X-ray Polarimetry Detectors

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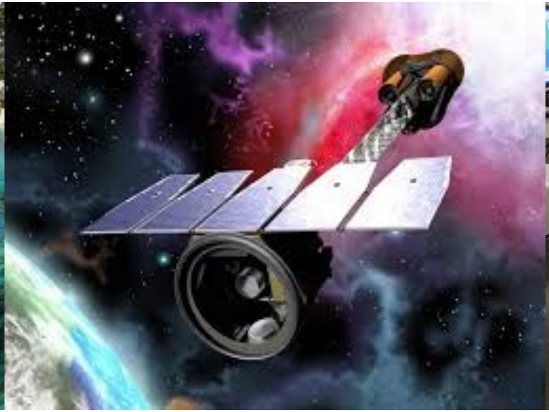
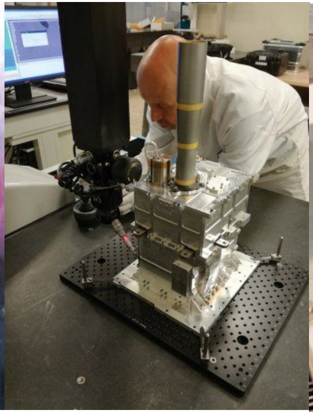
Outline

- Motivation - X-ray polarimetry in astrophysics
- Technology - the Gas Pixel Detector and the IXPE mission
- Laboratory - activities sneak peek

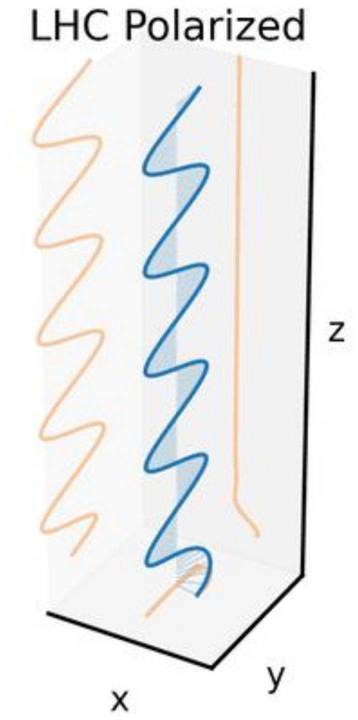

The importance of polarimetry in astronomy

Photons at all wavelength are ideal probe in astronomy as the carry information of

- Impact point → sky maps
- Energy → spectra
- arrival time → dynamics and transport

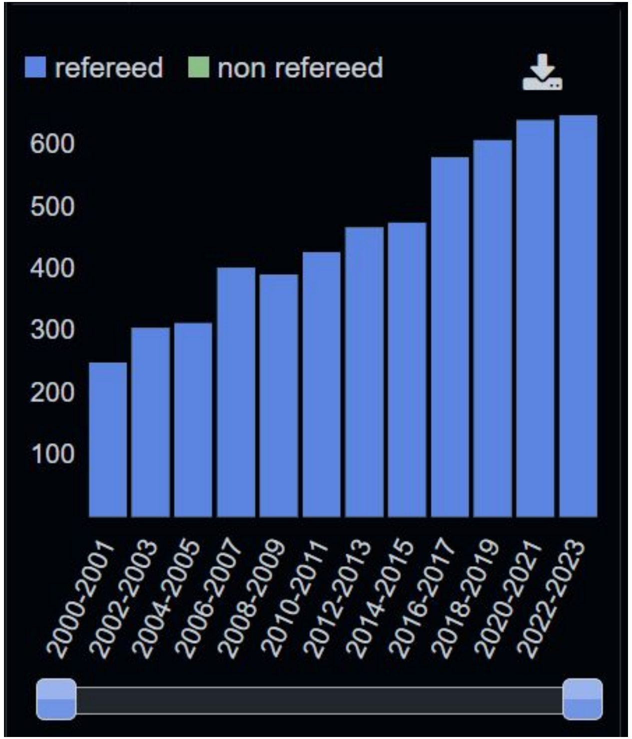
Besides these *obvious* information, polarization provides information on

- Emission processes → synchrotron, non-thermal bremsstrahlung, Inv Compton
- Source geometry → scattering with surrounding medium
- Transport processes and fundamental physics → LIV, ALP

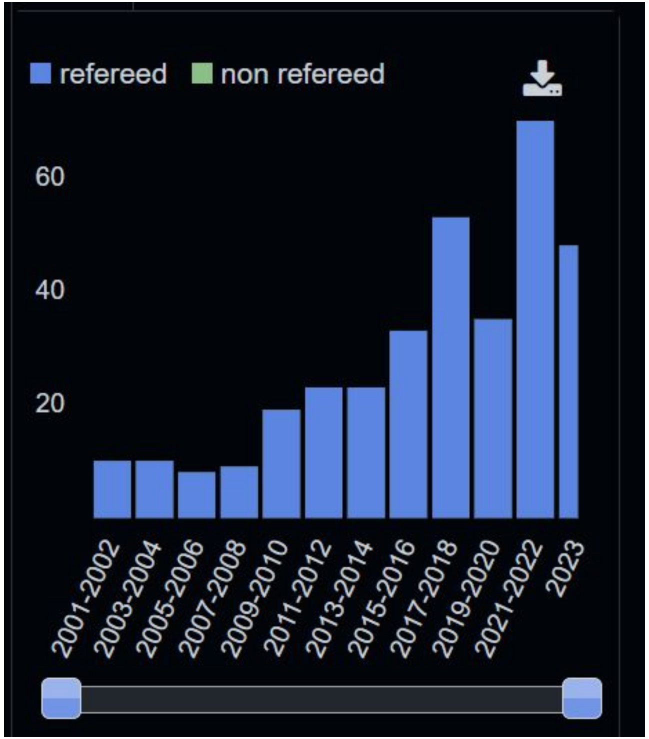


% polarization on Wikipedia

Polarimetry in astronomy (NASA ADS)



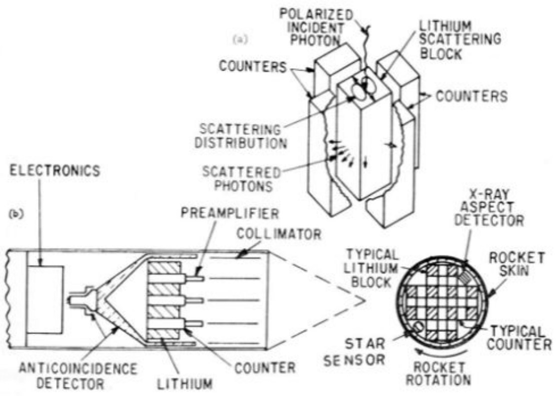
5.5k abstracts with *polarimetry*, rising trend

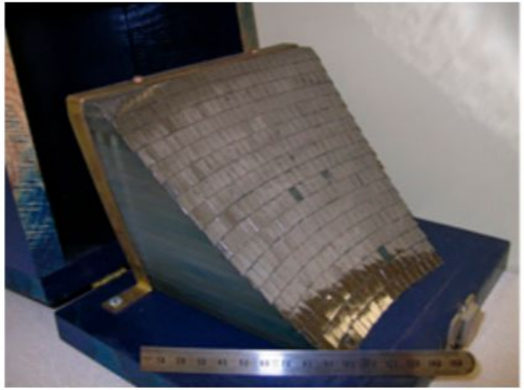


341 abstracts with *X-ray polarimetry*, peak in 2022

Astrophysical X-ray polarimetry primer

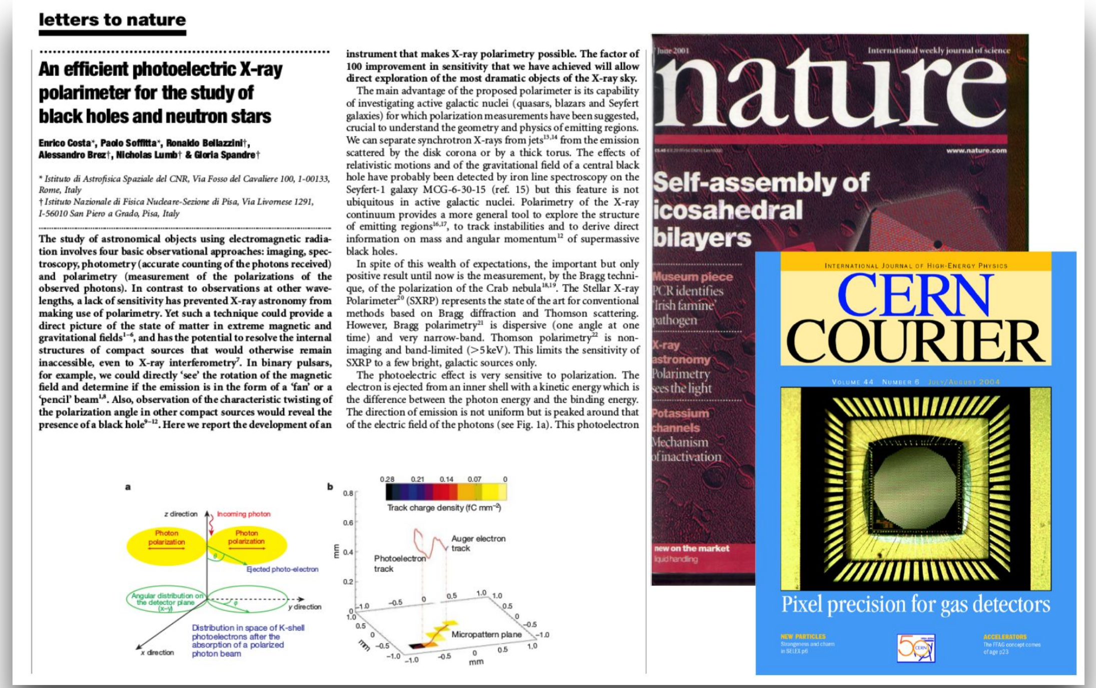
Limited to the historical OSO-8 measurement (1970s) until IXPE for lack of sensitive instruments.





Check-out a brief history of the field at Weisskopf, Galaxies 2018, 6, 33

KeV X-ray polarimetry in gas - a long development



letters to nature

An efficient photoelectric X-ray polarimeter for the study of black holes and neutron stars

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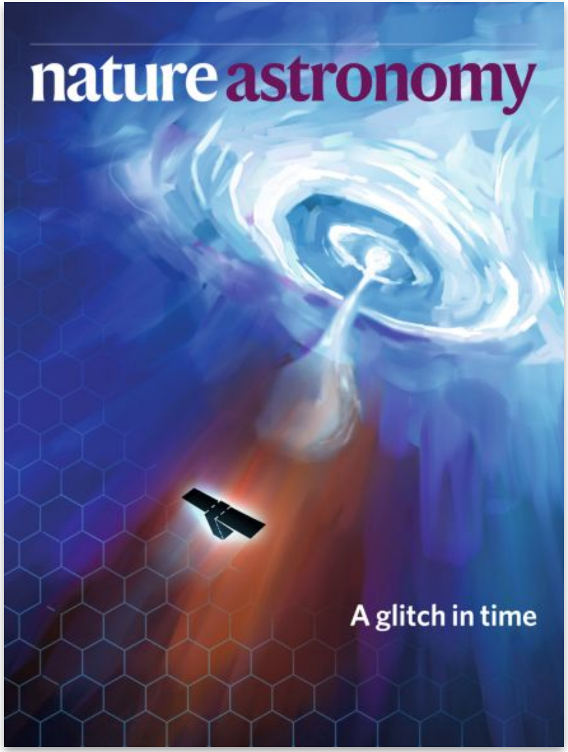
The study of astronomical objects using electromagnetic radiation involves four basic observational approaches: imaging, spectroscopy, photometry (accurate counting of the photons received) and polarimetry (measurement of the polarizations of the observed photons). In contrast to observations at other wavelengths, a lack of sensitivity has prevented X-ray astronomy from making use of polarimetry. Yet such a technique could provide a direct picture of the state of matter in extreme magnetic and gravitational fields[1–6], and has the potential to resolve the internal structures of compact sources that would otherwise remain inaccessible, even to X-ray interferometry[7]. In binary pulsars, for example, we could directly 'see' the rotation of the magnetic field and determine if the emission is in the form of a 'fan' or a 'pencil' beam[1,8]. Also, observation of the characteristic twisting of the polarization angle in other compact sources would reveal the presence of a black hole[9–12]. Here we report the development of an instrument that makes X-ray polarimetry possible. The factor of 100 improvement in sensitivity that we have achieved will allow direct exploration of the most dramatic objects of the X-ray sky.

The main advantage of the proposed polarimeter is its capability of investigating active galactic nuclei (quasars, blazars and Seyfert galaxies) for which polarization measurements have been suggested, crucial to understand the geometry and physics of emitting regions. We can separate synchrotron X-rays from jets[13,14] from the emission scattered by the disk corona or by a thick torus. The effects of relativistic motions and of the gravitational field of a central black hole have probably been detected by iron line spectroscopy on the Seyfert-1 galaxy MCG-6-30-15 (ref. 15) but this feature is not ubiquitous in active galactic nuclei. Polarimetry of the X-ray continuum provides a more general tool to explore the structure of emitting regions[16,17], to track instabilities and to derive direct information on mass and angular momentum[12] of supermassive black holes.

In spite of this wealth of expectations, the important but only positive result until now is the measurement, by the Bragg technique, of the polarization of the Crab nebula[18,19]. The Stellar X-ray Polarimeter[20] (SXRP) represents the state of the art for conventional methods based on Bragg diffraction and Thomson scattering. However, Bragg polarimetry[21] is dispersive (one angle at one time) and very narrow-band. Thomson polarimetry[22] is non-imaging and band-limited (>5 keV). This limits the sensitivity of SXRP to a few bright, galactic sources only.

The photoelectric effect is very sensitive to polarization. The electron is ejected from an inner shell with a kinetic energy which is the difference between the photon energy and the binding energy. The direction of emission is not uniform but is peaked around that of the electric field of the photons (see Fig. 1a). This photoelectron

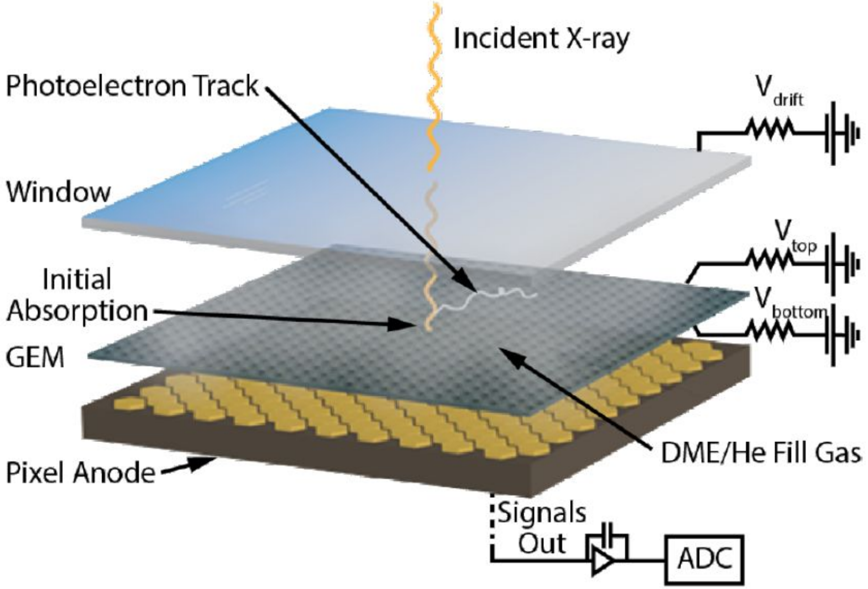
Nature - 2001 - TRL 4 (functional verification)



Nature Astronomy - 2020 - TRL 9 - flight proven

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



- ▷ Photoelectric effect dominant for soft (< 10 keV) X-rays
- ▷ K-shell photo-electron emission 100% modulated for linearly ploarized radiation:

$$\frac{d\sigma_C^K}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$

- ▷ Typical track length ∼ few μm in solid: a gaseous medium is needed!

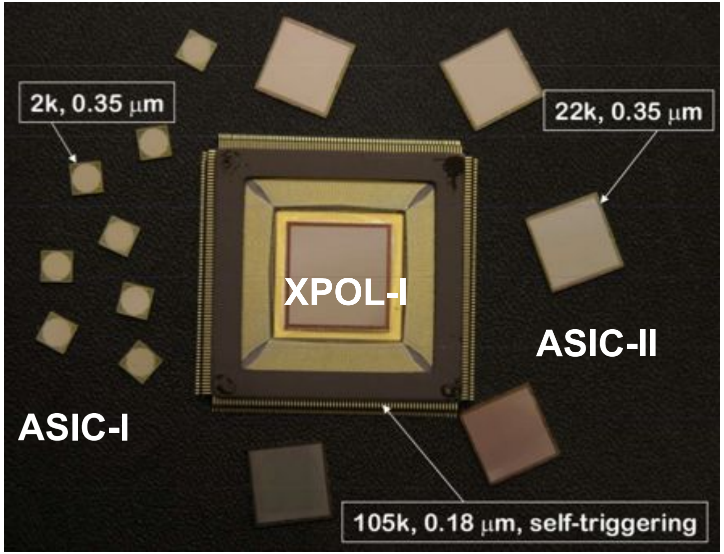
- ▷ X-ray absorption in a gas gap
- ▷ Signal amplification via a Gas Electron Multiplier (GEM)
- ▷ Finely pixelized ASIC as readout anode
- ▷ Sensitive in the $\sim 2-8$ keV band
- ▷ Full two-dimensional imaging and spectroscopy

The Gas Pixel Detector Concept

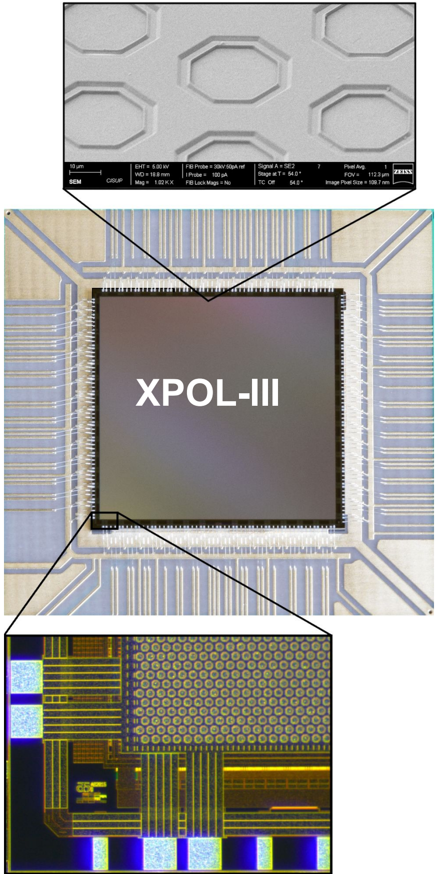
The XPOL ASICs family - a 20+ years development

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



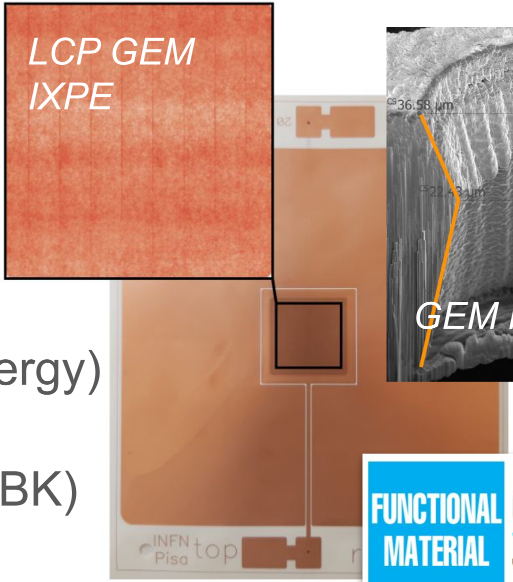
Electron multipliers

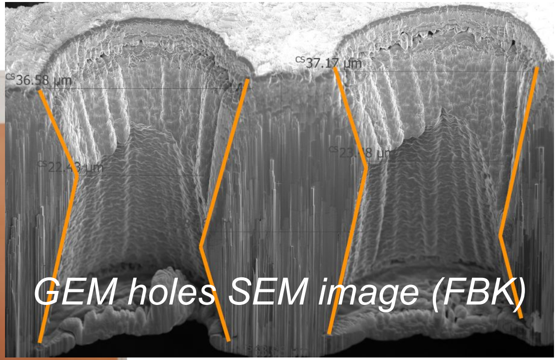
Gas Electron Multiplier (GEM)

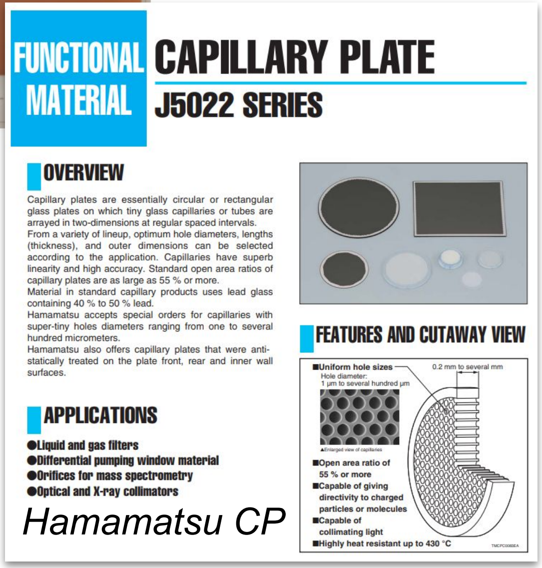
- LCP GEM qualified for space (SciEnergy)
- GEM wet-etched (Techtra, CERN)
- GEM RIE dry-etched (new R&D w/ FBK)

Capillary plates

- Demonstrated to work but far from being qualified







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
- 0.2 mm to several mm
- 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

Hamamatsu CP

Gas Electron Multiplier - GEM

33 *35. Particle Detectors at Accelerators*

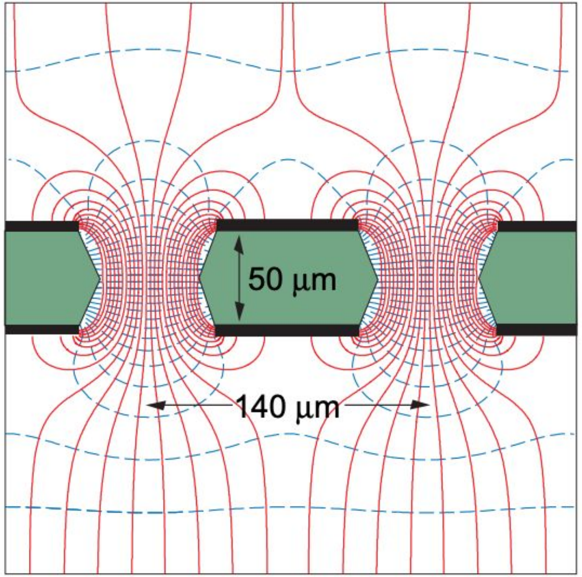


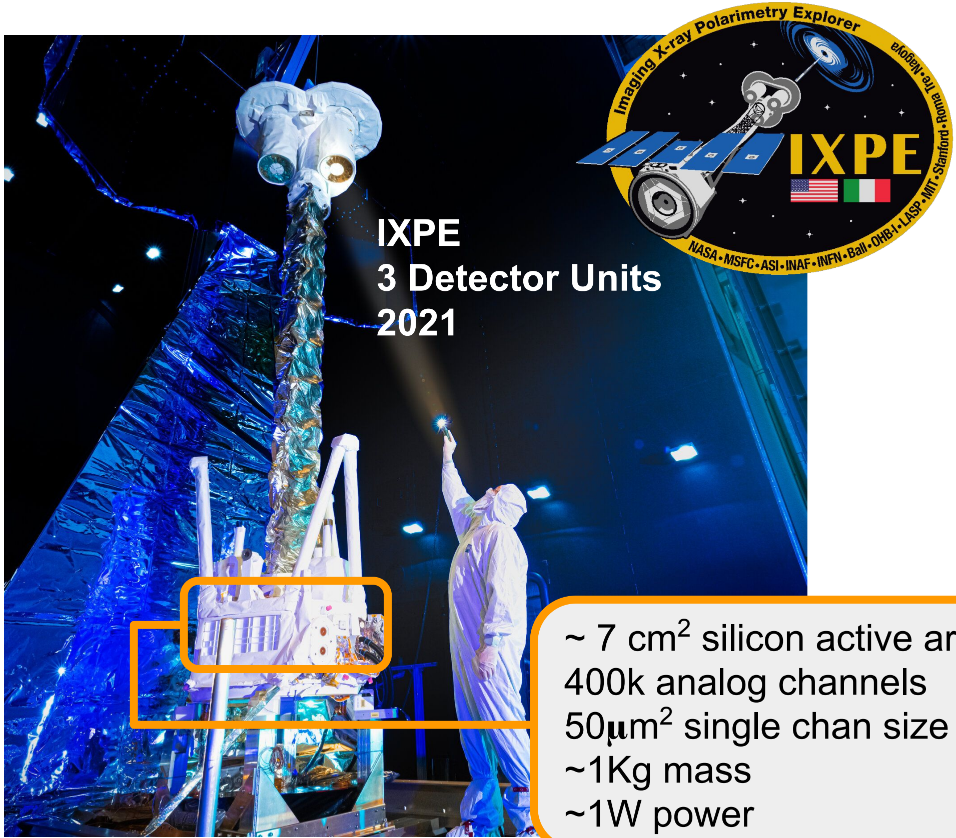
Figure 35.10: Schematic view and typical dimensions of the hole structure in the GEM amplification cell. Electric field lines (solid) and equipotentials (dashed) are shown. Electron trajectories do not strictly follow the field lines as drifting electrons scatter isotropically with gas molecules and diffuse transversally.

Principle of operation explained in the standard textbooks, eg PDG Review.

IXPE GEM are different in:

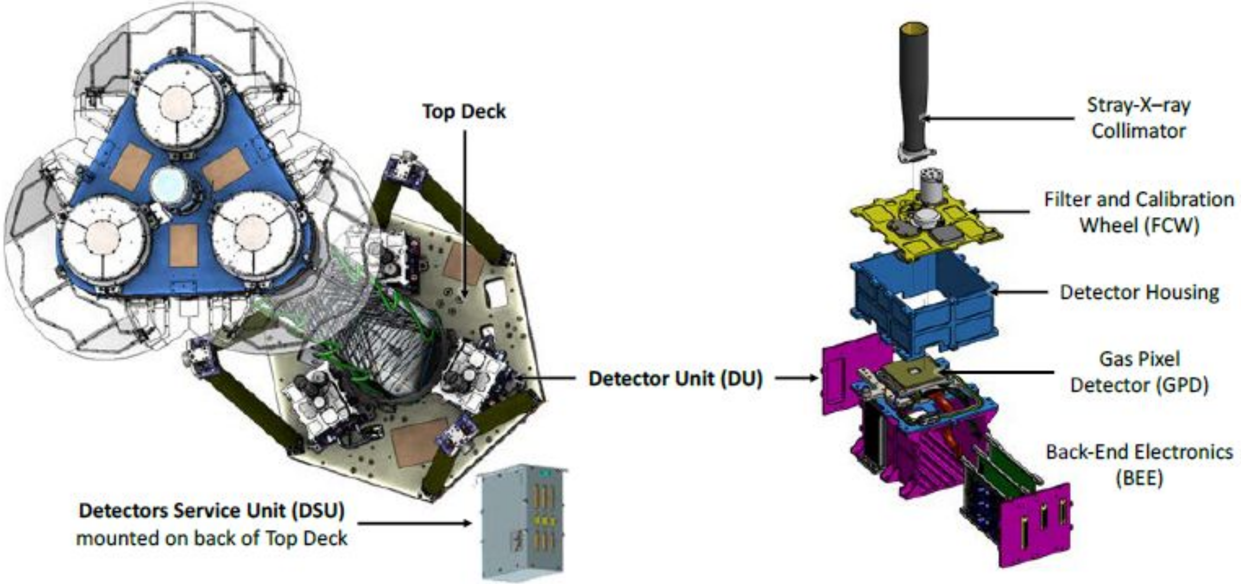
- Geometry (50um pitch, 50um thickness)
  - Matches ASIC pattern
  - Reduces operating voltage
- Insulation material (LCP vs Kapton)
  - Minimizes charging
- Footprint (15mm2 active surface)
  - Matches ASIC footprint

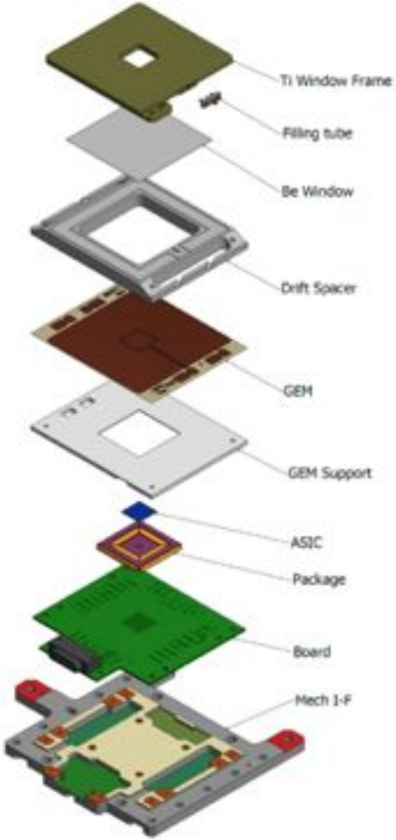
The Imaging X-ray Polarimetry Explorer Mission



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

IXPE Detector Unit and GPD breakouts





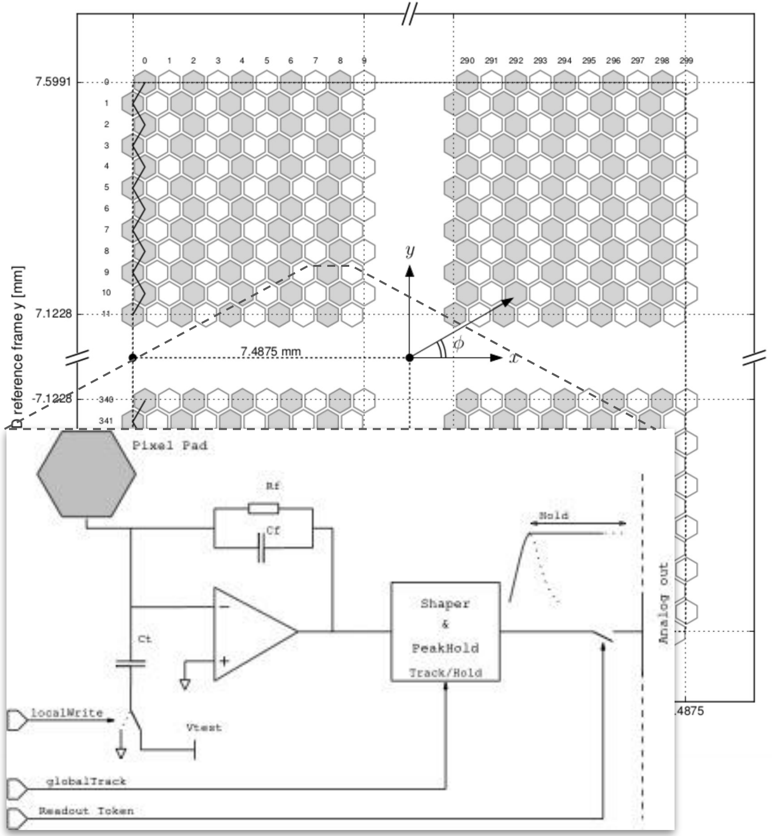
The IXPE XPOL chip layout and single pixel FE chain

CMOS VLSI chip built with 180nm technology

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

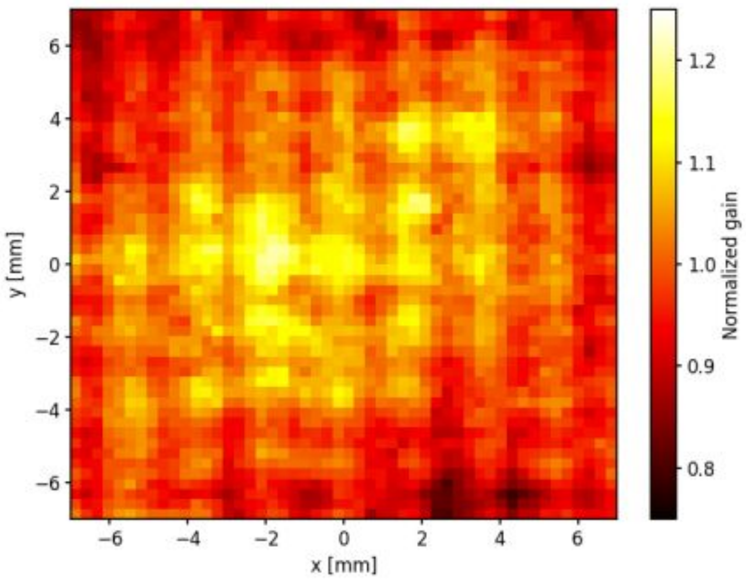
Each pixel contains

- Hexagonal metal top layer
- Charge sensitive amplifier (~400mV/fC)
- Shaping circuit (~4usec)
- Low noise (<30e ENC)
- Multiplexer to external ADC (1V dynamic, ~30ke)



The IXPE GEM

Parameter	Value
Number of holes	112008 (359 × 312)
Horizontal pitch	43.30 μm
Vertical pitch	50.00 μm
Hole diameter	30 μm
Hole diameter dispersion	$\sim$ 1 μm (typical)
Top-bottom alignment	$\sim$ 2 μm (typical)
Metal coating	Copper
Coating thickness	5 μm
Substrate	Liquid crystal polymer (LCP)
Substrate thickness	50 μm
Manufacturing process	Laser etching
Typical operating voltage	$\sim$ 470 V
Gain gain scaling	$\propto \exp(\sim 0.03$ V)
Working effective gain	$\sim$ 200

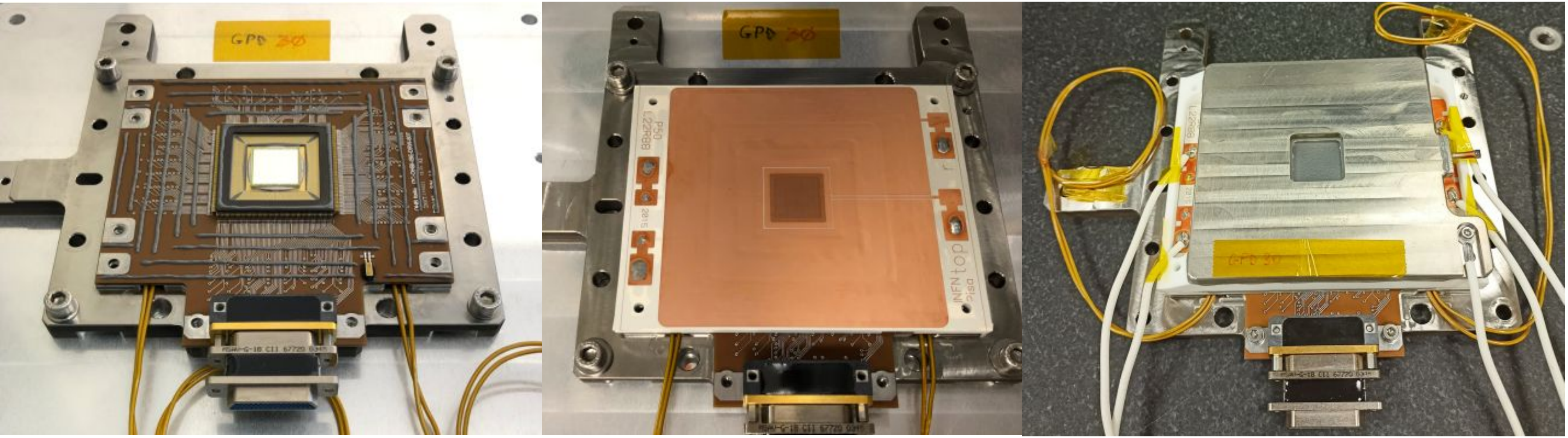


XPOL Laboratory Activity

Check list			
Activity	**Synopsis**	**Check**	**Note**
1	Feel & touch a GPD - GEM, XPOL and mechanics		
	Learn about the XCF - source, vacuum, scanners and beam monitors		
2	Charge injection on XPOL ASIC - readout test		
	Single event display and photo electron track reconstruction		
	Switch on the GPD: ramp up and gain curve - PHA vs HV GEM		
3	XCF test lines - visualize spectra with an SDD		
	GPD energy calibration and linearity		
	GPD rate effects		
4	GPD polarization sensitivity - modulation curves		
	Systematic effects - charging and residual modulation		

Main reference - https://arxiv.org/abs/2107.05496

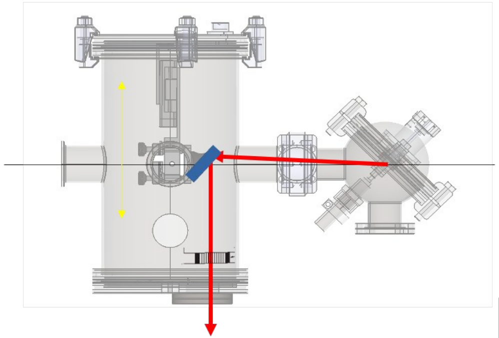
The actual IXPE GPD



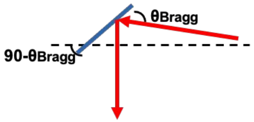
XPOL laboratory activity 1 - feel and touch a GPD

The X-ray Calibration Facility

Polarized beam



selecting vertical output with capillary plate, the geometry is fixed



Polarization by Bragg diffraction at 45°

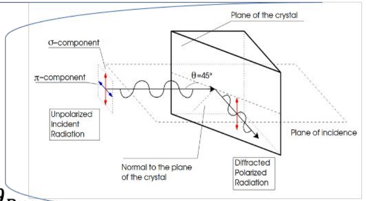
$sin(\theta_{Bragg}) = \frac{nhc}{...}$

Polarization degree:

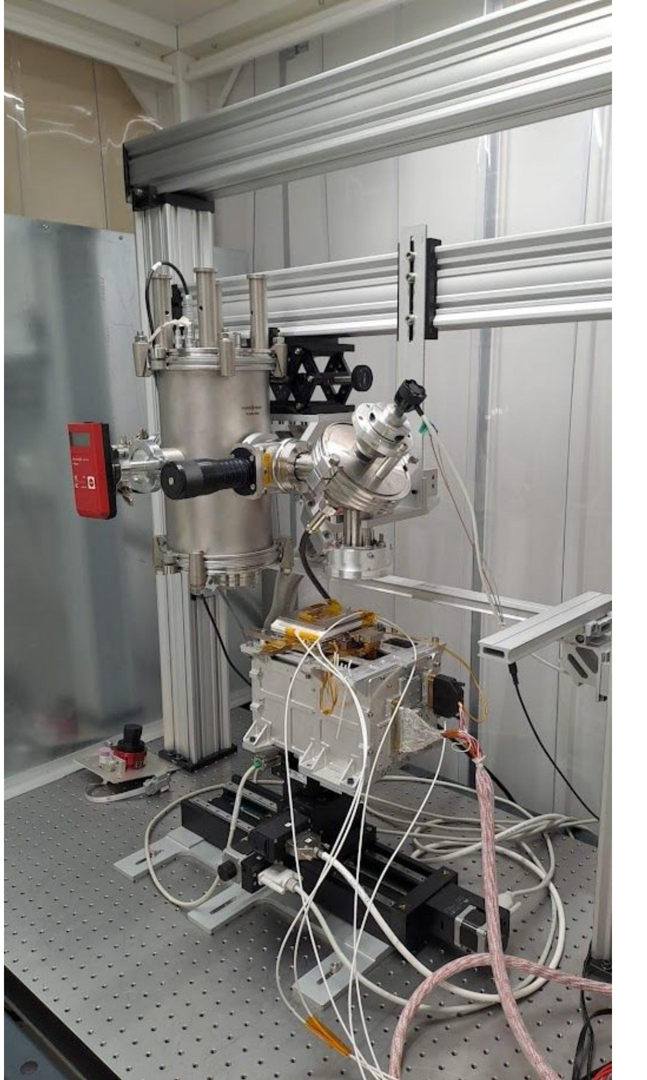
$$\mathcal{P} = \frac{1-k}{1+k}$$

With:

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

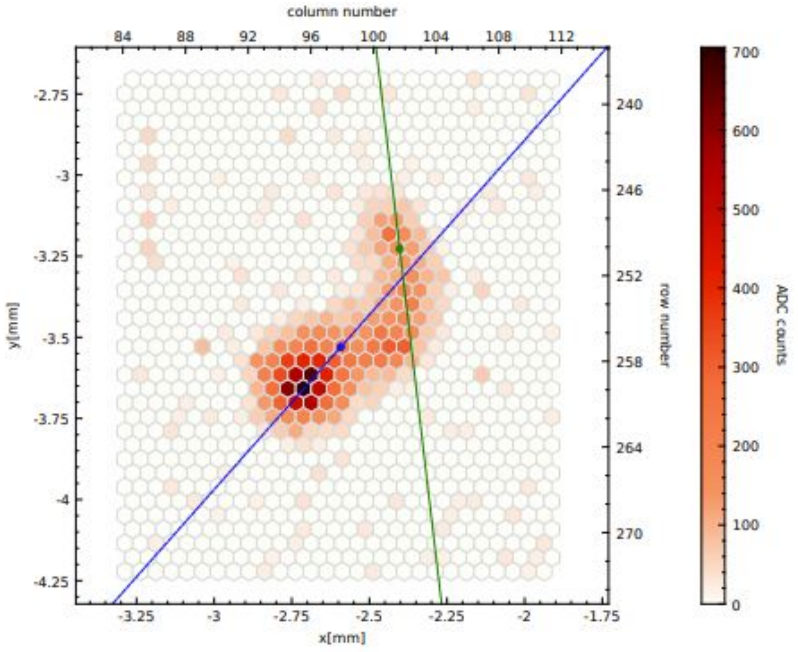


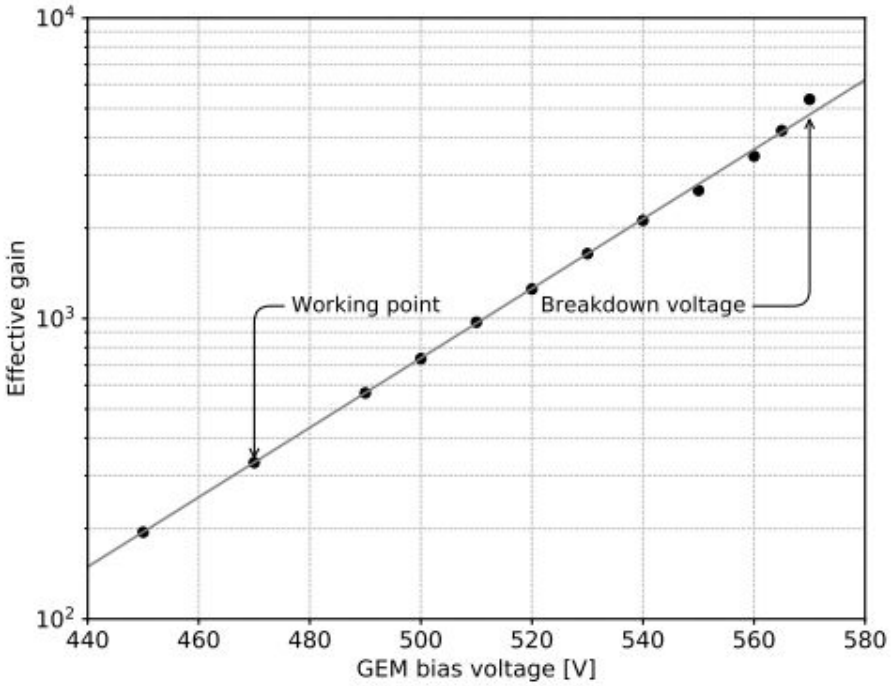
Anode line	E [KeV]	Xtal	2d (A)	θBragg	P
Mo Lα	2.2932	InSb111	7.481	46.28	99.32%
Rh Lα	2.697	Ge111	6.532	44.87	99.28%
Pd Lα	2.839	Si111	6.271	44.12	>95.08%
Ti Kα	4.511	Si 220	3.840	45.71	99.51%
Fe Kα	6.404	Si 400	2.7142	45.5	99.7% ??
Ni kα	7.478	Ge 422	2.31	45.86	99.04%



XPOL laboratory activity 1 - learn about the XCF

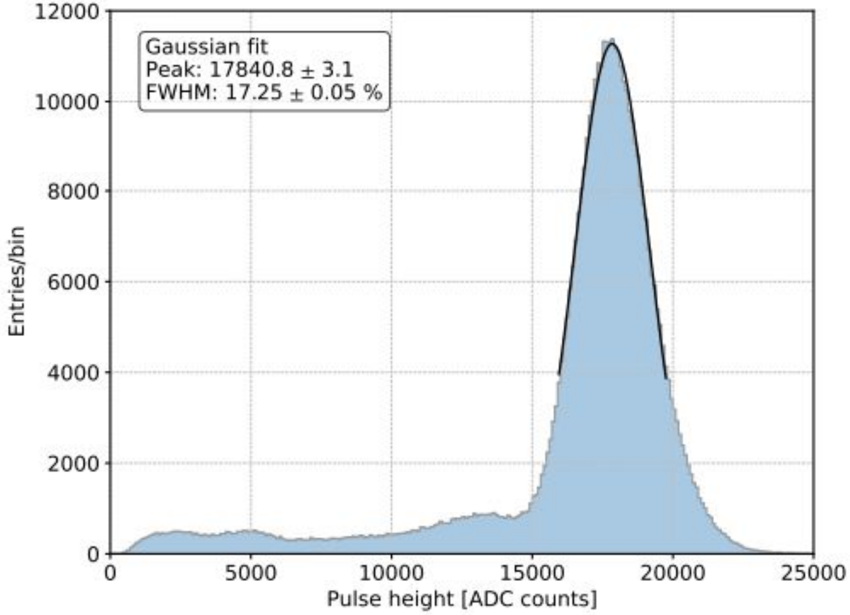
GPD setup and basic response

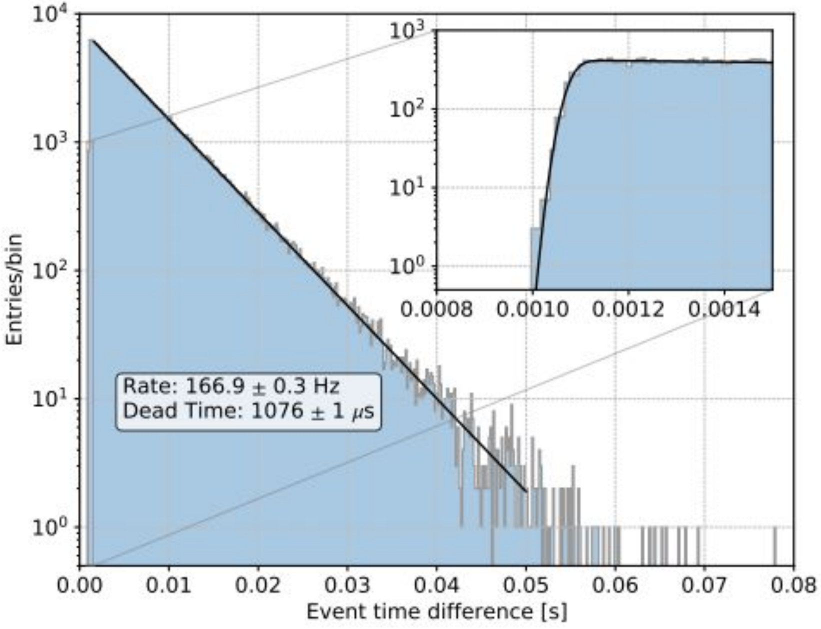




XPOL laboratory activity 2 - single event display and gain curve
Addon activity - GPD event reconstruction walkthrough

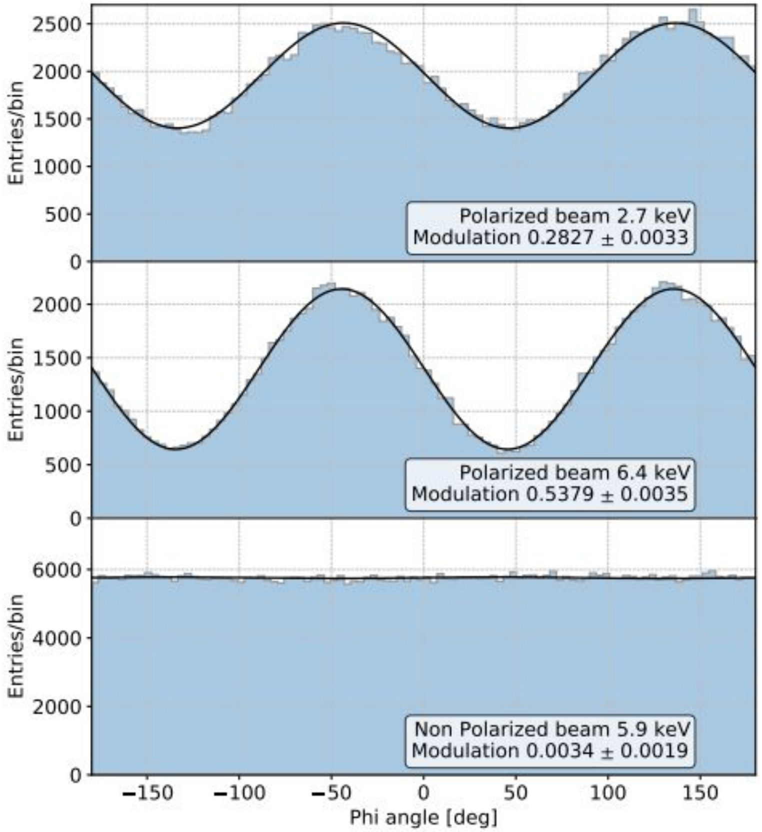
GPD Performance



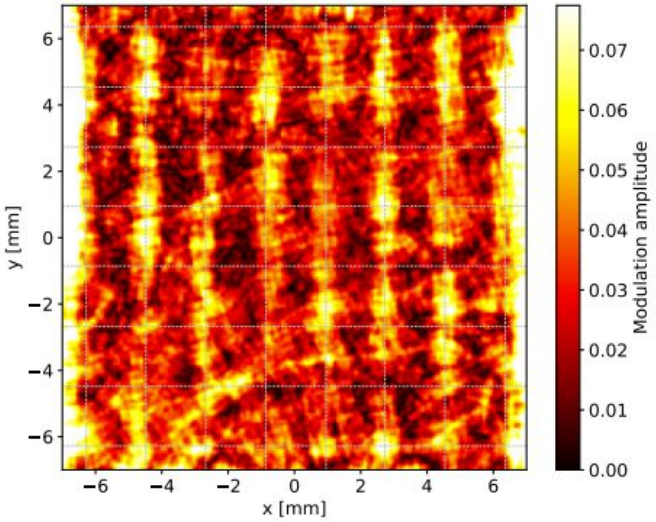


XPOL laboratory activity 3 - energy calibration and rate effects

GPD response to polarized photons



XPOL laboratory activity 4 - modulation curve



Addon activities

- Discuss systematic effects (charging, secular variation, residual modulation)
- Bragg scattering X-ray polarization focus

Team and acknowledgements

Contributing Teams

- INFN Torino and University of Torino: M. Aglietta, R. Bonino, N. Cibrario, A. Frassa, A. Gorgi, L. Latronico, S. Maldera, S. Tugliani
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Enjoy the laboratory!