# Tracking Detectors for X-rays

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## Outline

Tracking X-rays

- An example from astrophysical polarimetry

ASIC for X-rays

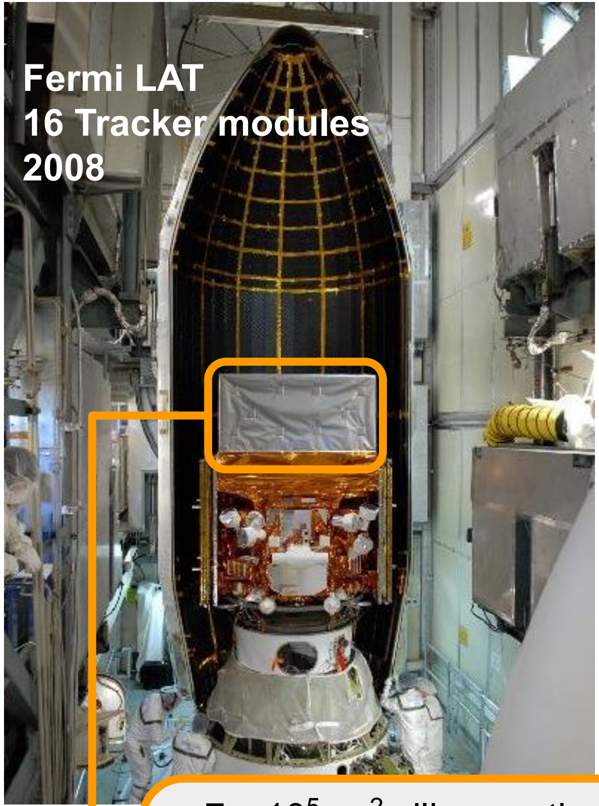
- The XPOL family of chips

Upcoming trends

- Solid state devices and new ASICs


## 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*

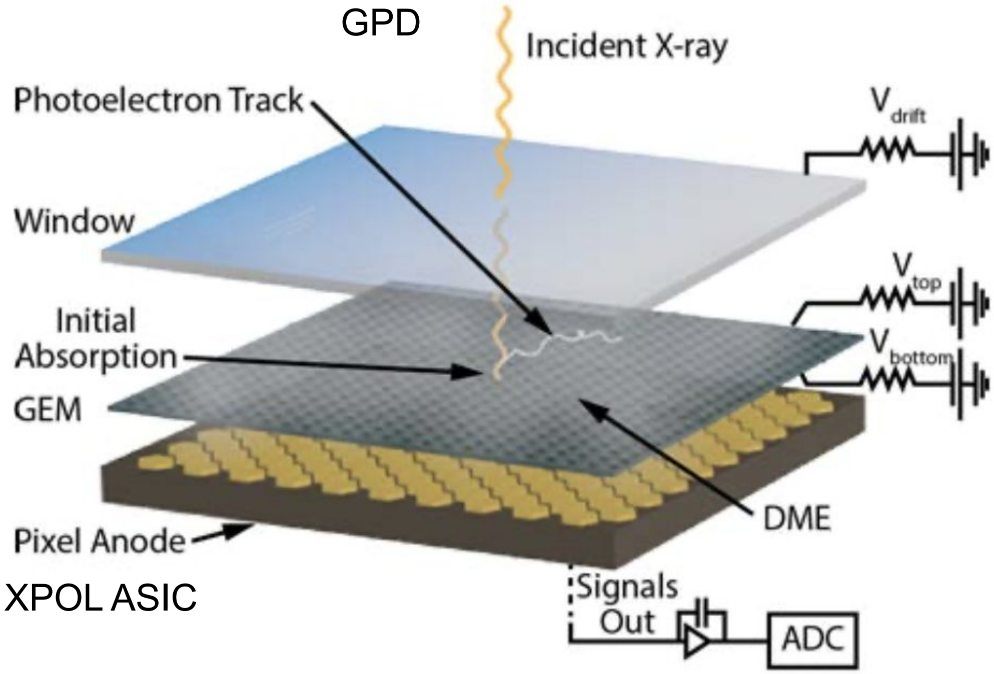


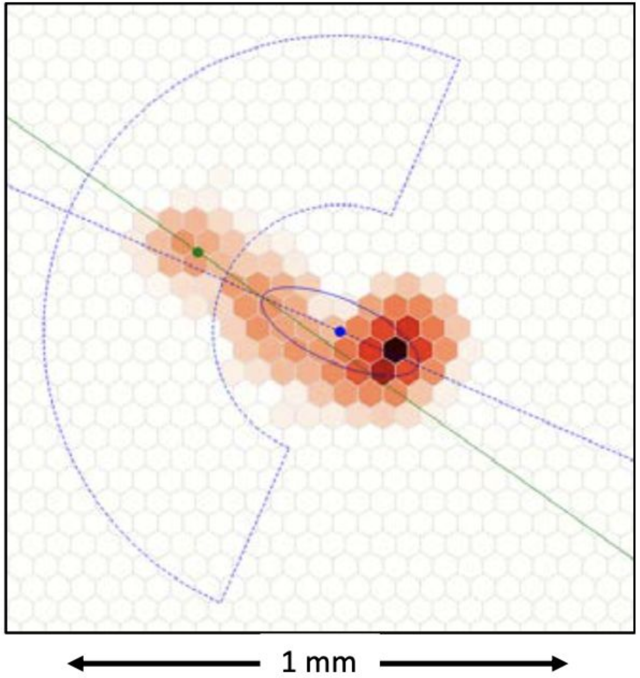


~ 7 x $10^5$cm$^2$ silicon active area
900k digital channels
40cm x 200μm single channel dimensions
~100 Kg mass
~100 W power

~ 7 cm$^2$ silicon active area
400k analog channels
50μm$^2$ single channel dimensions
~1Kg mass
~1W power

# Tracking X-rays with Gas Pixel Detectors




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

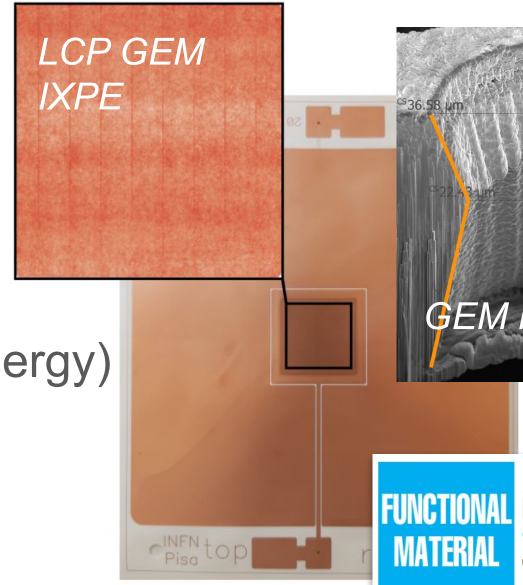
Gas Electron Multiplier (GEM)

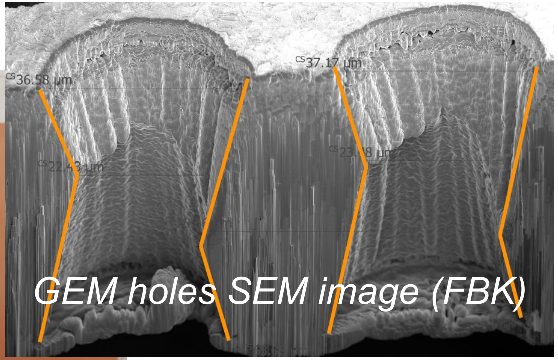
- LCP GEM qualified for space (SciEnergy)
- GEM wet-etched (Techtra, CERN)
- GEM dry-etched (new R&D)

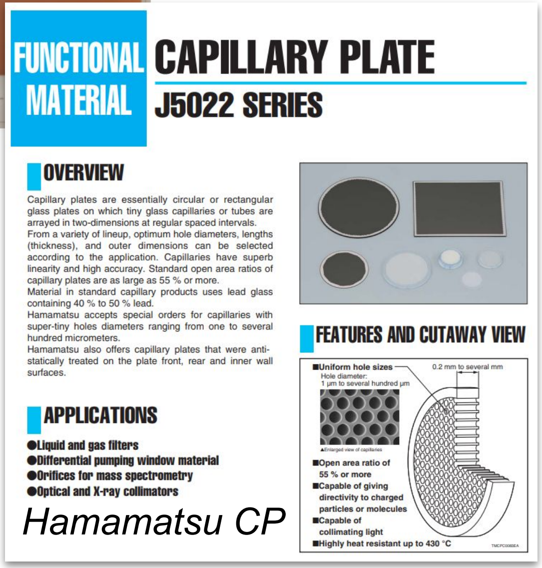
Capillary plates

- 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





FUNCTIONAL MATERIAL

CAPILLARY PLATE

J5022 SERIES

OVERVIEW

Capillary plates are essentially circular or rectangular glass plates on which tiny glass capillaries or tubes are arrayed in two-dimensions at regular spaced intervals.
From a variety of lineup, optimum hole diameters, lengths (thickness), and outer dimensions can be selected according to the application. Capillaries have superb linearity and high accuracy. Standard open area ratios of capillary plates are as large as 55 % or more.
Material in standard capillary products uses lead glass containing 40 % to 50 % lead.
Hamamatsu accepts special orders for capillaries with super-tiny holes diameters ranging from one to several hundred micrometers.
Hamamatsu also offers capillary plates that were anti-statically treated on the plate front, rear and inner wall surfaces.

APPLICATIONS

- Liquid and gas filters
- Differential pumping window material
- Orifices for mass spectrometry
- Optical and X-ray collimators

FEATURES AND CUTAWAY VIEW

- Uniform hole sizes
  Hole diameter: 1 µm to several hundred µm
- Open area ratio of 55 % or more
- Capable of giving directivity to charged particles or molecules
- Capable of collimating light
- Highly heat resistant up to 430 °C

0.2 mm to several mm

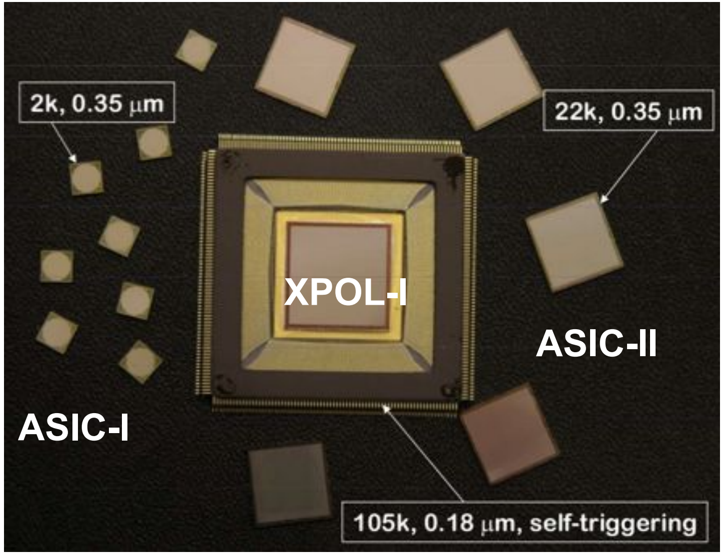
▲Enlarged view of capillaries

Hamamatsu CP

# The XPOL ASICs family - a 20+ years development

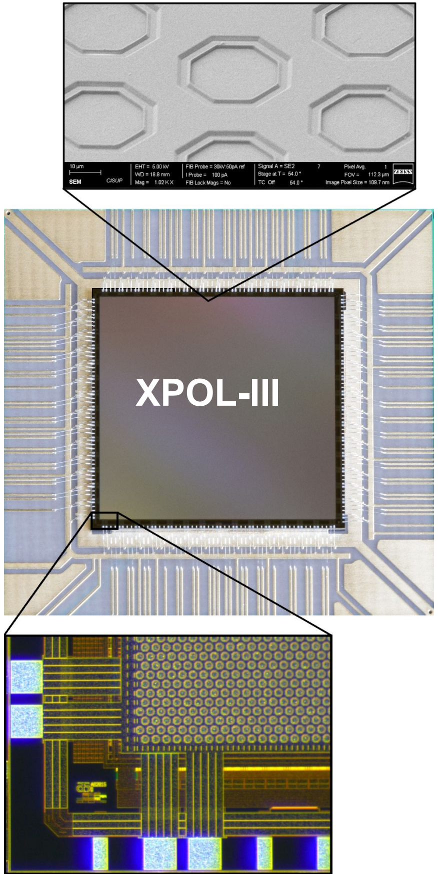
Four generations of increasing size, reduced pitch, improved functionality

- 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
7. eXTP, 2019, Sci. China Phys. Mech. Astron. 62

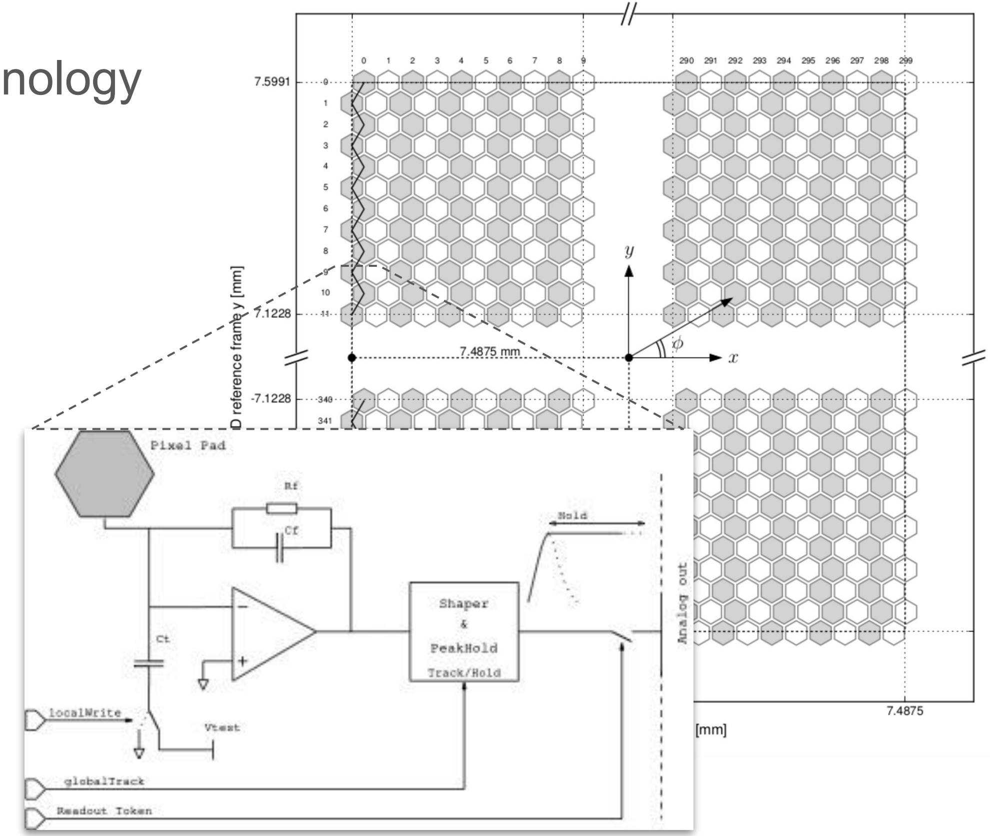
# XPOL chip layout and single pixel front-end chain

CMOS VLSI chip built with 180nm technology

- 16M+ transistors
- 105k hexagonal pixels (300x352)
- 15mm$^2$ - 470 pixel/mm$^2$ density

Each pixel contains

- Hexagonal metal top layer
- Charge sensitive amplifier
- Shaping circuit
- multiplexer



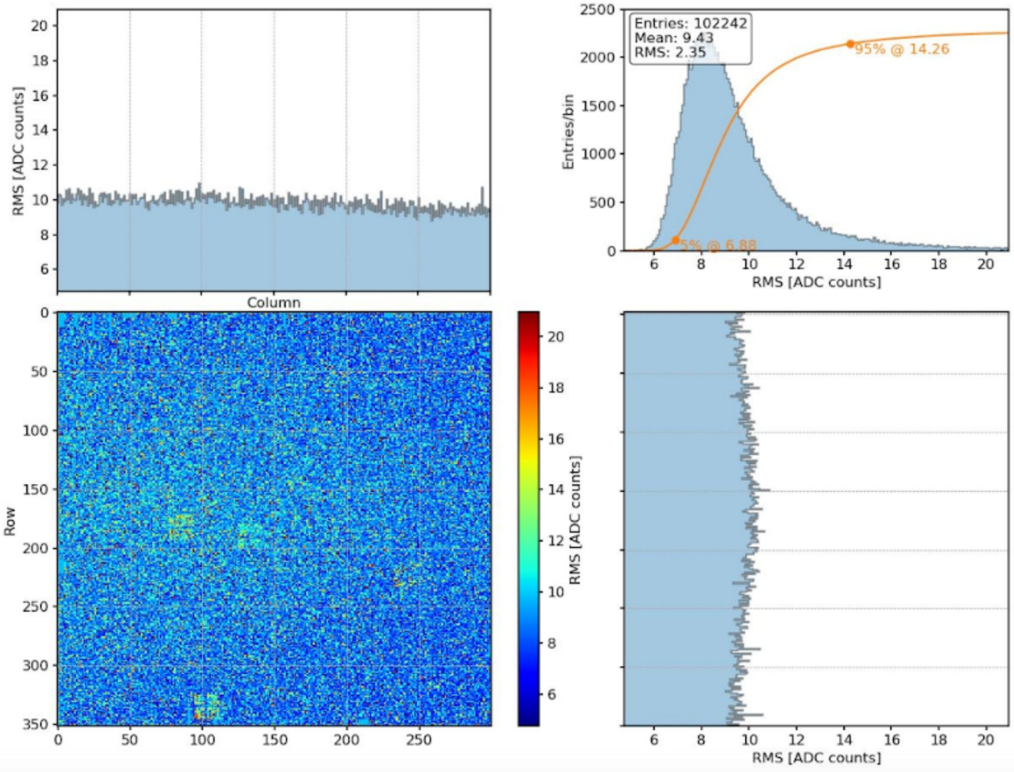
# XPOL - electrical properties and typical S/N

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*

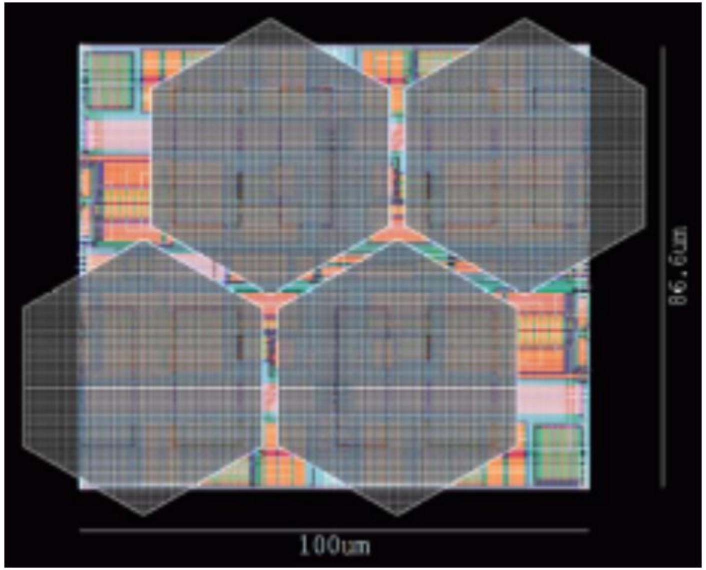
All triggered mini-clusters

*Region of Interest*

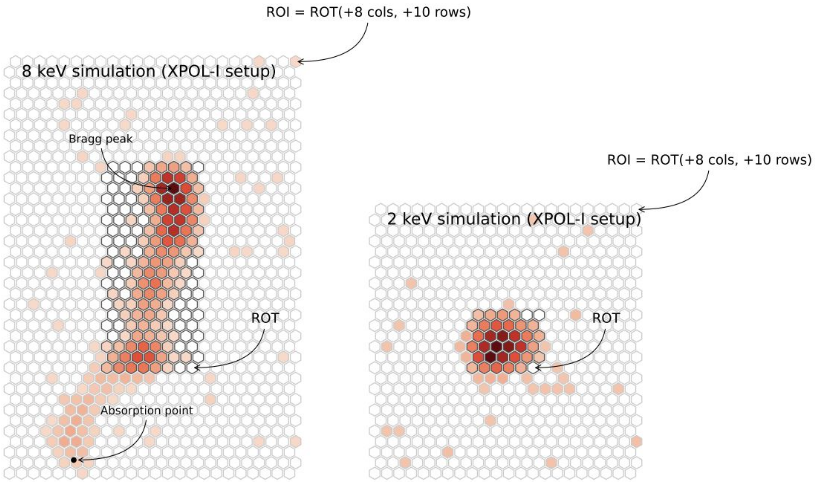
<Xmin,Ymin> - <Xmax, Ymax> around all triggered mini-clusters + padding

*Padding*

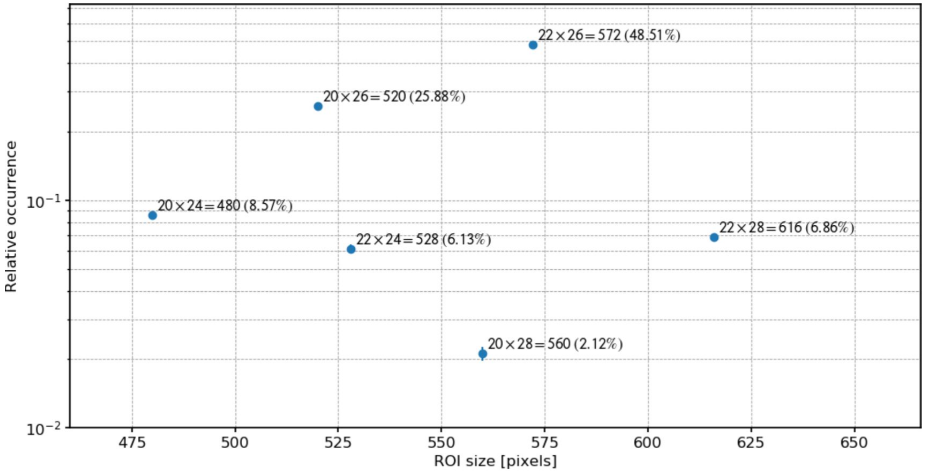
- +4 mini-clusters in X (400 um)
- +5 mini-clusters in Y (430 um)



# XPOL-I Region Of Interest




Distribution of ROI sizes for 2.7KeV X-rays




Typical ROI around triggered mini-clusters requires a relatively large padding to capture initial part of the track

# XPOL - considerations about Padding

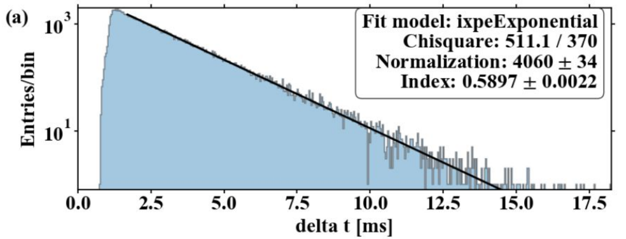
ROI dimension drives event readout time

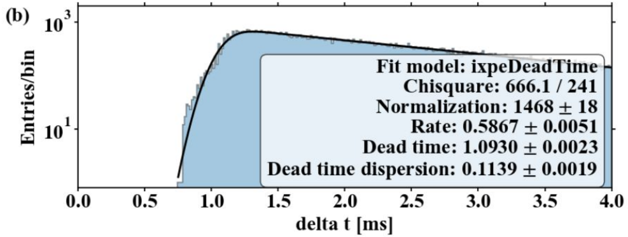
- ~600 pixels evt readout at 5MHz needs 120usec
- ROI should be ideally minimized around track

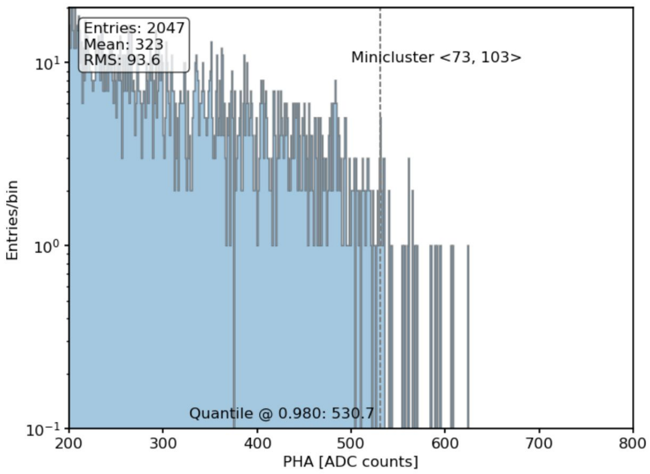
NOTE: actual deadtime for XPOL-I on IXPE is higher and ~1ms because of

- 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



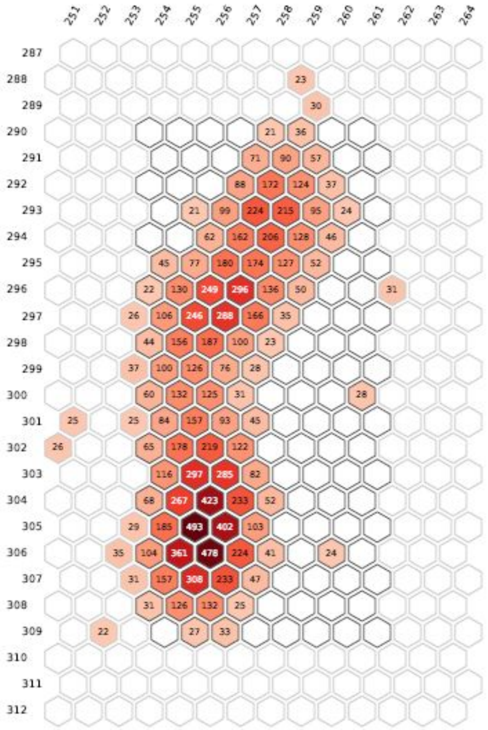
# Moving to XPOL-III

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

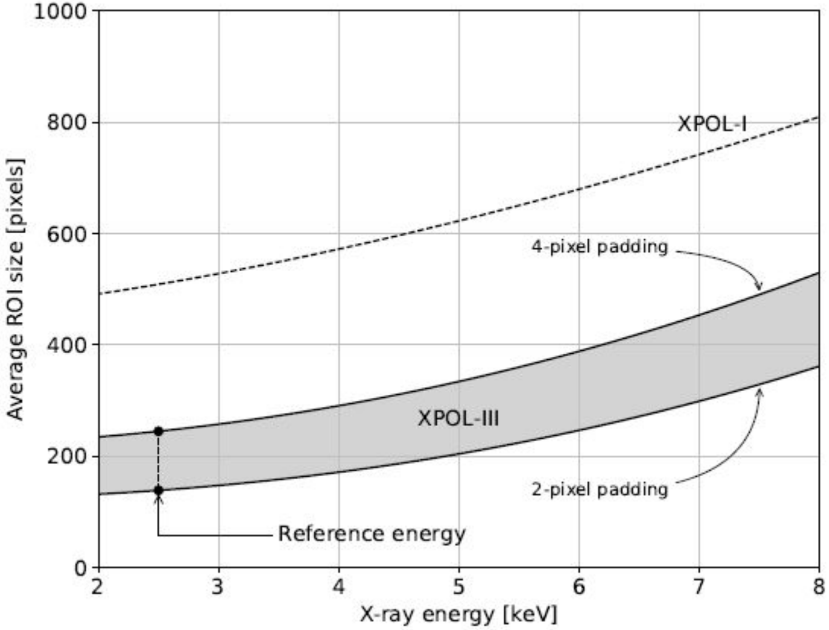
XPOL-III ASIC implementation relies upon

- 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

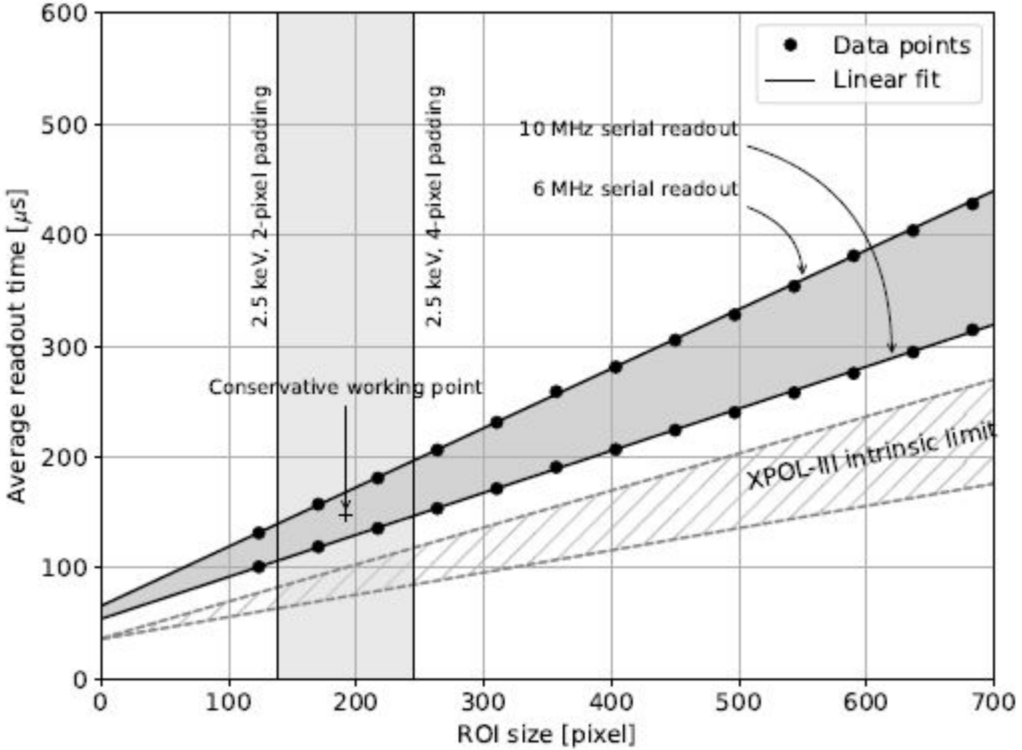


Lower trigger threshold confines track inside ROT



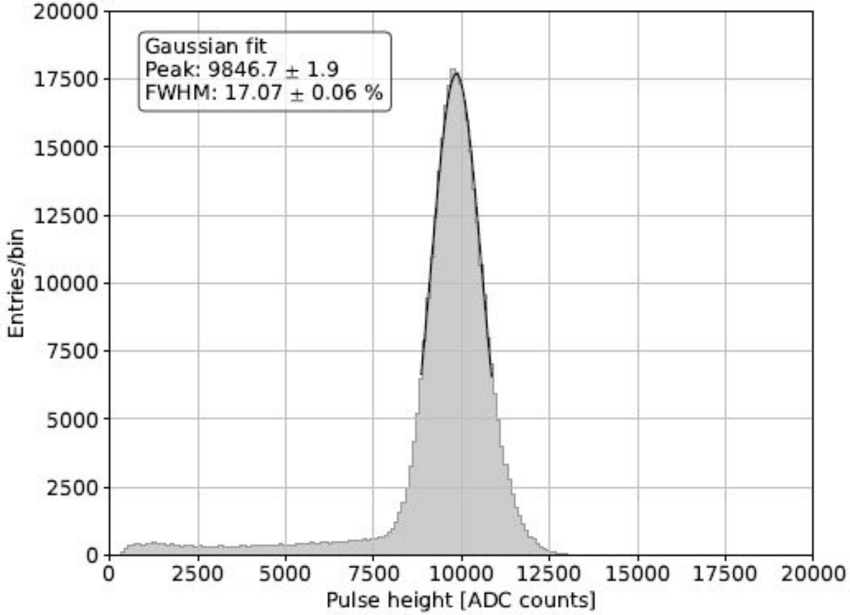

Flexible padding configuration minimizes readout time

# XPOL-III readout time

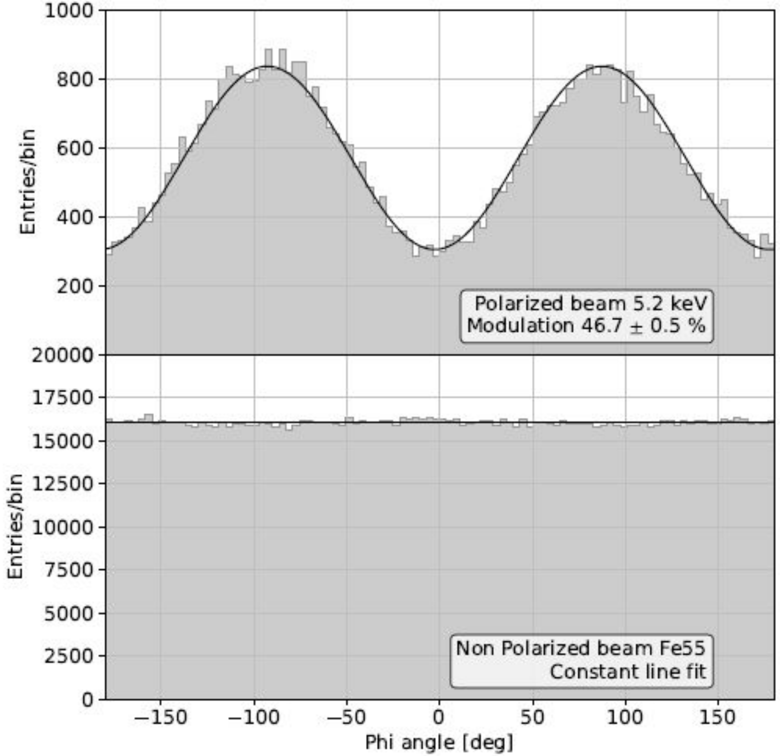



~<150μsec (vs ~1ms XPOL-I) from faster clock, smaller padding, minimized delays in the readout

# 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

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

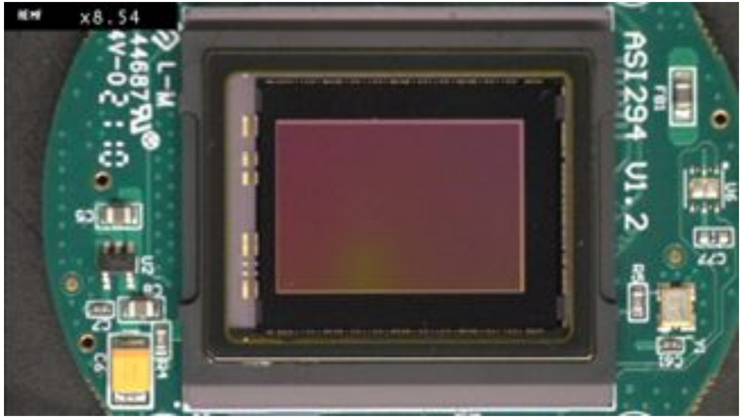
Tracking therefore becomes essentially spectral imaging.

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

Amateur astro-camera for X-ray beam monitoring (following 2018, Rev. Sc. Instr. 89,9)



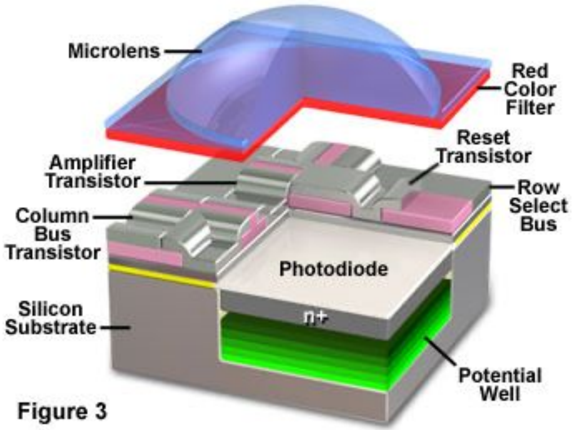




Figure 3

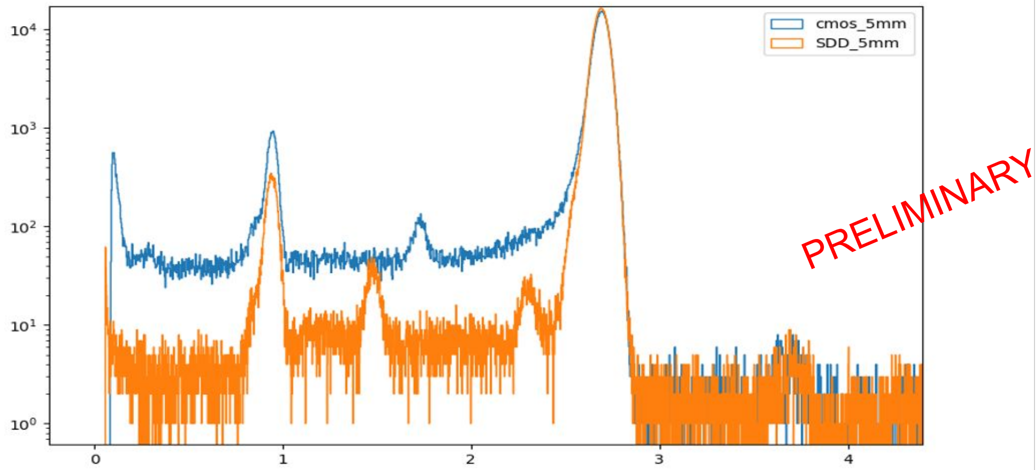
- Sony IMX291 CMOS sensor
- 4144x2822 pixels (4.63 $\mu$m)
- 10% efficiency @ 6KeV (after glass removal)

- manufacturing technique induces large dead areas
- optical filters reduce efficiency

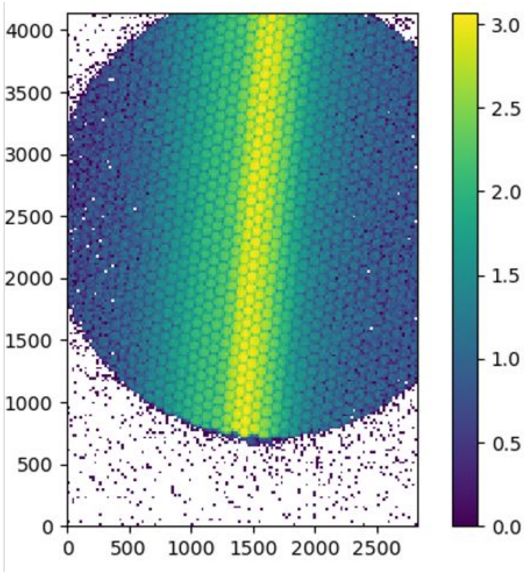
# Performance of commercial devices

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

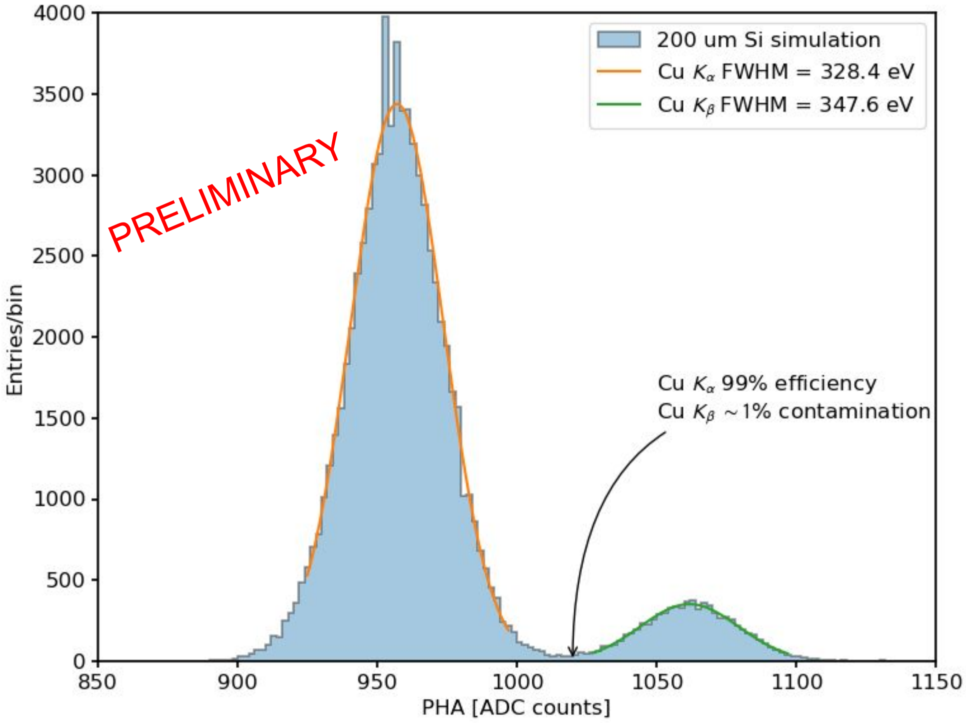


Polarized beam through Bragg diffraction

# Expected response with hybrid device based on XPOL-III

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

Addressing NASA Technology Gap of *Fast, Low-noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution* - see [https://apd440.gsfc.nasa.gov/tech_gaps.html](https://apd440.gsfc.nasa.gov/tech_gaps.html)




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

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- INFN Pisa and University of Pisa: R. Bellazzini, L. Baldini, M. Minuti, C. Sgro, G. Spandre

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- University of Torino (Grant XCF-2020)

# BACKUP

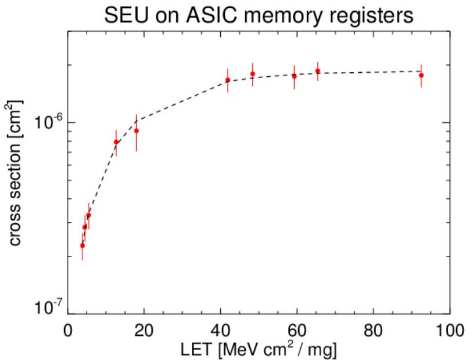
# XPOL-I radiation hardness for space qualification

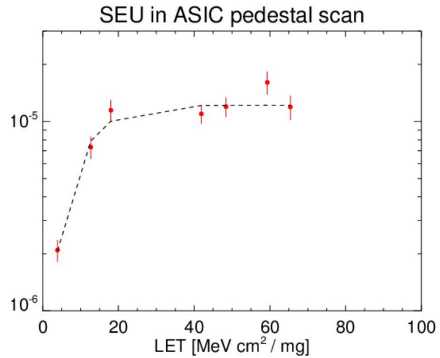
Tested for Single Event Effects with multiple ions at different LET

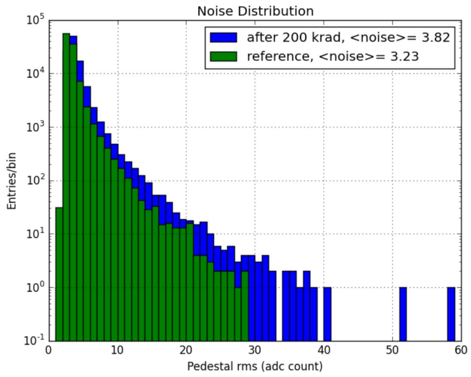
- No SEL on the ASIC
- SEU x-section < $10^{-13}$/s

Total dose effects after 500Krad

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

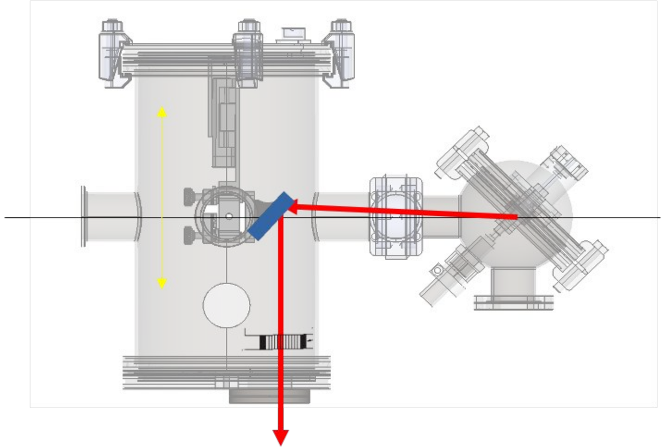


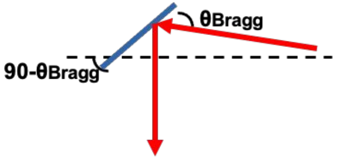



# Bragg scattering polarizer and energy dependence

**Polarized beam**



selecting vertical output with capillary plate, the geometry is fixed




Polarization by Bragg diffraction at 45°

$sin(\theta_{Bragg})$

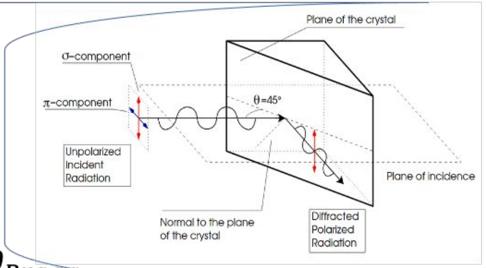
$nhc$

Polarization degree:

$$\mathcal{P} = \frac{1-k}{1+k}$$

With:

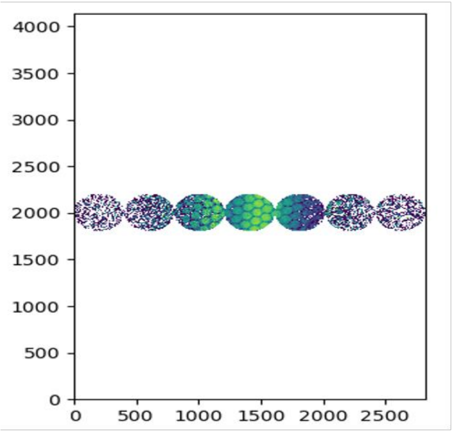
$$k = \frac{R^{\pi}}{R^{\sigma}} \approx 0$$ for $$\theta_{Bragg} \approx 0$$



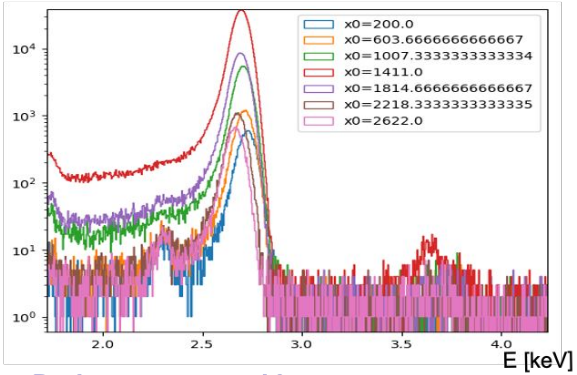

| Anode line | E [KeV] | Xtal | 2d (A) | θBragg | P |
|---|---|---|---|---|---|
| Mo Lα | 2.2932 | InSb111 | 7.481 | 46.28 | 99.32% |
| Rh Lα | 2.697 | Ge111 | 6.532 | 44.87 | 99.28% |
| Pd Lα | 2.839 | Si111 | 6.271 | 44.12 | >95.08% |
| Ti Kα | 4.511 | Si 220 | 3.840 | 45.71 | 99.51% |
| Fe Kα | 6.404 | Si 400 | 2.7142 | 45.5 | 99.7% ?? |
| Ni kα | 7.478 | Ge 422 | 2.31 | 45.86 | 99.04% |

# Energy resolution vs imaging power - Bragg scattering *spectrometer*

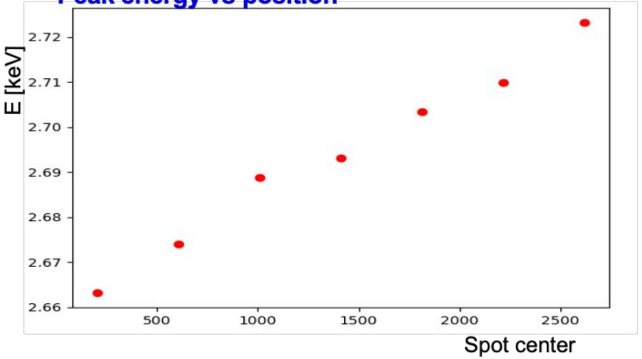
**Rh-Ge111: energy-position**




As expected different energies are diffracted at different angles




**Peak energy vs position**



# 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 $mm^2$ active area
Resolution of 122 eV FWHM at 5.9 keV ~2%
Count rates > 1,000,000 CPS
Windows: Be 12.5 µm