry.

Highly customized pixel geometry and trigger / readout scheme of front-end ASICs was key to achieve the necessary noise and rate performance.

Future developments will rely on further customization of the readout, more direct front-end - sensor interconnection and minimization of dead areas at the periphery.

Gas remain the best option for tracking morphology of single events within converter.

Access to commercial CMOS foundries offering advanced customization programs will be key for the next-generation of X-ray detectors, e.g. large area X-ray spectral imagers.
Acknowledgements

Contributing Teams

- INFN Torino and University of Torino: M. Aglietta, R. Bonino, N. Cibrario, L. Latronico, S. Maldera, S. Tugliani
- INFN Pisa and University of Pisa: R. Bellazzini, L. Baldini, M. Minuti, C. Sgro, G. Spandre

Financial support from

- INFN
- ASI (Agreements IXPE-2017.13-H.0, ADAM-2018.11-HH.0, eXTP-2020-3.HH.0)
- University of Torino (Grant XCF-2020)
BACKUP
XPOL-I radiation hardness for space qualification

Tested for Single Event Effects with multiple ions at different LET

- No SEL on the ASIC
- SEU x-section $< 10^{-13}/s$

Total dose effects after 500Krad

- Marginal noise increase
- No loss of functionality
- No loss of linearity
- Stable energy resolution

![Graphs showing SEU on ASIC memory registers and SEU in ASIC pedestal scan]
Bragg scattering polarizer and energy dependence

Polarization by Bragg diffraction at 45°

\[
\sin(\theta_{\text{Bragg}}) = \frac{\Phi}{n \hbar c}
\]

Polarization degree:

\[
P = \frac{1 - k}{1 + k}
\]

With:

\[
k = \frac{R \pi}{\sigma}
\]

for \( \theta_{\text{Bragg}} \approx 0 \)

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<th>Anode line</th>
<th>E [KeV]</th>
<th>Xtal</th>
<th>2d (A)</th>
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Energy resolution vs imaging power - Bragg scattering *spectrometer*

Rh-Ge111: energy-position

As expected different energies are diffracted at different angles
Example with commercial devices from X-ray beam monitors

Silicon Drift Detector: give up tracking and imaging, ~easily collect charge on large sensor.

Emphasis is on minimizing electronics noise to enhance S/N.

- 25 mm² active area
- Resolution of 122 eV FWHM at 5.9 keV ~2%
- Count rates > 1,000,000 CPS
- Windows: Be 12.5 μm