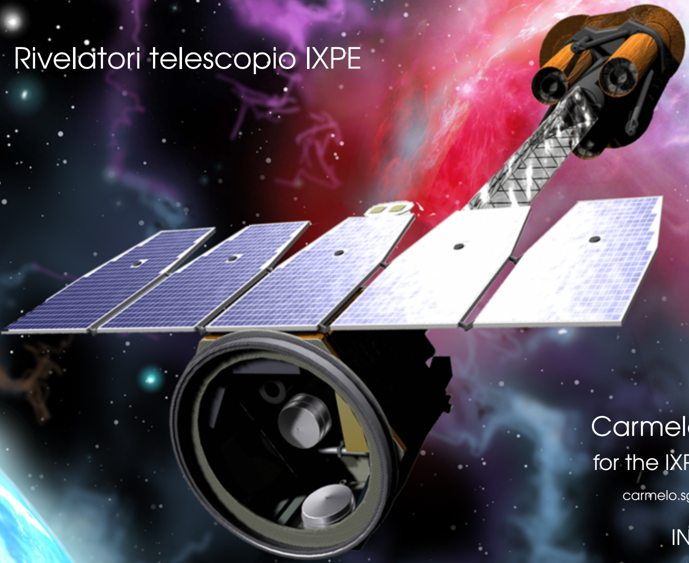
Rivelatori telescopio IXPE



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Giornate Studio sui Rivelatori

Outline

- Introduction
- Measuring X-ray polarization
- X-ray polarimetry techniques
  - Bragg diffraction
  - Photoelectric Effect
- The Gas Pixel Detector
  - Description of the components
  - Assembly process
  - Event readout and reconstruction
- The Detector Unit
- The IXPE satellite

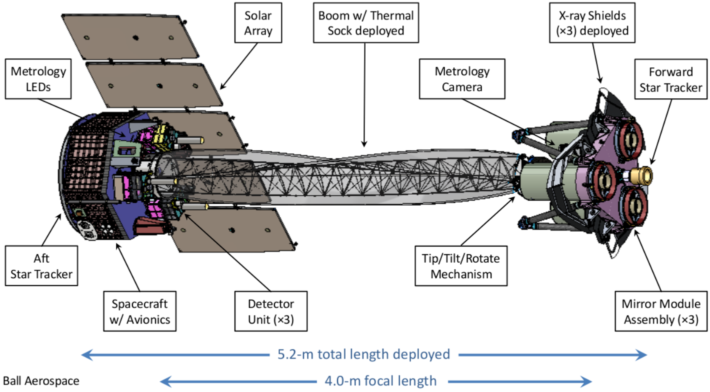
INTRODUCTION

The IXPE mission

- ▷ The Imaging X-ray Polarimetry Explorer (IXPE)
  - ▷ Imaging and polarimetry in the 2–8 keV band
  - ▷ Detectors developed and built at INFN-Pisa
- ▷ Next NASA SMall EXplorer (SMEX) mission
  - ▷ Launch in early 2021
  - ▷ 2-year mission (baseline), +1 year extension
  - ▷ Equatorial circular orbit at $\geq$ 540 km altitude
- ▷ International partnership:

- ▷ X-ray Mirror by NASA/MSFC
- ▷ X-ray Instruments by INFN, IAPS/INAF and ASI
- ▷ Spacecraft, payload structure and integration by Ball Aerospace

Overview of the observatory



- Three identical telescopes (redundancy, mitigation of systematic effects, larger acceptance)
- Conventional Wolter Type I grazing–incidence optics
- New imaging and polarization-sensitive detector at the focus
- Extensible boom to save space during launch

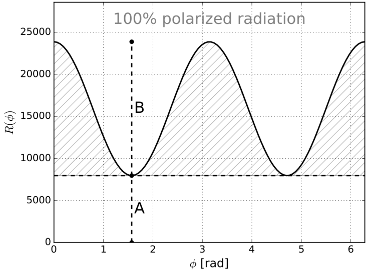
Polarimetry in X-ray Astrophysics

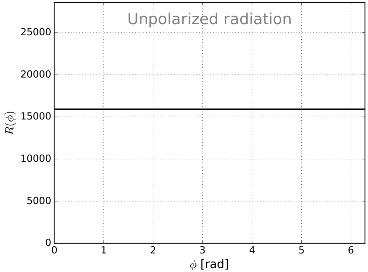
- Polarimetry is already common at many wavelengths
  - Not really exploited in X-ray
- Two additional parameters to the phase space:
  - (linear) polarization degree
  - polarization angle (phase)

- Linear polarization whenever there is some “preferred direction” in the system
- Which means information on many aspects of X-ray sources:
  - Non-thermal emission processes
    - Synchrotron radiation
    - Acceleration phenomena (supernova remnants, pulsar wind nebulae, jets)
  - Geometry
    - Photon scattering in aspherical geometries (accretion disks, X-ray reflection nebulae)
    - Photon propagation in magnetized plasmas (accreting pulsars, magnetars)
  - Fundamental physics
    - Quantum electrodynamics (photon propagation in strong magnetic fields)
    - General relativity (photon propagation in strong gravitational fields)

MEASUREMENT PROCESS

Measuring X-ray linear polarization





- Azimuthal modulation around the polarization angle ϕ_0:

$$R(\phi) = A + B\cos^2(\phi - \phi_0)$$

- Modulation factor: response to 100% polarized radiation:

$$\mu = \frac{R_{max} - R_{min}}{R_{max} + R_{min}} = \frac{B}{B + 2A}$$

- Equivalent representation: $R(\phi) = N(1 + m\cos(2(\phi - \phi_0))$
  - Exercise: calculate μ in this case

Measuring X-ray linear polarization

- A real measurement process is thus
  1. Collect a sample of photons
  2. Evaluate ϕ distribution (not as trivial as it may look like)
  3. Extract modulation parameters: amplitude m and ϕ_0

- Polarization angle is obviously ϕ_0
- Polarization degree is $p = m/\mu$

- Notice that p is always positive!
  - You will get a number even in case of non-polarized beam
  - Need to understand if it is compatible with zero
  - Need to understand your sensitivity

The Minimum Detectable Polarization (MDP)

- Minimum Detectable Polarization (MDP): (at 99% CL) is the degree of polarization corresponding to the amplitude of modulation that has a 1% probability of being detected by chance
  - See e.g. M. Weisskopf 2010, https://arxiv.org/pdf/1006.3711.pdf

$$MDP = \frac{4.29}{\mu S}\sqrt{\frac{B+S}{T}}$$

S: source rate B: background rate T: observation time

- In case of negligible background:

$$MDP = \frac{4.29}{\mu\sqrt{ST}} = \frac{4.29}{\mu\sqrt{N}}$$

with N: total number of collected events

- Commonly used to estimate statistical sensitivity of detectors (and compare them)

MDP or how many events do I need?

- Let's think positive and assume no bkg and $\mu = 1$
- How many events to reach a MDP = 1%?
  - Using $MDP = \frac{4.29}{\mu\sqrt{N}} \Rightarrow N \approx 184000$
- If we want to be a bit more realistic and assume $\mu = 0.5$
  - $N \approx 7.36 \times 10^5$
- Think at these number in comparison with the statistics needed for other measurements
  - Source detection: $\sim$ 10 events
  - Spectrum measurement: $\sim$ 1000 events
  - Polarimetry: $> 10^5$ events
- What we need is:
  - a lots of counts – large collecting area, long observation time
  - a good polarimetric response – maximize μ

Another formalism: Stokes Parameters

https://arxiv.org/pdf/1409.6214.pdf

- For each event, define a set of Stokes Parameters

$$i_k = 1 \qquad q_k = \cos 2\phi_k \qquad u_k = \sin 2\phi_k$$

- Sum up the parameters for the entire data set:

$$I = \sum i_k \qquad Q = \sum q_k \qquad U = \sum u_k$$

- Normalize the Stokes parameters:

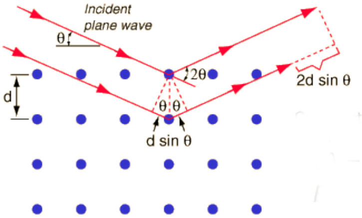
$$\mathcal{Q} = \frac{Q}{I} \qquad \mathcal{U} = \frac{U}{I}$$

- Evaluate polarization degree and angle as:

$$p = \frac{2}{\mu}\sqrt{\mathcal{Q}^2 + \mathcal{U}^2} \qquad \phi_0 = \frac{1}{2} arctan \frac{\mathcal{U}}{\mathcal{Q}}$$

Measurement techniques

Bragg diffraction



- X-ray can be diffracted by crystal lattice
- Constructive interference occurs when

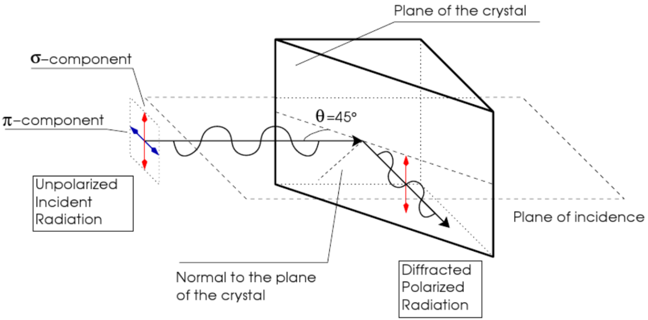
$$n\lambda = 2d \sin\theta$$

or

$$E(\theta) = \frac{nhc}{2d \sin\theta}$$

- Can be used to deflect X-rays, select energy, and select polarization...

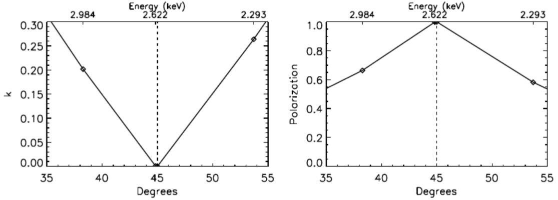
Bragg polarimeter: diffraction at 45°



- Diffraction at 45 ° select one polarization plane
- Intensity of diffracted beam depends on polarization of incident beam
- Notice that θ is fixed, so Energy depends only on crystal lattice spacing

Bragg polarimeter: crystal selection

Graphite Crystals:



k is the ratio between integrated reflectivity the two polarization components ($\parallel$ and $\perp$ to the diffraction plane)

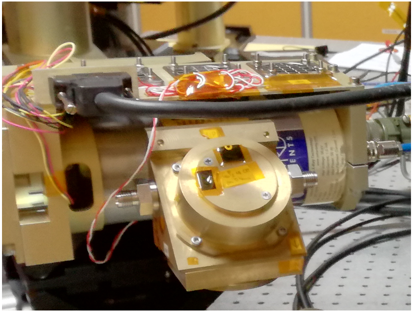
$$P = \frac{1-k}{1+k}$$

- ▷ Several crystals are suitable for lines in energy range 1–10 keV
- ▷ e.g. graphite works fine at 2.6 keV (and higher order)
- ▷ Mosaic crystals can be used to increase the reflectivity

- ▷ Always keep in mind that real life is complicated:
  - ▷ Try to think at the alignment procedure and the mechanical tolerances that you would need in this kind of setup...

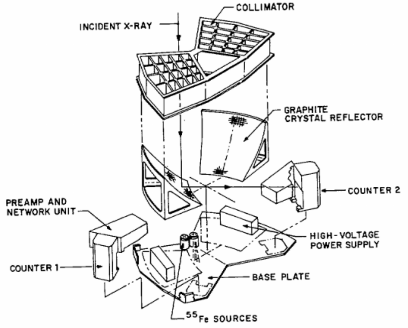
Bragg polarimeter: applications

Production of polarized beam:



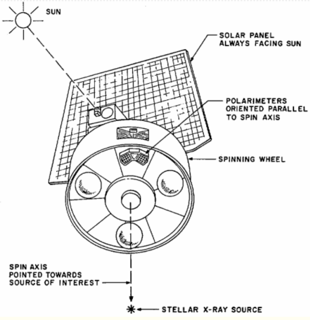
- ▷ For detector calibration
- ▷ Relevant for the IXPE mission

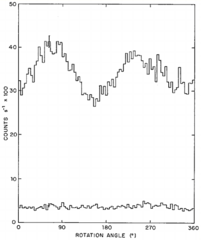
Detection of polarized beam:

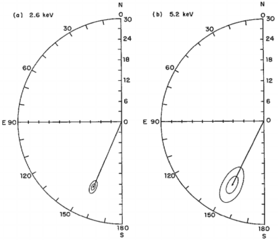


- ▷ Used in the first (and only, up to now) polarimeter ever flown
- ▷ One of the instrument on OSO-8 satellite

The OSO-8 mission and the Crab polarization

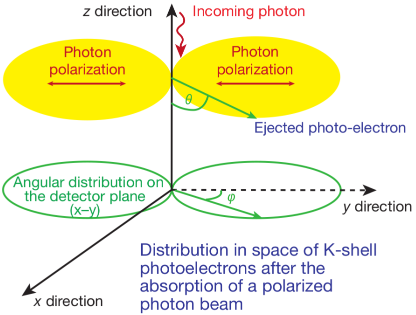






- ▷ Instrument rotate around pointing axis (spin stabilization of the satellite)
- ▷ Two narrow energy band 2.4–2.8 keV & 4.8–5.6 keV, but $\mu = 0.93$
- ▷ Measurements of the Crab Nebula: $P = 19.22 \pm 0.92\%$
  - ▷ M. C. Weisskopf, ApJL 220 (1978) L117-121

Photoelectric effect



- Dominant interaction process at low energy ($<$ 10 keV)
- Distribution of the direction of emission of a K-shell photoelectron 100% modulated for linearly polarized radiation:

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

- Need to reconstruct the direction of emission of the photoelectron
- This is the technique used in IXPE detector

Measurement principle

- The challenge is to be able to measure the initial part of the photoenectron track
  - Reconstruct the interaction point and the emission direction
- A good sampling of the photoelectron track is needed
- Detector granularity should be much smaller than the typical range
  - Energy dependent effect
  - In the 1–10 keV energy band typical photoelectron range is a few μm in a solid and a few hundreds μm in a gas
  - A gas is preferred in this application
    - There are attempts to use Si detectors at higher energies ($\sim 20 - 100$ keV)
- Electron scattering at large angle is also a problem
  - It can smear out the emission direction information
- Don't forget the highest ionization density is at the end of the track
  - Bragg peak contains most of the energy
  - A feature used in track reconstruction

Gas property selection, efficiency and diffusion

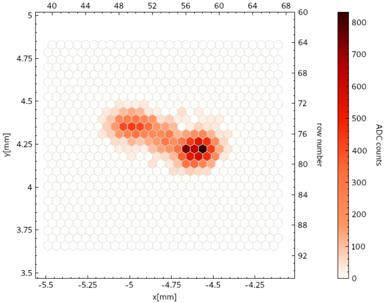
- Now the tricky part, we have to choose the gas:
  - Best gas – pure or mixture
  - Working pressure
  - Gas gap size
- Good photon efficiency
  - Deep absorption gap
  - High pressure and high Z gas
- Small diffusion of photoelectron ionization cloud
  - Diffusion destroys information on ionization point
  - Gas mixture is fundamental
  - Cloud drift length is important
  - Pressure plays a role: diffusion $\sim 1/\sqrt{P}$, but range $\sim P$
- Interaction must be in k–shell
  - High-Z element won't work at low energy (e.g. Argon)
- Auger electron is better than fluorescence
  - Photoelectron energy is lower than X-ray: $E_{ph} = E_{\gamma} - E_k$
  - Auger electron is absorbed immediately while fluorescence can travel far or escape

Effect of the transverse diffusion

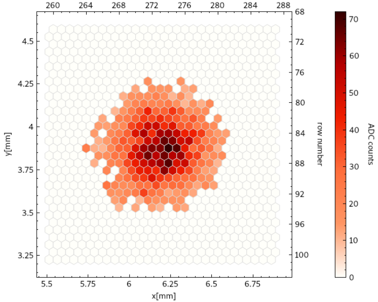
Gas example Ar CO_2 vs DME

How a 5.9 keV photon looks like in a low (DME) and high (Ar) diffusion gas

DME 0.8 bar

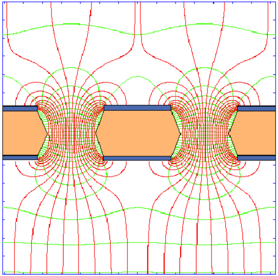


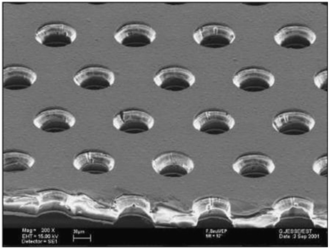
Ar/CO_2 70/30 at 1 bar



Track sampling and signal amplification

- Readout pitch as small as possible
  - Track length a few hundreds μm in the keV energy range
- 2D readout is necessary: pixel pattern
- An amplification stage is needed for gas detector and current amplifier
  - A 1 to 10 keV photon produces between 40 and 400 electron-ion pairs (assuming a W$\sim$25)
  - Then divide by the number of pixels involved
- The amplification stage must preserve position information
  - e.g. a Gas Electron Multiplier (GEM) with fine pitch
  - A first track sampling is done by the amplification stage

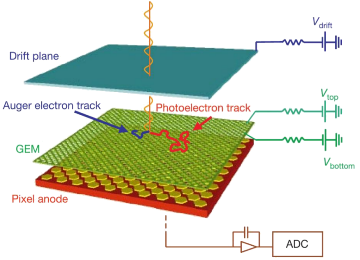




Detector geometry

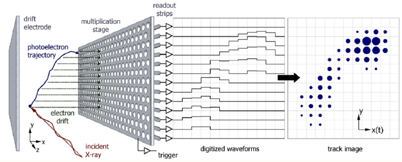
The two concept proposed up to now

IXPE detector



- Readout plane orthogonal to photon direction
- Absorption gap limited by diffusion
- Imaging and polarimetry at the same time
- Azimuthally asymmetric

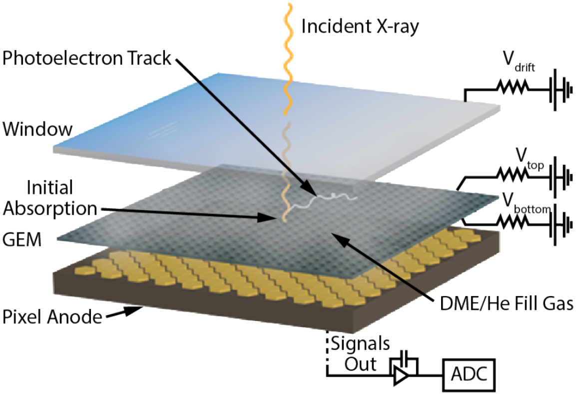
TPC concept



- Readout plane parallel to photon direction
- Drift to the side allows for a deep absorption gab (efficiency)
- Imaging only in one direction (no absorption time available)
- Highly azimuthally asymmetric

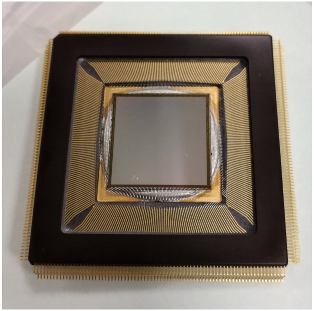
THE GAS PIXEL DETECTOR

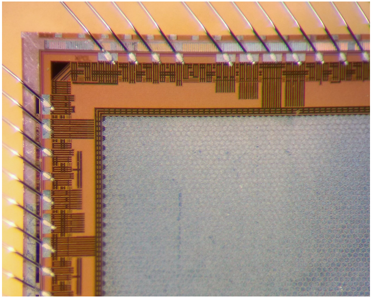
The Gas Pixel Detector (GPD)



- Gas gap for X-ray absorption
  - 1 cm of DME at 800 mbar
- Signal amplification via a Gas Electron Multiplier (GEM)
- Finely pixelized ASIC as readout anode
- Designed for energy range $\sim 2 - 8$ keV

The core of the detector: the ASIC

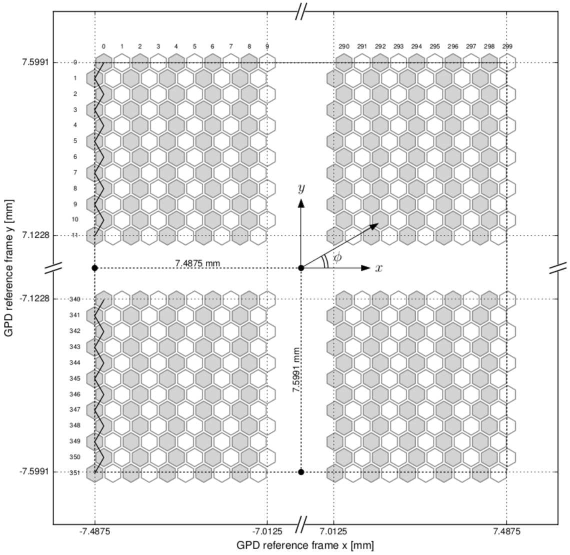




Properties

Pixels organization	300×352 pixels in hexagonal pattern
Pixel pitch	50 μm
Active area	15×15 mm^2
Shaping time	4 μs
Pixel Noise	$\sim$ 50 electrons ENC
Trigger	internal, with definition of a region of interest
Output	analog (external ADC required)
Technology	CMOS 0.18 μm

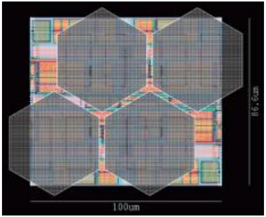
ASIC pixel matrix organization

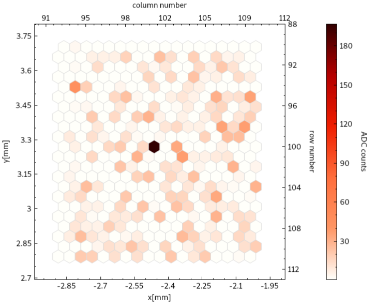


Each pixel has:

- Hexagonal electrode, top layer is metal
- A charge-sensitive amplifier followed by a shaping circuit
- Address by it column and row, (0,0) on top-left

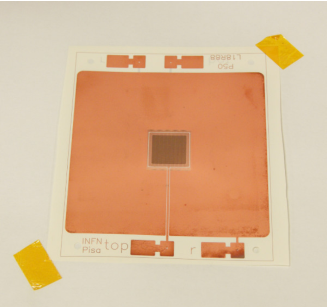
ASIC self-trigger and readout

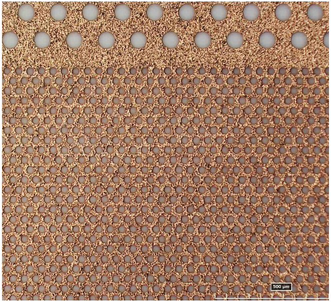




- Pixels are grouped in 2×2 minicluster to contribute to a single trigger with dedicated shaping amplifier
- Single trigger threshold for all the ASIC
- Pixels can be individually masked to the trigger
- Autonomous definition of a square region-of-interest (ROI) around the triggering miniclusters
  - With a margin of $\sim$ 10 pixels
- Serial readout of the pixels inside the ROI
  - A clock is sent to the ASIC
  - At each cycle the next pixel is connected to the analog output buffer
  - An external ADC read the charge of the pixel

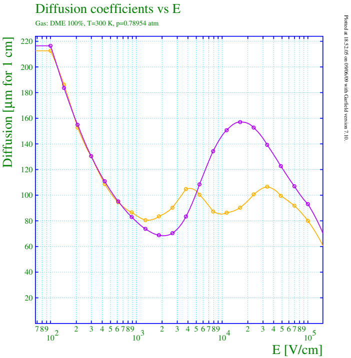
The Gas Electron Multiplier (GEM)

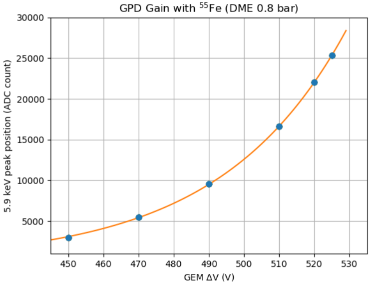




- ▷ Produced by RIKEN and SciEnergy in Japan
- ▷ Hexagonal hole pattern, with 50 μm pitch, 50 μm thick
- ▷ Active size matching ASIC + large guard ring for uniform drift field
- ▷ Liquid crystal polymer (LCP) insulator (laser etching technique)
- ▷ Mask alignment at a few μm level

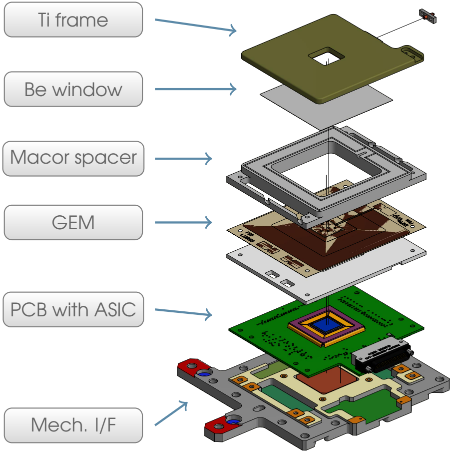
GPD Voltage selection





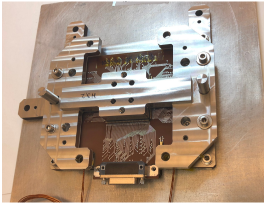
- ▷ Drift voltage optimum is around diffusion minimum: $\sim$ 2 kV/cm
- ▷ GEM Bottom voltage kept as low as possible to minimize the risk of sparks on the ASIC: $\sim$ 0.5 – 0.6 kV/cm
- ▷ GEM top to adjust gain
  - ▷ Gain variation is exponential with the ΔV on the GEM
  - ▷ A too high gain increase the risk of sparks

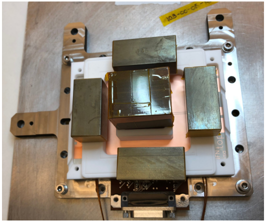
The GPD assembly

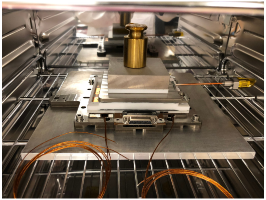


- Sealed detector
  - No gas system needed
- Ceramic parts for gas cell and GEM support
  - Low outgassing, for space application and gas purity
- A Ti frame acts as "drift" electrode
- X-ray window in Be, 50 μm thick
- ASIC in a standard package mounted on a custom PCB
  - Commercial ceramic package
  - Space compatible PCB
- A Ti frame for mechanical and thermal interface

Gluing everything together

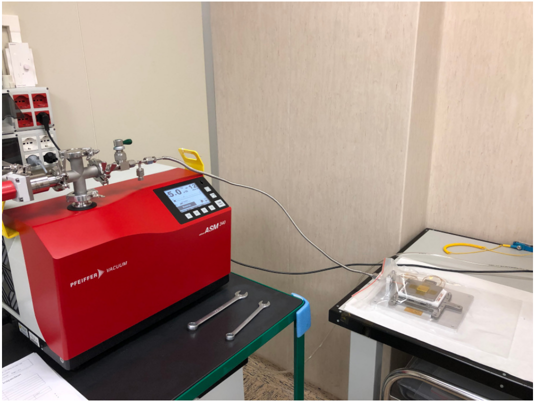






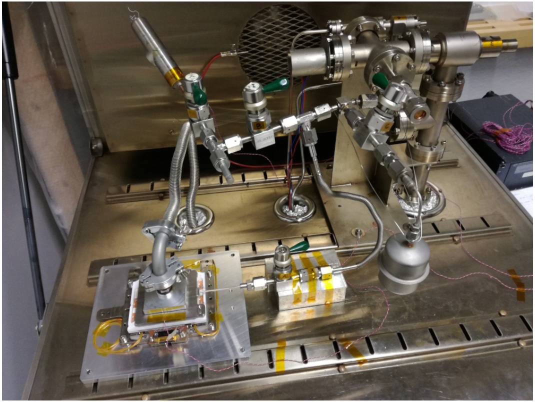
- ▷ Use space compatible adhesive
  - ▷ Service temperature $>$ 100 °C (detector bake-out)
- ▷ Find the right glue pattern (for a good sealing)
- ▷ Find the right gluing sequence (avoid thermal stress)
- ▷ Keep items in place during glue curing

Testing for leaks



- Detector is sealed and has to last the entire mission without refilling
- Severe requirement on leak rate: $< 1 \cdot 10^{-9}$ mbar l/s
- All GPD are tested with He leak detector after assembly

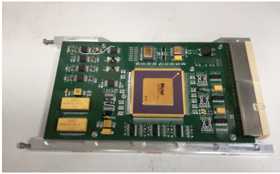
GPD filling

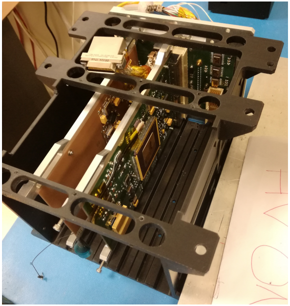


- ▷ Detector bake-out and filling is done in a dedicated facility at OIT in Finland
- ▷ A 2 weeks bake-out at 100 °C to clean the gas chamber
- ▷ Filling with DME at 0.8 bar is done in the same facility
- ▷ Finally GPD is sealed by crimping the filling tube

GPD readout

The Back-End Electronics (BEE)

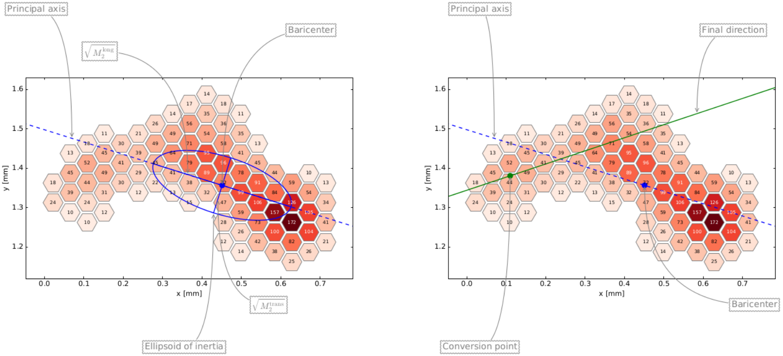




- Four PCBs in a dedicated housing:
  - Data Acquisition board (DAQ)
  - Low Voltage Power Supply, Board (LVPS)
  - High Voltage Supply Board (HVPS)
  - Back Plane (BP)
- FPGA based DAQ, with a 14-bit ADC for GPD data
- Two custom digital interfaces for communication:
  - Command and Control Interface (CCI)
  - Science Data Interface (SDI)
- Event timing via 1-PPS (from spacecraft GPS) and a 1 MHz clock
- Dedicated mechanical frames provide stiffness and thermal control

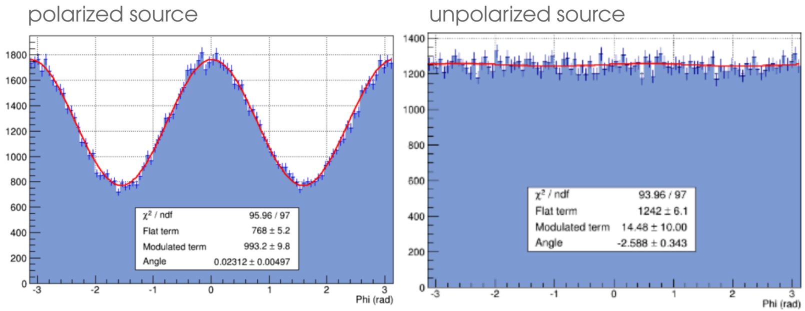
Event reconstruction

Real 5.9 keV photoelectron track



- Event by event reconstruction
- Iterative moment analysis to reconstruct relevant information
  - Interaction point: imaging
  - Photoelectron direction: polarimetry
  - Trigger output: timing
  - Pixel charge content: spectroscopy

Performance of the GPD as a focal-plane polarimeter

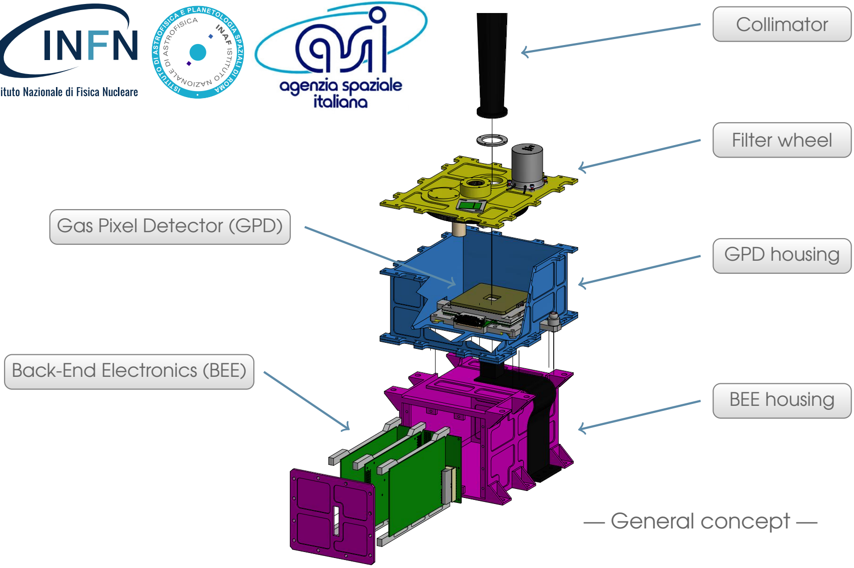


- ▷ Modulation factor: 0.2 (0.7) at 2 (8) keV
  - ▷ Stability over $\sim$ 3 years demonstrated with a sealed detector
- ▷ $\sim$90 μm spatial resolution at 5.9 keV, measured ($\ll$track length)
  - ▷ Good match for a $\sim$25 arcsec-type X-ray optics with $\sim$4 m focal length
- ▷ $<$20% energy resolution (FWHM) at 5.9 keV
  - ▷ Enough for spectrally-resolved polarimetry (in a few energy bins) when statistics allow it
- ▷ μs-type time resolution
  - ▷ More than adequate for the shortest time scales of interest

THE DETECTOR UNIT

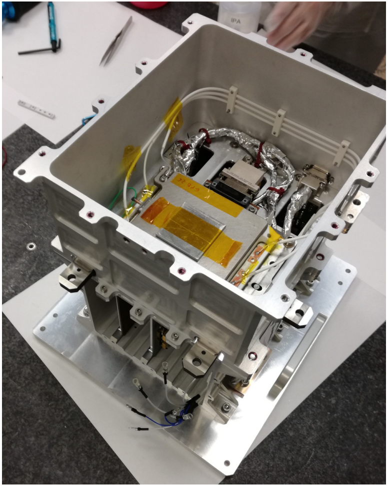
The Detector Unit (DU)

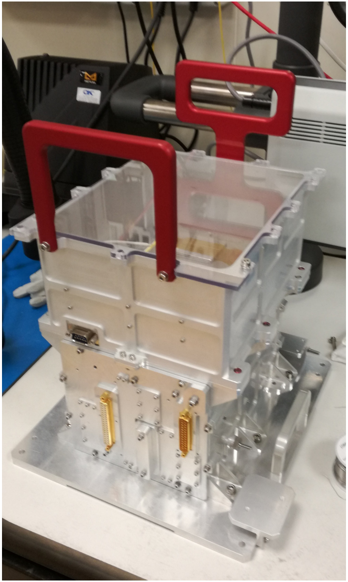
Basic unit of the IXPE instrument



The Detector Unit (DU)

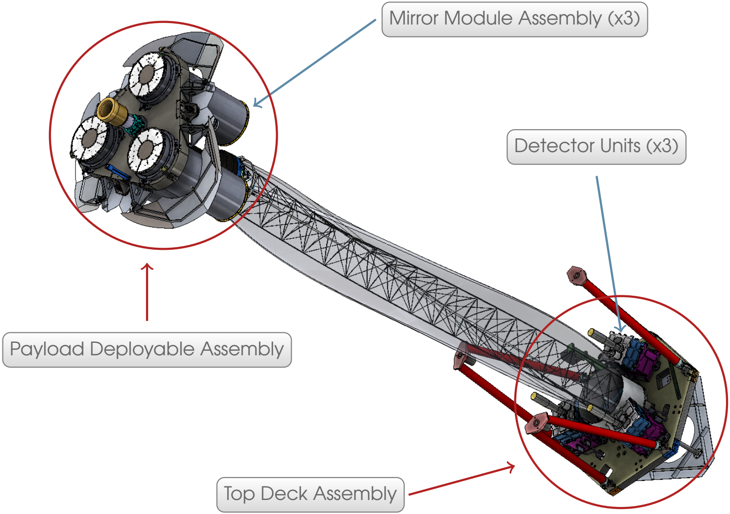
First assembly of the Engineering Model





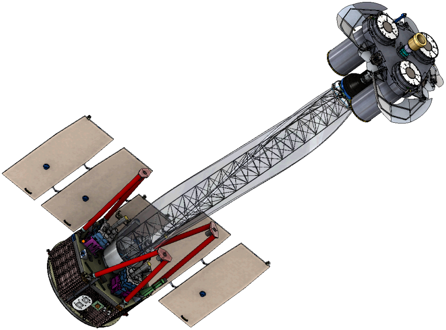
The IXPE Satellite

IXPE Payload components

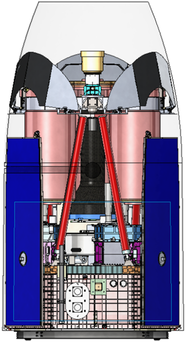


IXPE Satellite design

Deployed



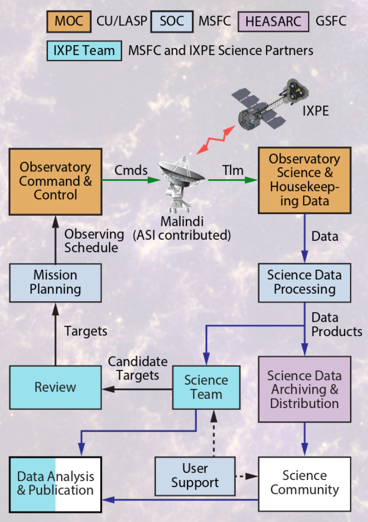
Stowed



- Optical boom to be deployed after launch to extend the optics at the right position
- Satellite 3-axis stabilized, GPS positioning and star-tracker for pointing
- S-band communication
- Launch in stowed configuration, compatible with Pegasus XL fairing

Mission operation concept

- ▷ Point-and-stare observations of known target
- ▷ S-band downlink via ground station (Malindi)
- ▷ Observation plan for the first year almost ready
- ▷ Open to community requests in the second year
- ▷ Data are immediately public (after downlink and validation)



THE END