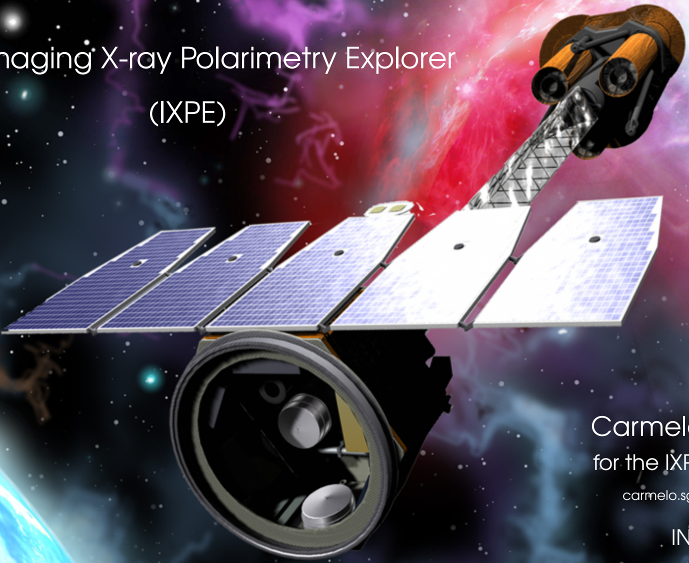
The Imaging X-ray Polarimetry Explorer

(IXPE)



Carmelo Sgrò

for the IXPE team

carmelo.sgro@pi.infn.it

INFN–Pisa

May 6, 2019

Outline

- ▷ Introduction to the IXPE mission
- ▷ Scientific case
- ▷ The telescope
- ▷ The detector
  - ▷ How it works
  - ▷ Assembly and test
  - ▷ Readout electronics
  - ▷ Performance
  - ▷ Construction status
- ▷ X-ray mirrors
- ▷ Conclusions

The IXPE mission

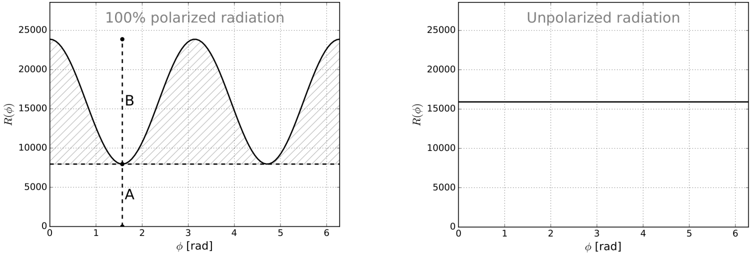
- The Imaging X-ray Polarimetry Explorer (IXPE)
  - Imaging and polarimetry in the 2–8 keV band
  - The observation technique and the mission were made possible by the introduction of a polarization-sensitive detector developed at INFN-Pisa
- Next NASA SMall EXplorer (SMEX) mission
  - Launch in early 2021
  - 2-year mission (baseline), +1 year extension
  - Equatorial circular orbit at $\gtrsim$ 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

A new exploration window

- Spectroscopy, imaging and timing are routine techniques in X-ray astronomy
- Polarimetry adds two parameters to the phase space:
  - (linear) polarization degree
  - polarization angle (phase)
- Significant X-ray linear polarization expected in most classes of non-thermal X-ray sources:
  - Emission processes
    - Synchrotron radiation and Inverse Compton
    - 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)

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:

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

- Polarization degree is $p = m/\mu$ (angle is obviously ϕ_0)
- Notice that p is always positive!
  - You will get a number even in case of non-polarized beam
  - Need to understand the 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:

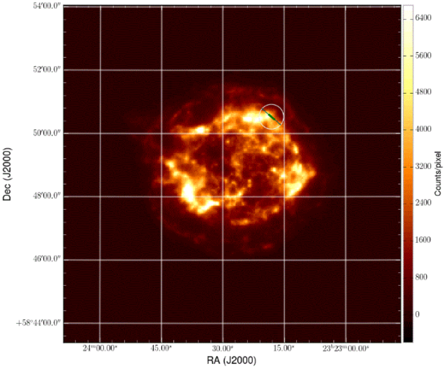
$$MDP = \frac{4.29}{\mu\sqrt{ST}} = \frac{4.29}{\mu\sqrt{N}}$$

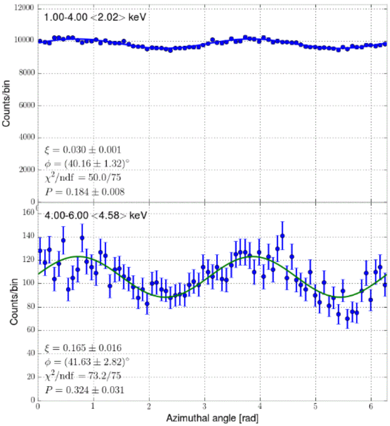
with N: total number of collected events

- Inverting the formula we can estimate how many event are needed:
  - Assuming $\mu = 0.5$ and a MDP = 1%, $N \approx 7.36 \times 10^5$
- Polarimetry requires a lot of events (much more than spectroscopy of imaging)
  - Large optics, long observation time, large μ

Map magnetic field of bright extended source

Example: Cassiopeia A (Cas A) Supernova Remnant (SNR)

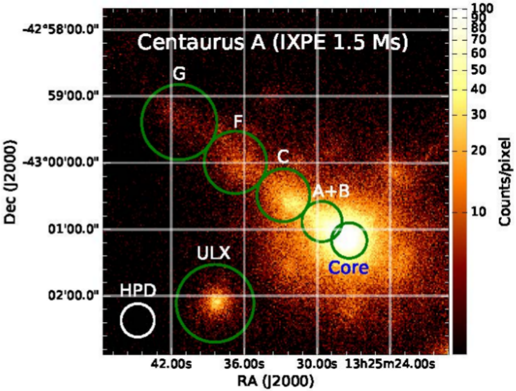




- Probe sites of cosmic-ray acceleration
  - Lines and thermal continuum dominate 1–4 keV
  - Non-thermal emission dominates 4–6 keV
- 1.5 Ms simulated IXPE observation

Polarization properties of bright AGN jets

Example: Centaurus A (CenA or NGC 5128)

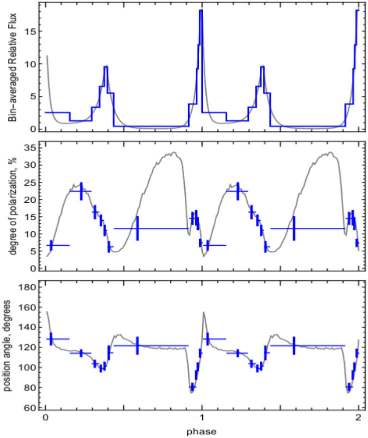


Region	MPD_{99}
Core	<7.0%
Jet	10.9%
Knot A+B	17.6%
Knot C	16.5%
Knot F	23.5%
Knot G	30.9%
ULX	14.8%

- 1.5 Ms simulated IXPE observation of central region

Phase-resolved polarimetry

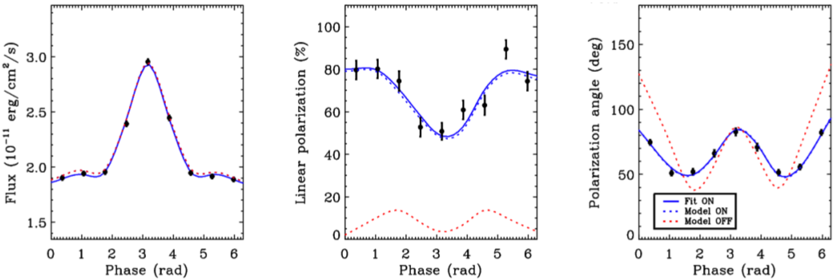
Example: Crab Pulsar



- Isolated pulsar in pulsar wind nebula (PWNe)
- 34-ms period
- 140 ks of simulated observation
  - IXPE expectation (in blue)
  - visible-band profile (in gray)
- The geometry of the system determines the polarization pattern
  - Adding 2 more panels to the phasogram

Test of Quantum Electrodynamic

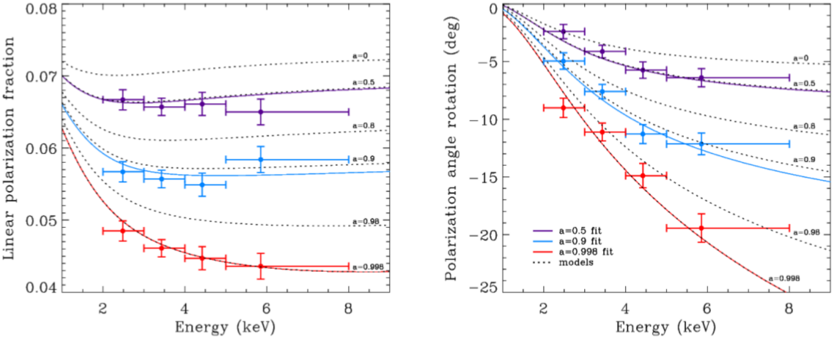
Example: 1RXS J170849.0-400910



- Magnetar is a neutron star with magnetic field up to 10^{15} Gauss
- Non-linear QED predicts birefringence in magnetized vacuum
  - Impacts polarization and position angle as functions of pulse phase
- 250 ks simulated IXPE observation to exclude QED-off

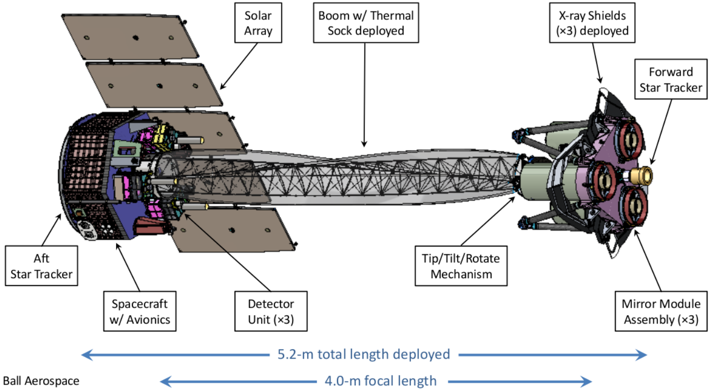
Measure Black-hole spin

Example: GRX1915+105



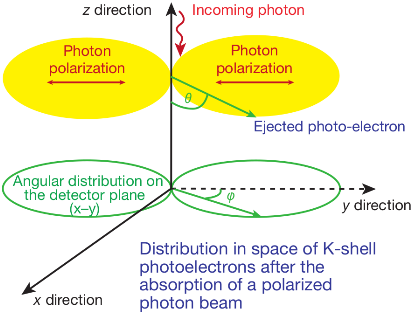
- Microquasar in accretion-dominated state
  - Scattering polarizes the thermal disk
  - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays
- 200 ks simulated IXPE observation

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

Detection principle: the photoelectric effect

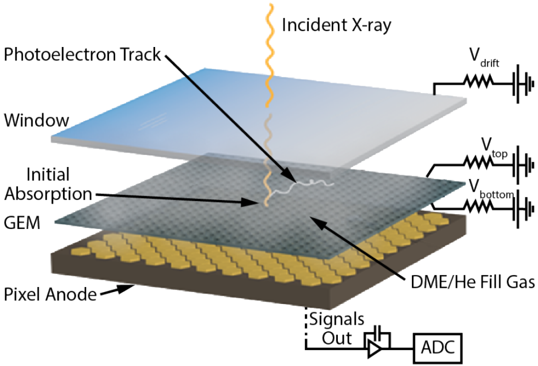


- ▷ Dominant interaction process at low energy (< 10 keV)
- ▷ Distribution of the direction of emission of a K-shell photoelectron 100% modulated for linearly polarized radiation:

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

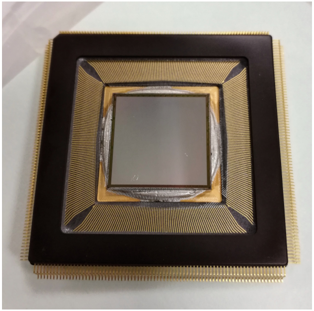
- ▷ Need to reconstruct the direction of emission of the photoelectron
  - ▷ The challenge is to be able to measure the initial part of the photoenectron track
- ▷ In principle this is the perfect polarization analyzer, but...
  - ▷ Granularity significantly smaller than the typical range (e.g. few μm in a solid for a 5 keV photoelectron)
  - ▷ Diffusion and scattering can smear out the emission direction information
  - ▷ Event reconstruction plays a significant role
- ▷ Modulation factor is always < 1 and energy dependent

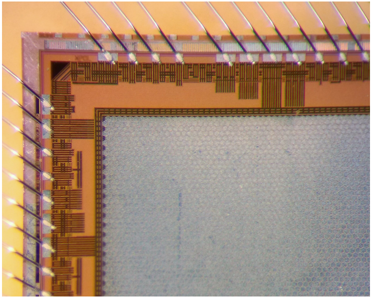
The Gas Pixel Detector (GPD)



- 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
- Fully two-dimensional (imaging)

The core of the detector: the ASIC

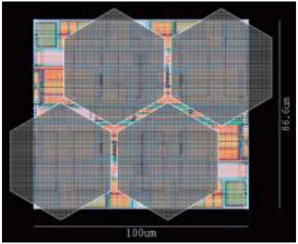


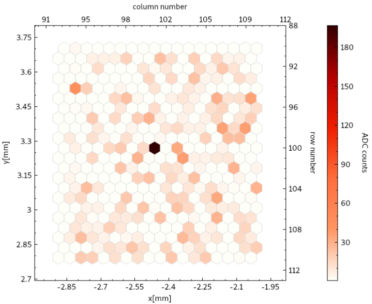


Properties

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

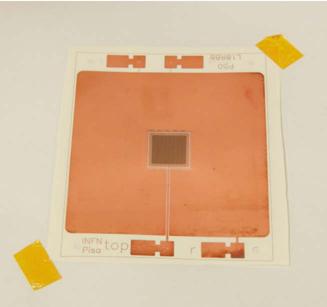
ASIC self-trigger and readout

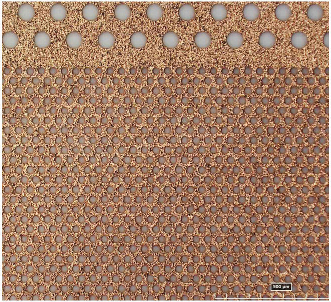




- Pixels are grouped in 2×2 minicluster to contribute to a single trigger with dedicated shaping amplifier
  - Single trigger threshold for all the ASIC
  - Pixels can be individually masked to the trigger
- Autonomous definition of a square region-of-interest (ROI) around the triggering miniclusters
  - 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

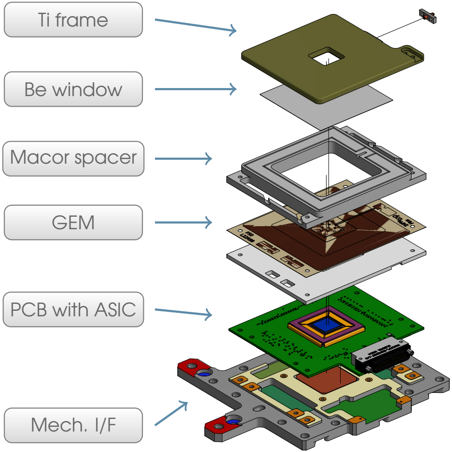
The Gas Electron Multiplier (GEM)





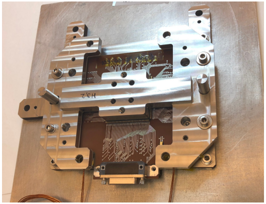
- Produced by RIKEN and SciEnergy in Japan
- Hexagonal hole pattern, with 50 μm pitch, 50 μm thick
- Active size matching ASIC + large guard ring for uniform drift field
- Liquid crystal polymer (LCP) insulator (laser etching technique)
- Mask alignment at a few μm level

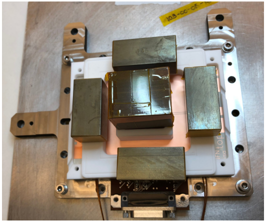
The GPD assembly

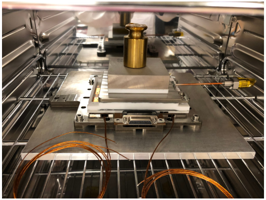


- ▷ Sealed detector
  - ▷ No gas system needed
- ▷ Ceramic parts for gas cell and GEM support
  - ▷ Low outgassing, for space application and gas purity
- ▷ A Ti frame acts as “drift” electrode
- ▷ X-ray window in Be, 50 μm thick
- ▷ ASIC in a standard package mounted on a custom PCB
  - ▷ Commercial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

Gluing everything together

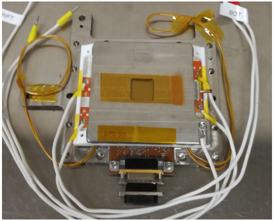


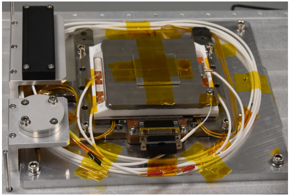


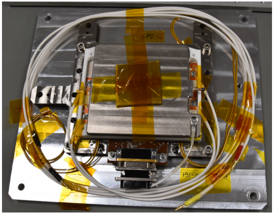


- ▷ Part procurement from different vendors
- ▷ Assembly at INFN-Pisa
  - ▷ Gluing with space compatible adhesive
- ▷ Final leak test with He at INFN-Pisa
  - ▷ Severe requirement on leak rate: $< 1 \cdot 10^{-9}$ mbar l/s
- ▷ Bake-out and filling at Oxford Instrument (OIT) in Finland
  - ▷ A 2 weeks bake-out at 100 °C
  - ▷ Filling with DME at 0.8 bar is done in the same facility
  - ▷ Finally GPD is permanently sealed by crimping the filling tube

The first GPD flight models



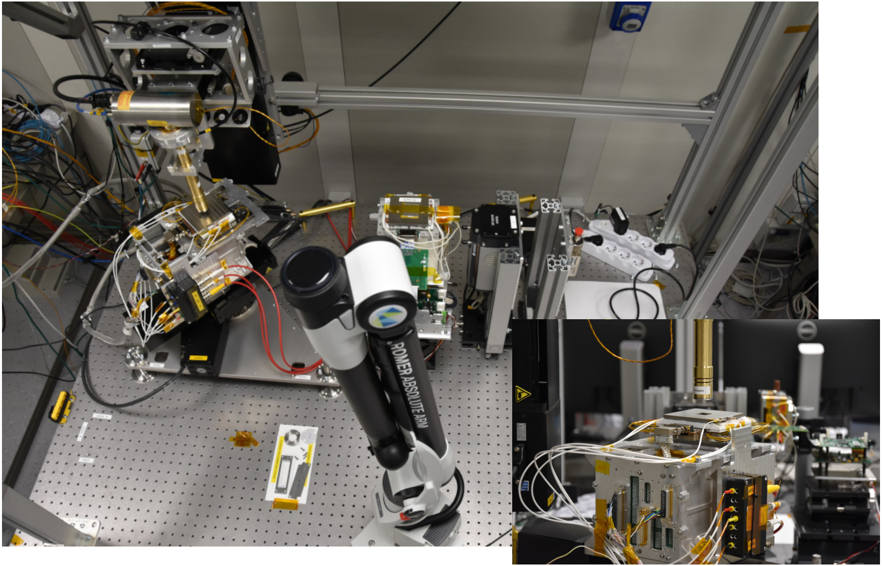




- ▷ A few EM produced in the last year
  - ▷ Refine the production process
  - ▷ Make additional test on the GPD
  - ▷ Exercise the calibration facilities (INAF in Rome and at MSFC)
- ▷ First 3 GPD FM ready
- ▷ Production well underway
- ▷ We plan to build $\sim$ 10 FM

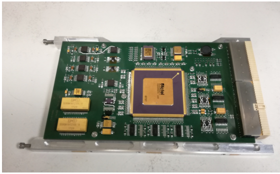
Testing the GPD with x-ray beams

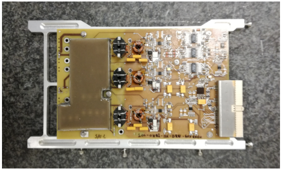
Calibration facility at INAF in Rome

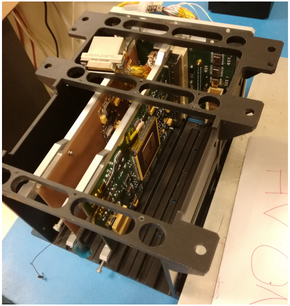


GPD readout

The Back-End Electronics (BEE)



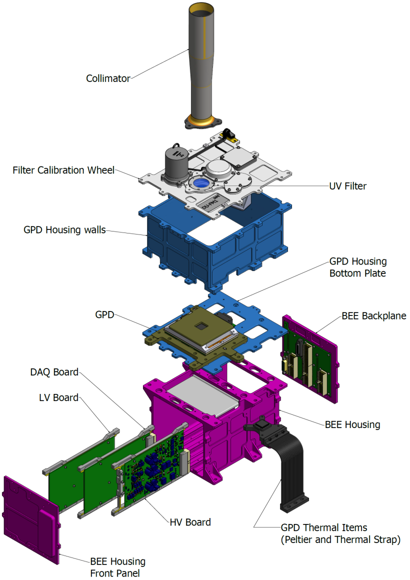




- Four PCBs in a dedicated housing:
  - Data Acquisition board (DAQ)
  - Low Voltage Power Supply, Board (LVPS)
  - High Voltage Supply Board (HVPS)
  - Back Plane (BP)
- FPGA based DAQ, with a 14-bit ADC for GPD data
- Two custom digital interfaces for communication:
  - Command and Control Interface (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

The Detector Unit (DU)

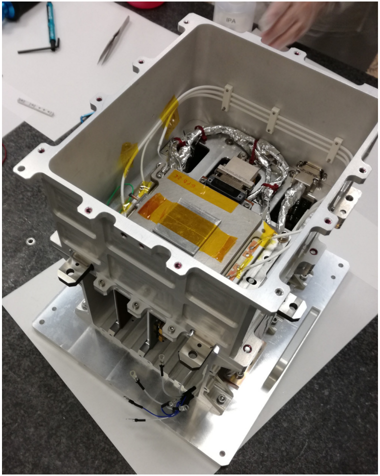
Exploded view

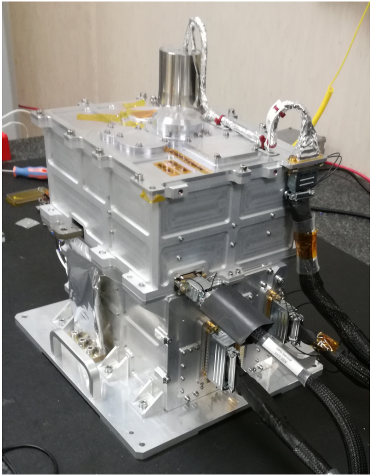


- The DU is the basic unit of the IXPE instrument
- DU sits on the top deck of the spacecraft
  - Mechanical and thermal interface at the bottom
- Back-end electronics mounted belod the GPD on a dedicated housing
- Dedicated GPD thermal control via TEC (Peltier) and thermal strap
- Filter and Calibration Wheel on top of the detector for in flight calibration and GPD monitoring
  - Both polarized and non polarized sources
- Stray light collimator to block diffuse light
  - Carbon fiber and Mo (and Au) coating

The Detector Unit (DU)

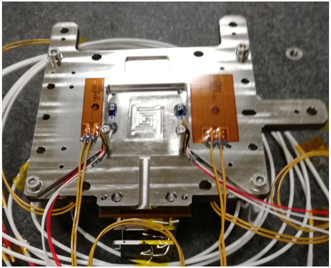
First assembly of the Engineering Model

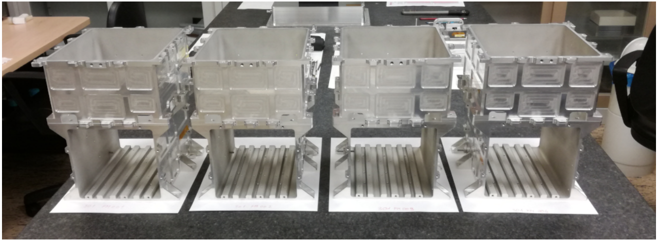




The DU FM assembly

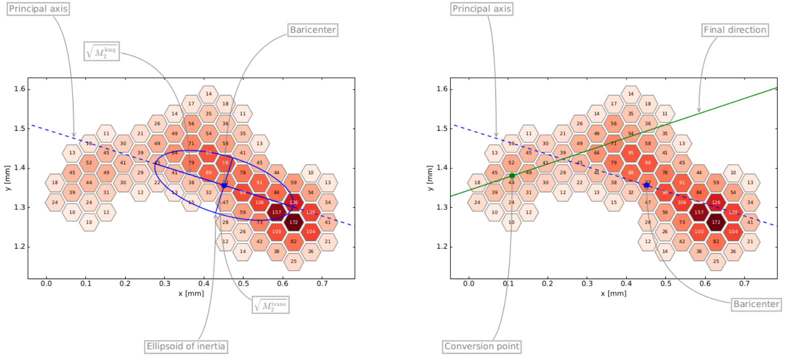
- ▷ Assembly of first DU just started
- ▷ Some components already available for the entire instrument
- ▷ Integration procedure developed with the EM
- ▷ FM integration & test is a quite long process:
  - ▷ Assembly and metrology
  - ▷ Electrical/functional test
  - ▷ Environmental test (Vibe, TVAC)
  - ▷ Full calibration with X-ray beams





Event reconstruction

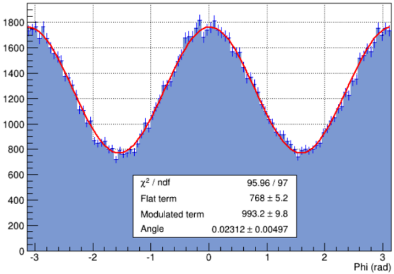
Real 5.9 keV photoelectron track



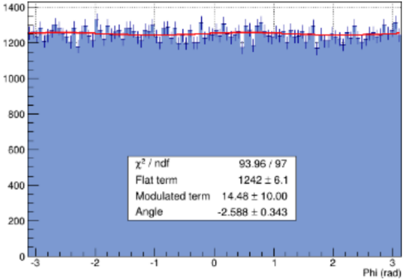
- Event by event reconstruction
- Iterative moment analysis to reconstruct relevant information
  - Interaction point: imaging
  - Photoelectron direction: polarimetry
  - Trigger output: timing
  - Pixel charge content: spectroscopy

Performance of the GPD as a focal-plane polarimeter

polarized source

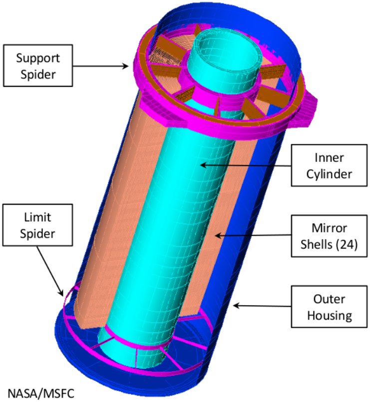


unpolarized source



- Modulation factor: 0.2 (0.7) at 2 (8) keV
  - Stability over ∼ 3 years demonstrated with a sealed detector
- ∼90 μm spatial resolution at 5.9 keV, measured ($\ll$track length)
  - Good match for a ∼25 arcsec-type X-ray optics with ∼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

Mirror Module Assembly (MMA)



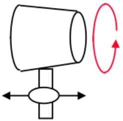
MMA Properties

Number of MMAs	3
Number of shells per MMA	24
Focal length	4000 mm
Shell length	600 mm
Inner–outer shell diameter	162–272 mm
Inner–outer shell thickness	0.18–0.26 mm
Shell material	Nickel–Cobalt alloy
Mass per MMA	30 kg (CBE)
Effective area per MMA	210 cm^2 (2.3 keV) $>$230 cm^2 (3–6 keV)
Angular resolution	$\leq$ 25 arcsec HPD
Field of view (detector-limited)	12.9 arcmin

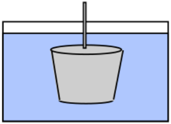
Mirror Production Process

Mandrel fabrication

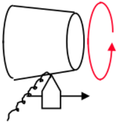
1. Machine mandrel from aluminum bar



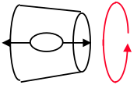
2. Coat mandrel with electroless nickel (Ni–P)



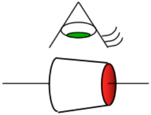
3. Diamond turn mandrel to sub-micron figure accuracy



4. Polish mandrel to 0.3-0.4 nm RMS

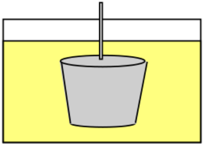


5. Conduct metrology on the mandrel

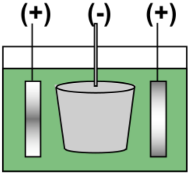


Mirror-shell forming

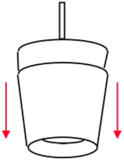
6. Passivate mandrel surface to reduce shell adhesion



7. Electroform Ni–Co shell onto mandrel



8. Separate shell from mandrel in chilled water



Ni–Co electroformed mirror shells

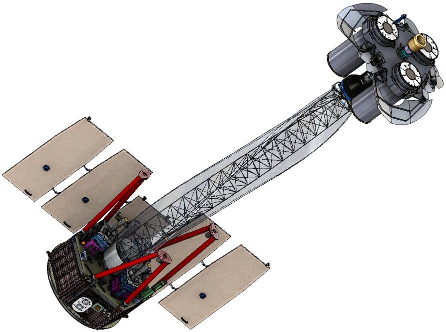
Conclusions

- A new NASA mission dedicated to X-ray polarimetry
  - After 40 years from the last polarimeter in orbit
- The IXPE satellite will explore the polarization of celestial sources in the 2-8 keV energy band
  - GPD at the focal plane of a X-ray optics
  - Will allow spatially-resolved polarimetry
- GPD FM production in progress
  - Three GPD FM already assembled and tested
  - Fourth FM in progress
  - Material available for $\sim$ 10 GPDs
- DU production started
  - DU EM already assembled – currently under electrical and functional test
  - First DU FM integration in progress
  - Proto-flight model philosophy: no test-dedicated qualification article foreseen
- Mirror construction at MSFC
  - Mandrell fabrication in progress
  - An EM already produced and under test
- Next milestone is the Mission CDR next June
- On our way for launch in 2021

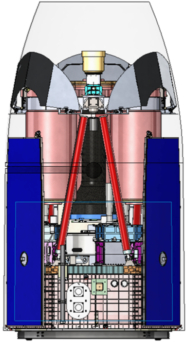
Spare slides

IXPE Satellite design

Deployed



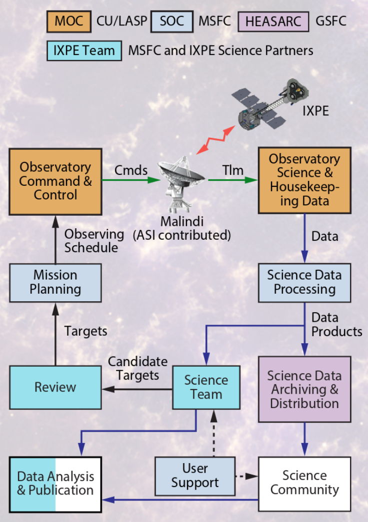
Stowed



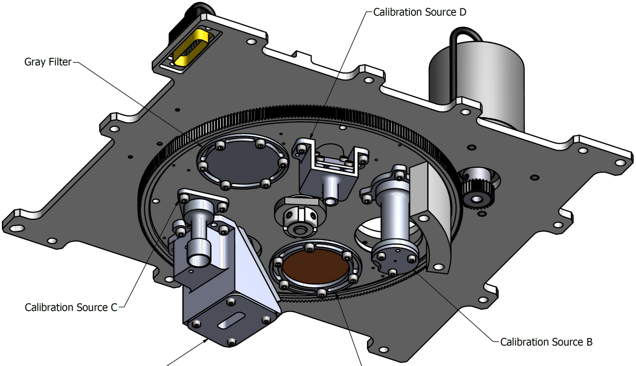
- Optical boom to be deployed after launch to extend the optics at the right position
- Satellite 3-axis stabilized, GPS positioning and star-tracker for pointing
- S-band communication
- Launch in stowed configuration, compatible with Pegasus XL fairing

Mission operation concept

- ▷ Point-and-stare observations of known target
- ▷ List of 49 targets defined for the first year of the mission
  - ▷ Evaluate observation plan
  - ▷ Evaluate pointing constraints
- ▷ 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)

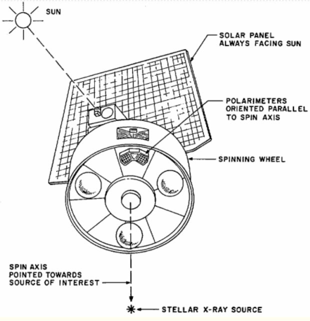


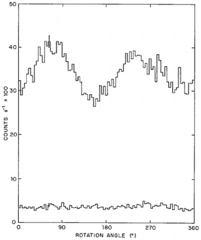
Filter and Calibration Wheel (FCW)

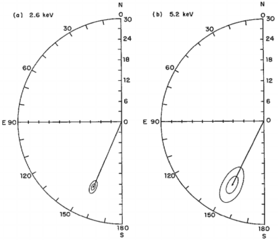


- 7 positions: open, closed, gray and 4 calibration sources:
  - Cal A: polarized at 5.9 keV and 2.9 keV
  - Cal B: collimated, non-polarized at 5.9 keV
  - Cal C: full-illumination at 5.9 keV
  - Cal D: full-illumination at 1.7 keV
- ^{55}Fe sources can be replaced from a dedicated aperture on the top side
- Position measurement with potentiometer and Hall sensors

The OSO-8 mission and the Crab polarization



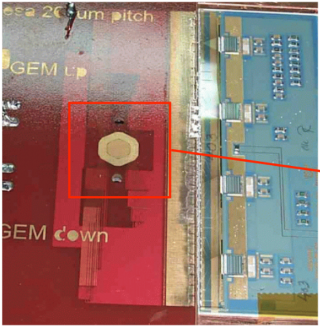




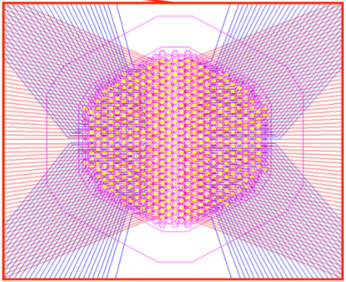
- ▷ Instrument rotate around pointing axis (spin stabilization of the satellite)
- ▷ Two narrow energy band 2.4–2.8 keV & 4.8–5.6 keV, but $\mu = 0.93$
- ▷ Measurements of the Crab Nebula: $P = 19.22 \pm 0.92\%$
  - ▷ M. C. Weisskopf, ApJL 220 (1978) L117-121

The proof of concept for the readout plane

circa 2000



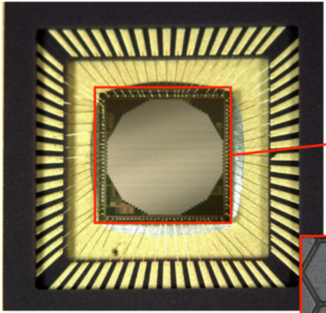
- Main technical challenge: fan-out from the readout anode to the front-end electronics.
- Yet it worked as a proof of principle.

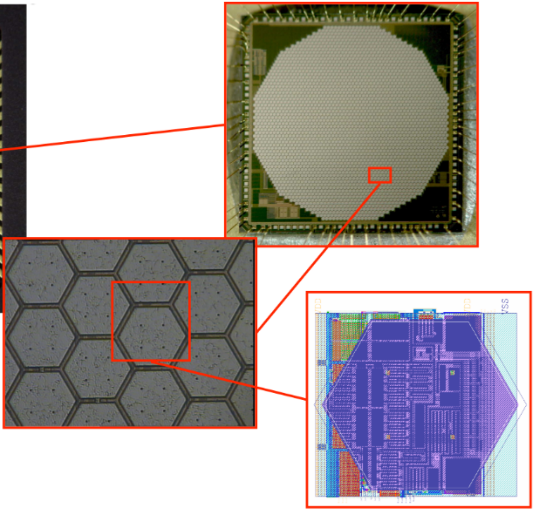


- Maximum number of channels: ~ 1000 at $\sim 200\ \mu$m pitch.
- High input capacitance to the preamplifier (high noise).
- Cross-talk between adjacent lines.

The turning point: a dedicated readout ASIC

Bellazzini et al., NIM A 535, 477–484 (2004)





- ▷ 2101 hexagonal pixels.
- ▷ 80 μm pitch.
- ▷ Metal top layer acting as a charge collecting anode.
- ▷ Integrating preamplifier, shaper, S/H, multiplexer.
- ▷ Serial readout via external ADC.