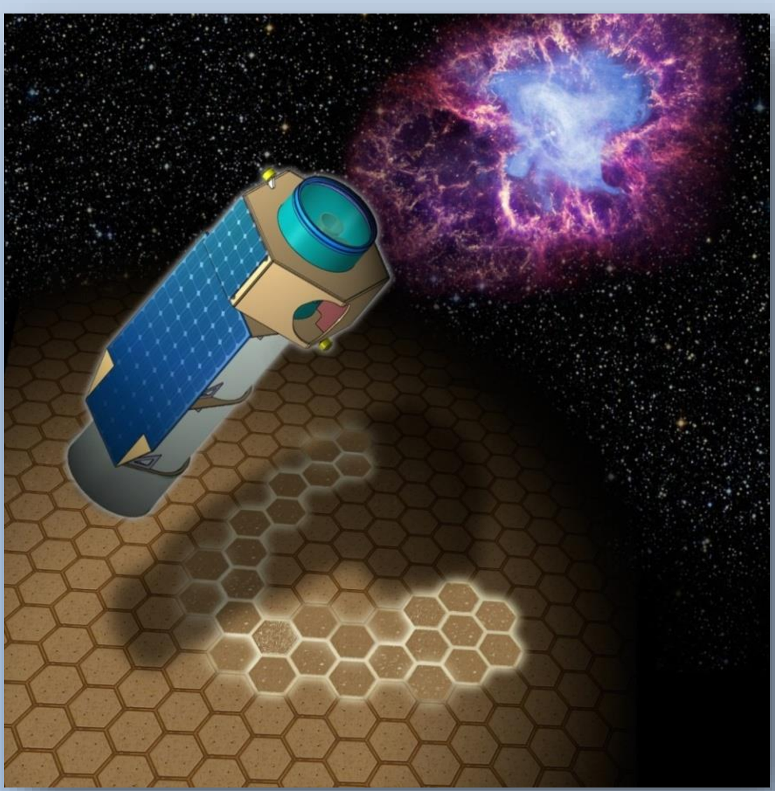
On ground and in-flight calibration

Picking the right direction

Xipe



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INFN-Torino, 4 May 2015

From XIPE Science Requirement Document

On-ground calibrations will be dedicated to verify the overall scientific performance of the instrument

- Sensitivity to polarization: Measurement of the **Modulation Factor, Efficiency** and **Collecting Area**
  SCI-POL-R-010: MDP 10% in 100 ks for 2x10-11 erg s^{-1} between 2 and 8 keV
  SCI-POL-R-020: Spurious polarization < 0.5%

- Imaging capability: Measurement of the **Point Spread Function** Vs **Energy**
  SCI-RES-R-030: Half-Energy Width < 30 arcsec (<20 arcsec goal)

- Spectral capability: Measurement of the **Energy Resolution** Vs **Energy**
  SCI-ENE-R-050: Full Width Half Maximum < 25% at 5.9 keV for point sources (20% goal)

In-flight calibrations are dedicated to monitor the performance during operation

Calibrations philosophy

On-ground calibrations

- Each Mirror Unit (MU, 3 flight models + 1 flight spare) and each Detector Unit (DU, 3 flight models + 1 flight spare) will be first calibrated alone and separately (*stand-alone calibrations*).
- Then, each assembly MU+DU (Telescope) will be calibrated together (*Telescope calibrations*).

In-flight calibrations

- Calibration sources on Filter Wheels (FWs) will allow for stand-alone calibrations at the DU level
- The observation of well-characterized celestial sources will instead provide calibrations for the XIPE telescopes.
- Calibrations of the MUs will not be possible in-flight.

On-ground calibrations facilities

On-ground calibration of the **DU** will be performed at the INAF-IAPS (Rome, Italy)

INAF-IAPS facility has been already used for basically the same measurements to be carried out for flight models.

We “only” need to move the equipments in a clean room.

The calibration campaign will take about 60 days for each DU (including margins and the time to set-up the measurements).

MU and **Telescope** calibrations will be performed at MPE PANTER X-ray testing facility in Garching (Germany)

PANTER facility is routinely used for the calibration of X-ray optics and instruments for High Energy Astrophysics

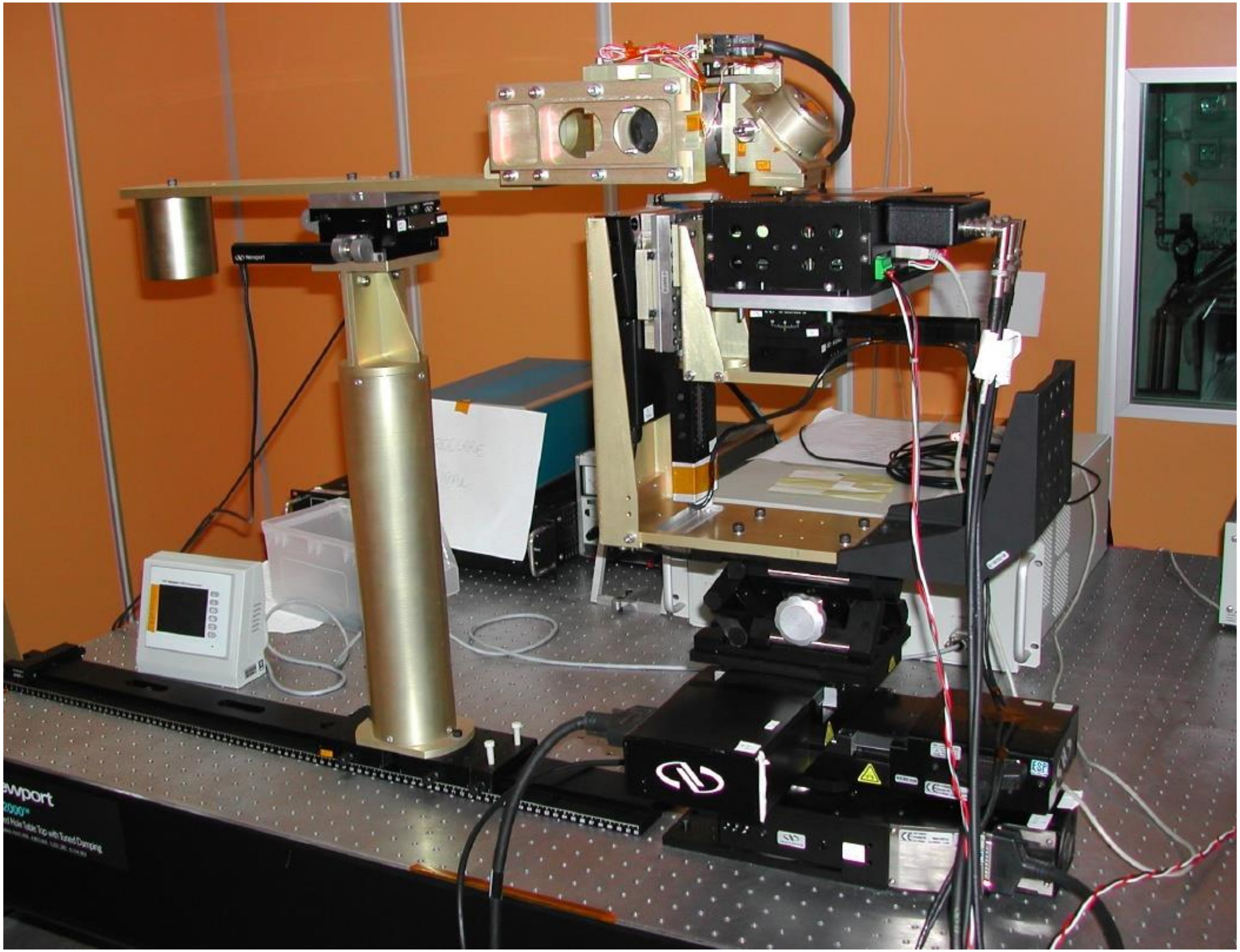
PANTER was used for the calibration of a GPD with a Mirror in a calibration campaign in November 2012

INAF-IAPS facility

Picking the right direction

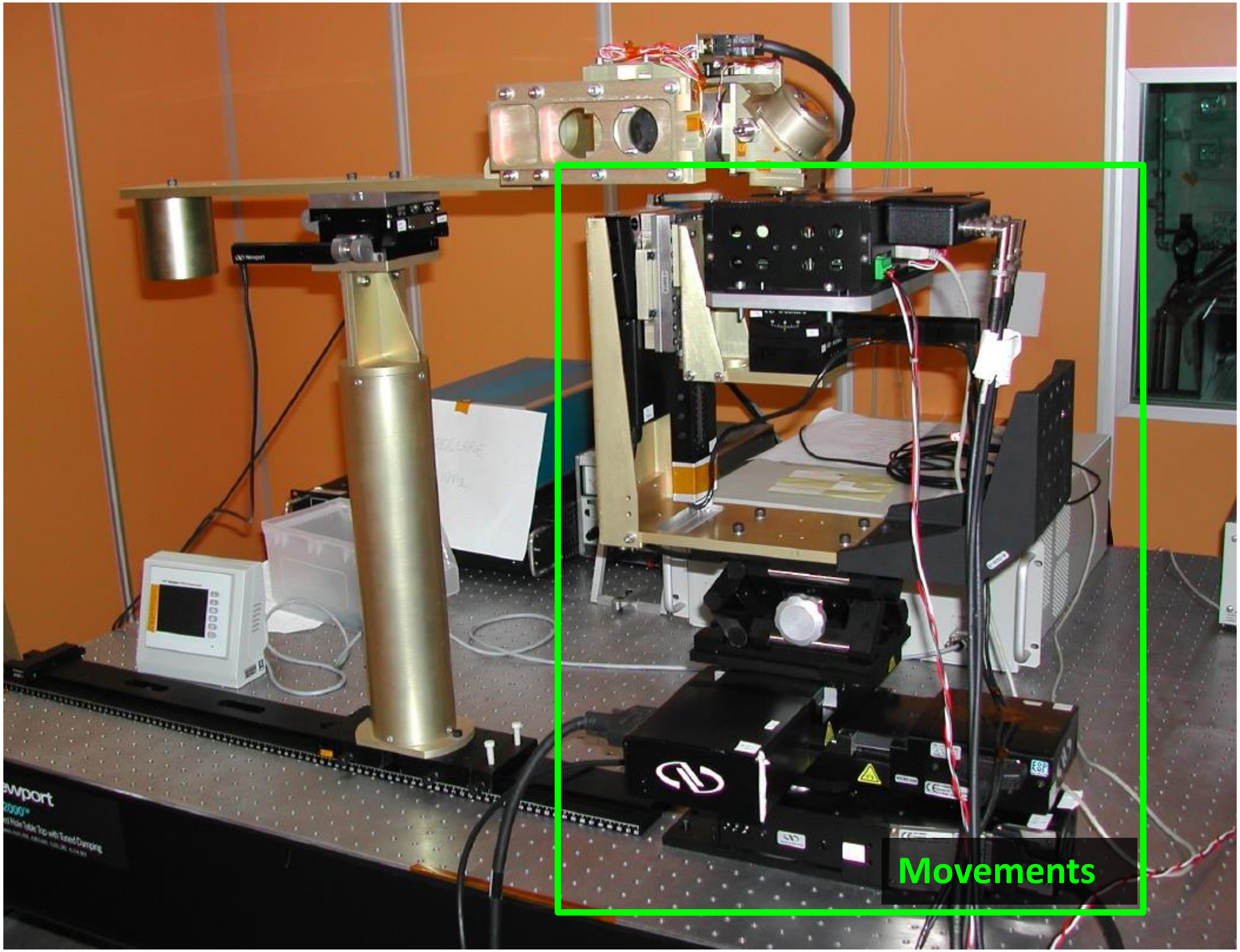
Xipe

Facility at INAF-IAPS



Muleri et al. 2008

Facility at INAF-IAPS

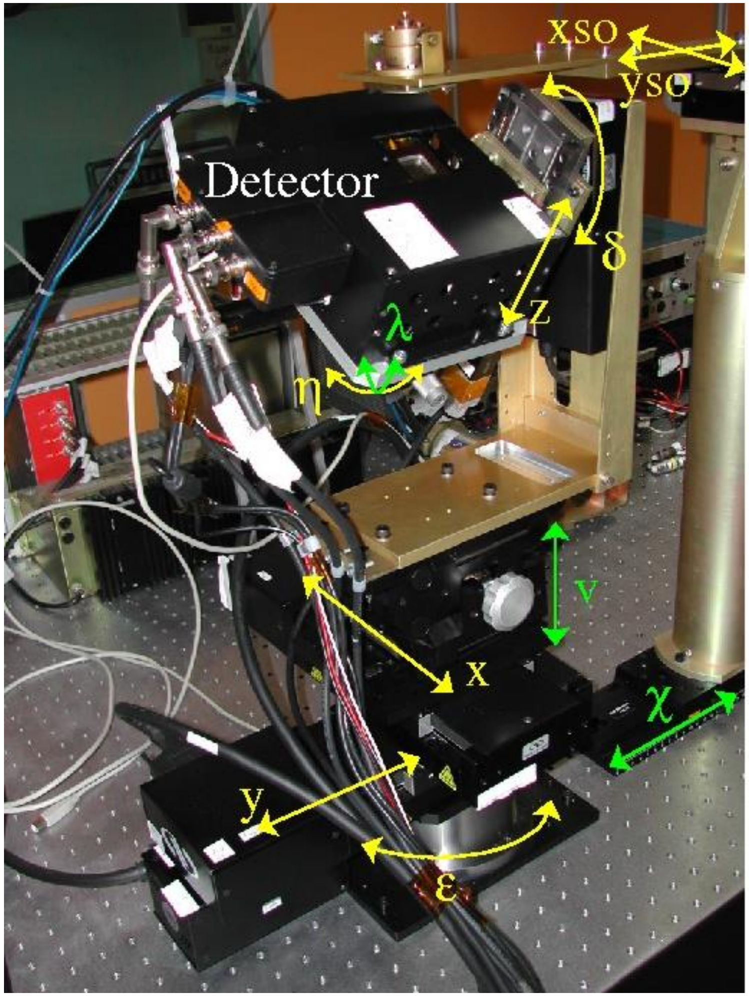


Muleri et al. 2008

Facility at INAF-IAPS

10 movements (8 motorized + 2 manual)
- controlled via LabView
- high resolution

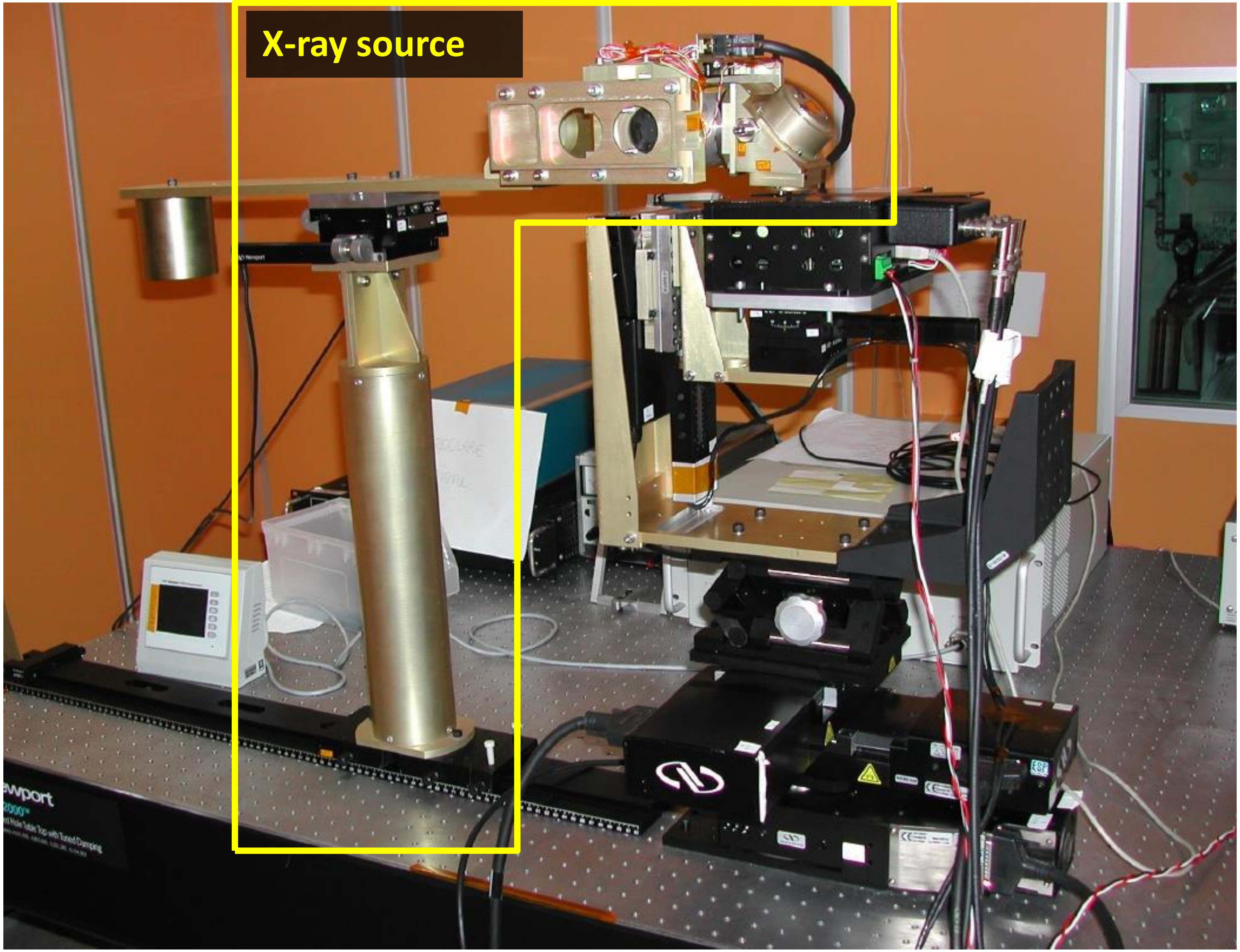
Name	Range	Resolution	Load (kg)	Allowed positions
δ	$0 \Leftrightarrow 360°$	$1''$	20.4	$0° \Leftrightarrow 60°, 300° \Leftrightarrow 0°$
ϵ	$0 \Leftrightarrow 360°$	$0.2''$	183.7	$0° \Leftrightarrow 180°, 180° \Leftrightarrow 0°$
x	$-25 \Leftrightarrow +25$ mm	0.5 μm	25.5	-25 mm $\Leftrightarrow$ 25 mm
y	$-25 \Leftrightarrow +25$ mm	0.5 μm	25.5	-25 mm $\Leftrightarrow$ 25 mm
z	$0 \Leftrightarrow 50$ mm	—	10.	0 mm $\Leftrightarrow$ 50mm
η	$0 \Leftrightarrow 25$ mm	0.1 μm	9.2	0 mm $\Leftrightarrow$ 25 mm
xso	$0 \Leftrightarrow 25$ mm	0.1 μm	9.2	0 mm $\Leftrightarrow$ 25 mm
yso	$0 \Leftrightarrow 25$ mm	0.1 μm	9.2	0 mm $\Leftrightarrow$ 25 mm



Motorized stages
Manual stages

A second "tower" is available.
Main differences:
X range 50 cm
Y range 25 cm

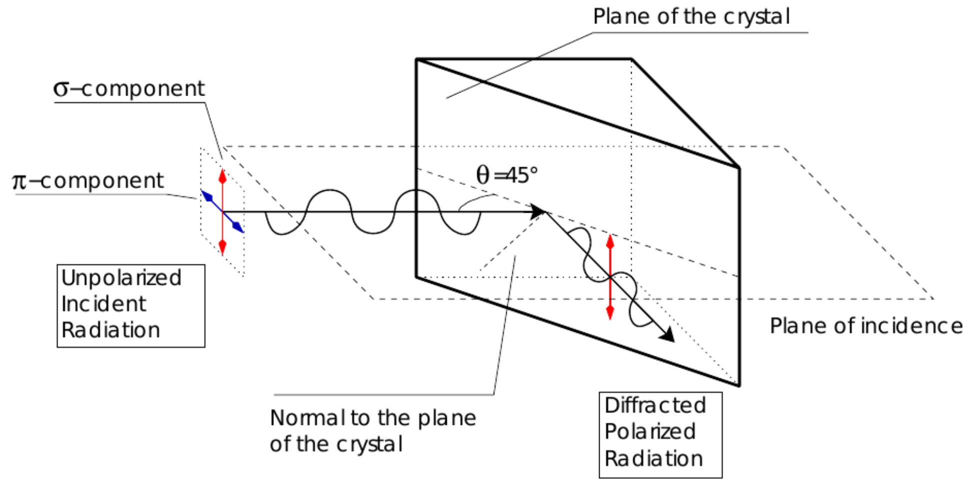
Facility at INAF-IAPS



Muleri et al. 2008

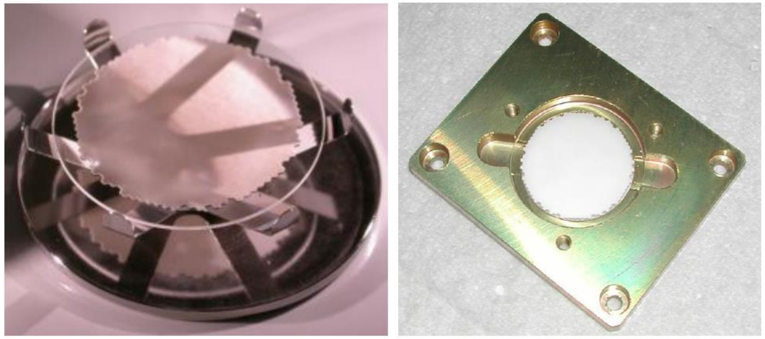
Facility at INAF-IAPS

Based on Bragg diffraction at 45 degrees



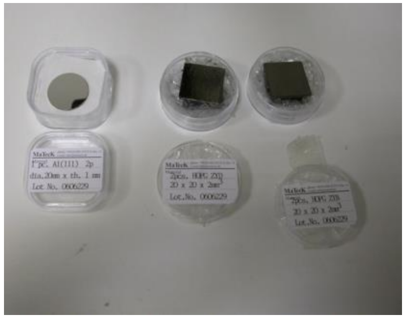
Different crystals can diffract at 45° photons at different energies: $E = \frac{nhc}{2d\sin\theta}$

Incident and diffracted radiation collimated with capillary plates



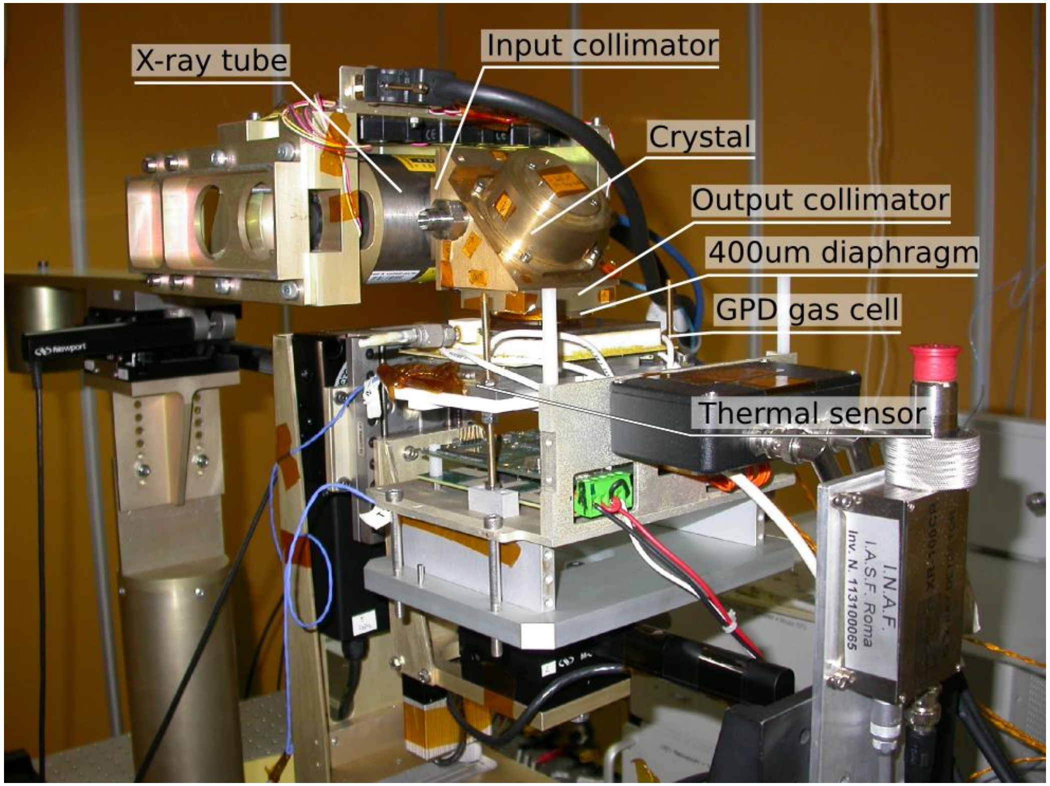
Capillary plates by Hamamatsu

LiF crystal



Al / Gr /Gr crystals

Facility at INAF-IAPS



Energy (keV)	Crystal	X-ray source
1.64	ADP	Continuum
2.01	PET	Continuum
2.62	Graphite	Continuum
2.69	Ge (111)	Rh Lα, 50 W
3.69	Al	Ca Kα, 0.2 W
4.51	CaF_2	Ti Kα, 50 W
5.90	LiF (220)	^{55}Fe
6.40	Si (100)	Fe Kα, 50 W
8.05	Ge (111)	Cu Kα, 2 W
9.71	LiF (420)	Au Lα, 25 W
17.48	LiF (800)	Mo Kα, 50 W

+ integer multiples

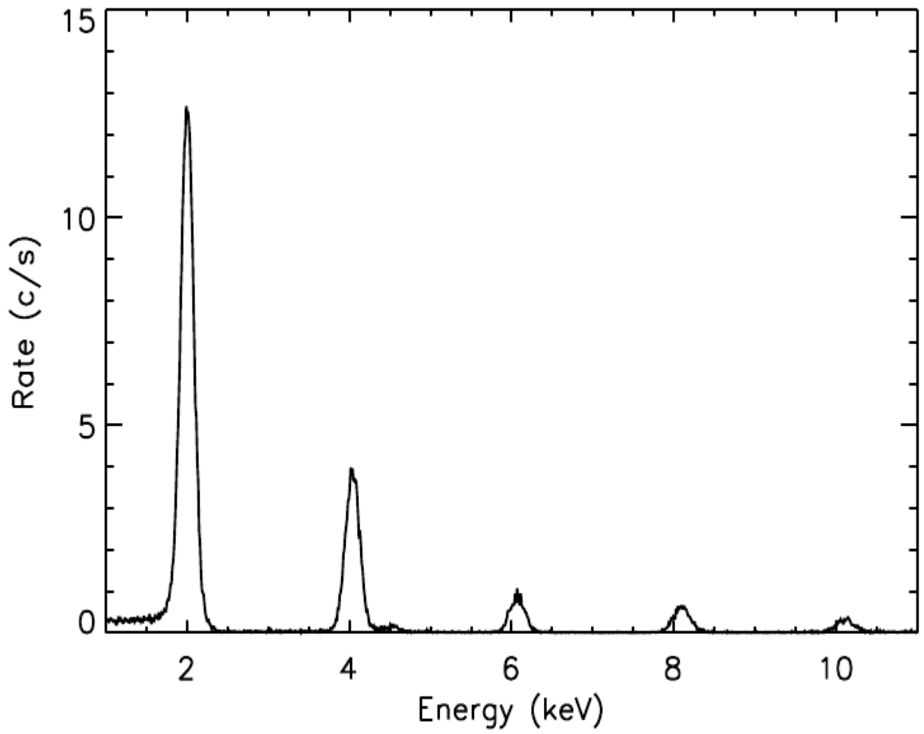
Diaphragms (2 mm – 25 µm) and collimators also available

Flux produced – Polarized source

Facility at INAF-IAPS

- Diffraction of continuum emission on PET crystal (Ti tube, HV=15 kV, I=0.5 mA)
- Flux measured with a Amptek XR100CR Si-PIN detector

Energy	Flux produced (c/s)
2.01 keV – I order	224.0+-1.5
4.02 keV – II order	73.5+-1.0
6.03 keV – III order	17.10+-0.39
8.04 keV – IV order	13.44+-0.43
10.5 keV – V order	7.41+-0.27



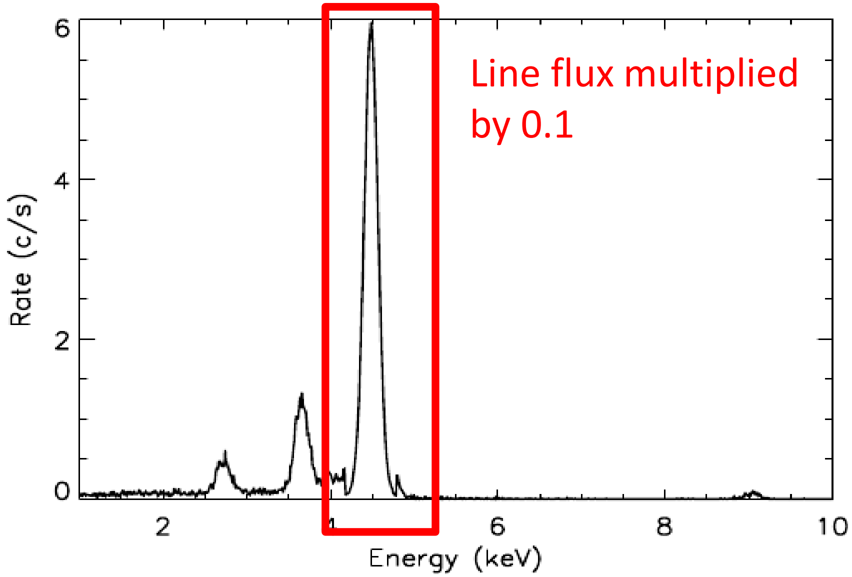
At full power, fluxes 22 times higher (but some background at high energy)

Flux produced – Polarized source

Facility at INAF-IAPS

- Diffraction of Ti Kα emission on CaF_2 crystal (Ti tube, HV=10 kV, I=0.04 mA)
- Flux measured with a Amptek XR100CR Si-PIN detector
- Beam ~2x2 mm^2

Energy	Flux measured (c/s)
4.511 keV – I order	1073.7±3.0
3.69 keV – Ca fluorescence	18.04±0.47



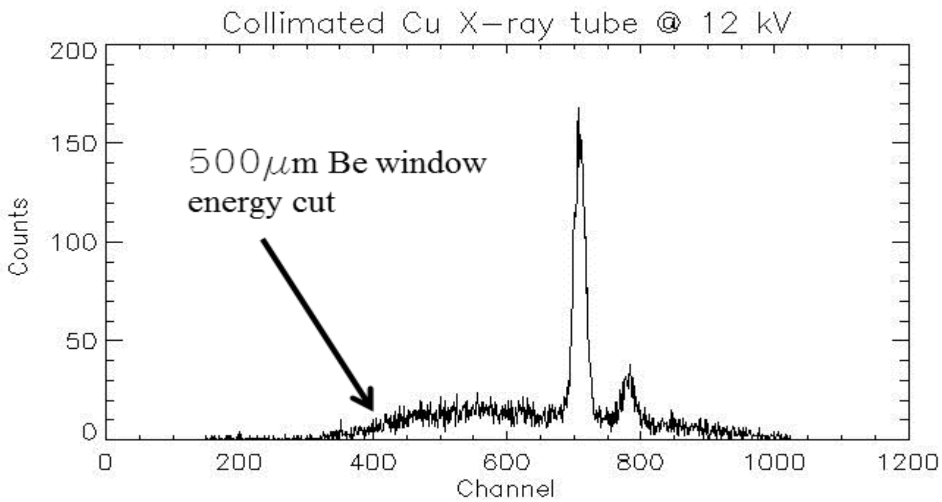
At full power, fluxes 250 times higher (but some background at high energy)

Facility at INAF-IAPS

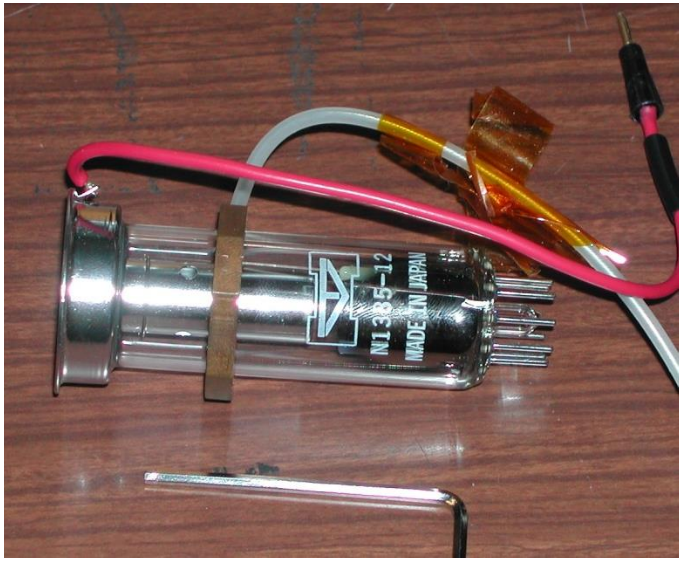
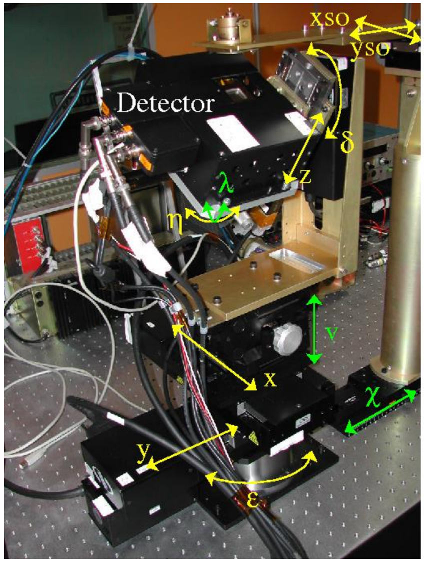
(Nearly) unpolarized photons can be produced with:

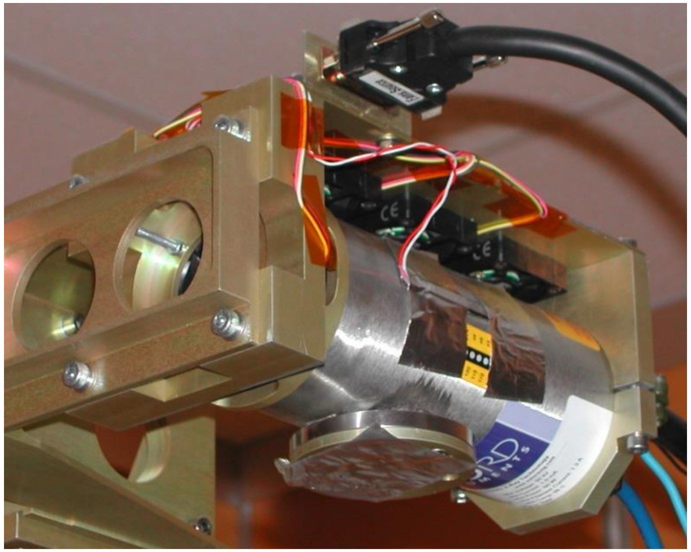
- ^{55}Fe radioactive source at 5.9 keV
- Calcium Head-on X-ray at 3.7 keV (P<1%)
- Copper Head-on X-ray tube at 8.05 keV

Polarization of other X-ray tubes small but probably not negligible



Rotation of the detector can be used to average it



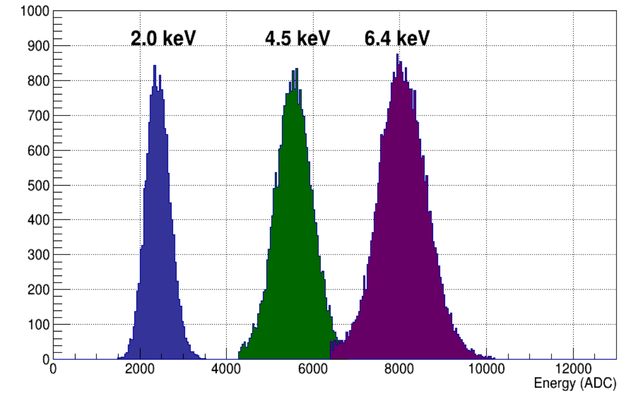
DU stand-alone calibration

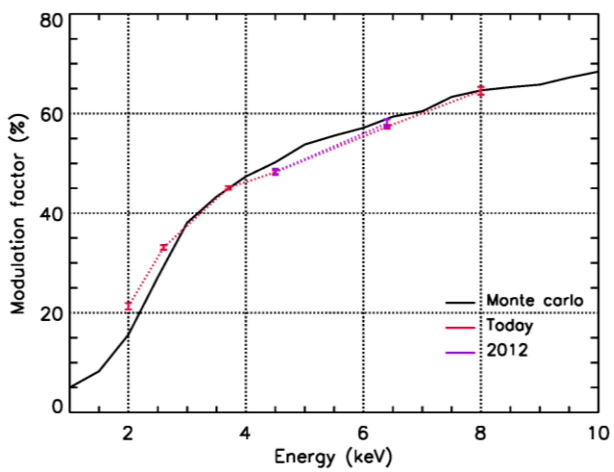
Picking the right direction

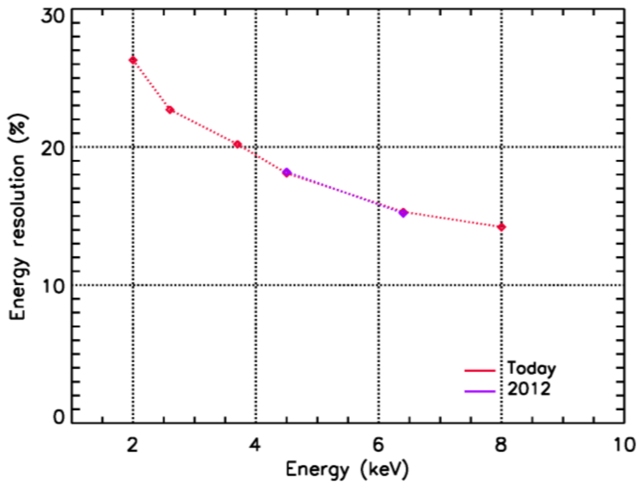
Xipe

DU stand-alone calibration

- Different crystal/X-ray tube assembly for entirely covering the energy range of the GPD: **1.7, 2.0, 2.6, 3.7, 4.5, 5.2, 6.4, 8.0, 9.7 keV**
- Beam with a 0.4 mm diameter (comparable with the telescope point spread function).
- Modulation factor measured at the center of the detector.
- For a reference energy (4.5 keV TBV), μ will be measured in 5x5 positions of the instrument sensitive area + 5 measurements to check the stability of the source.
- The same measurements can be used to derive the dependence of the energy resolution on energy.



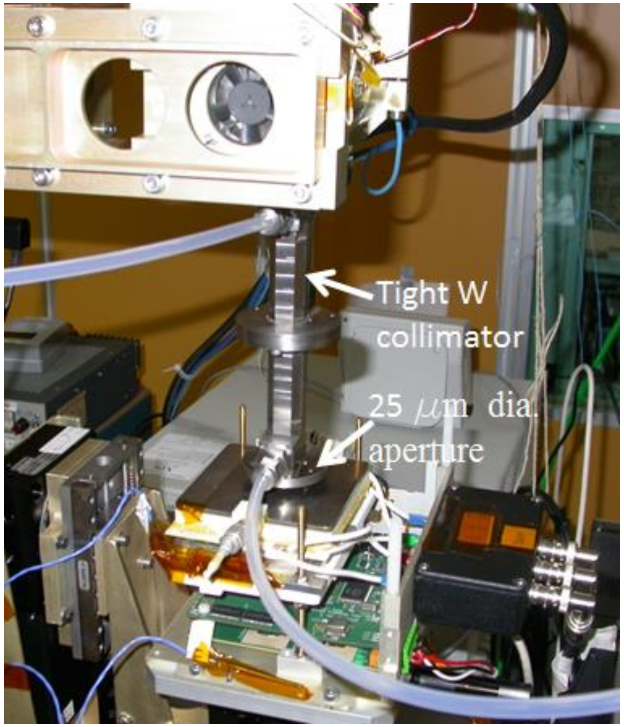




DU stand-alone calibration

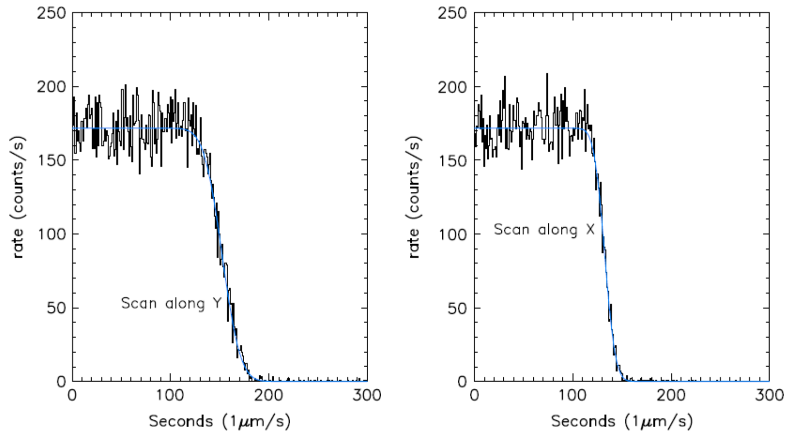
Measurements with a pencil beam
- 25 μm diaphragm at 17 cm
- Spot dimensions depend to some extent on the X-ray tube

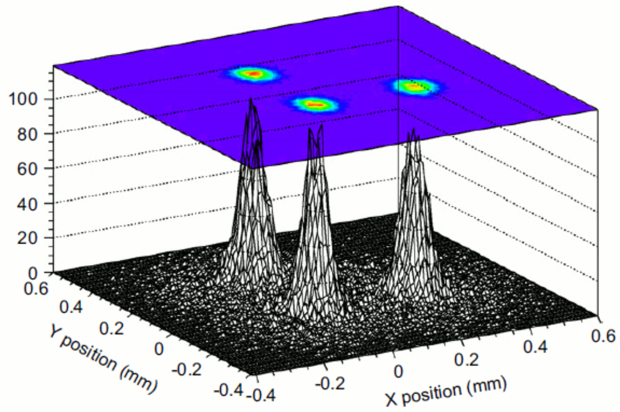
Molybdenum HV=20 kV, I = 0.5 mA	Titanium HV = 30 kV, I = 0.4 A	Copper HV = 12 kV, I=0.15 mA
σ_X	σ_X	σ_X
11.7 μm	8.7 μm	14.1 μm
σ_Y	σ_Y	σ_Y
32.9 μm	14.7 μm	11.6 μm



Soffitta et al. 2013

Measured with a scanning technique





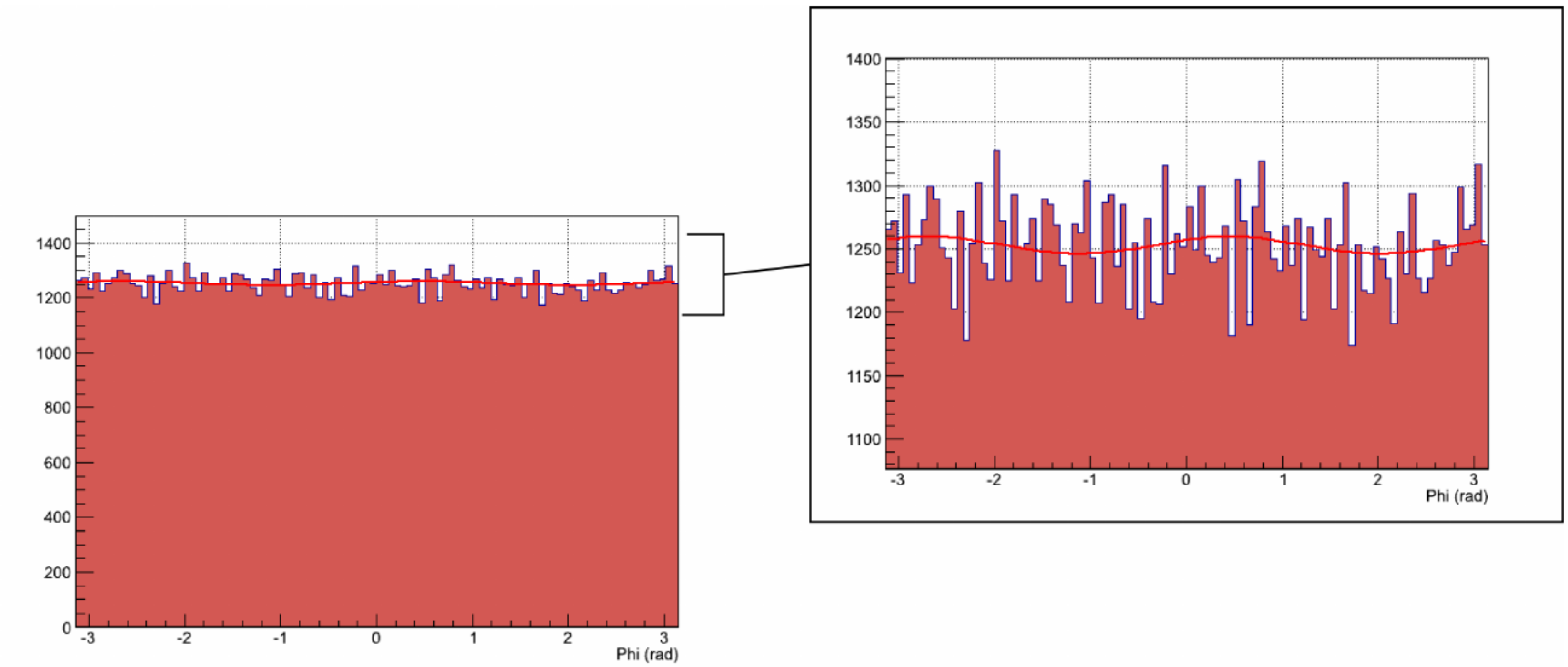
3x3 positions and at three energies (2.3, 4.5 and 9.7 keV, TBV)

Absence of spurious polarization

DU stand-alone calibration

3 energies: ^{55}Fe (5.9 keV) + head-on X-ray tube (either 3.7 or 8.0 keV) + 2.3 keV

3x3 positions

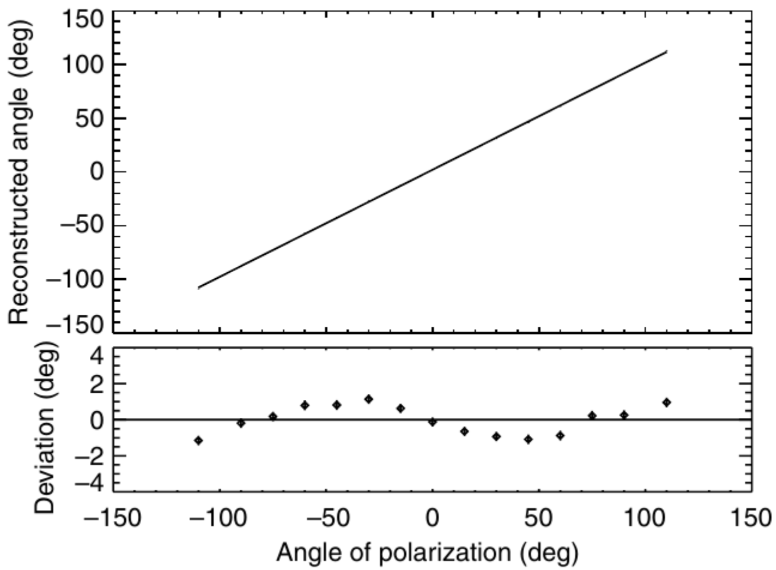


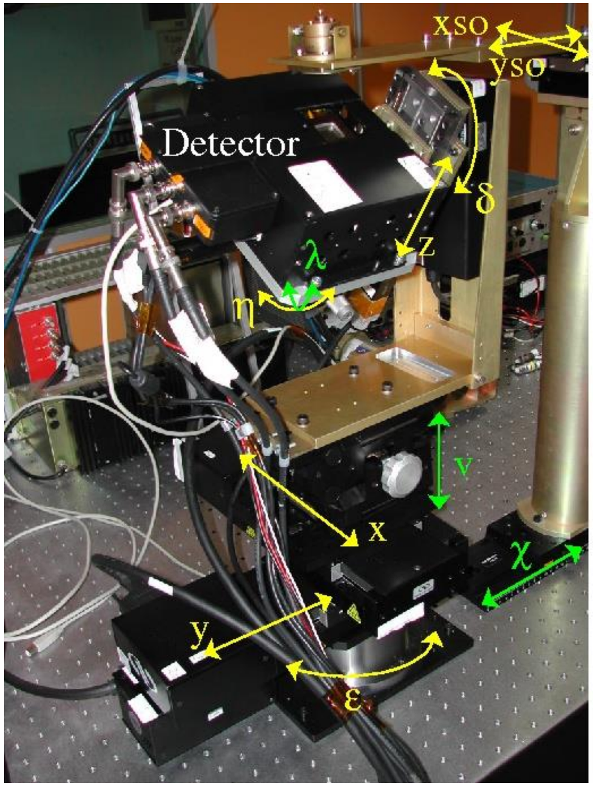
DU stand-alone calibration

The peak of the modulation curve corresponds to the angle of polarization

➢Need to check (and, in case, calibrate) the relation between the expected and measured angle of polarization

1. Center the beam with the axis of rotation of ε
2. Move the spot in the area of the detector to study with X and Y
3. Rotate ε of the appropriate angle



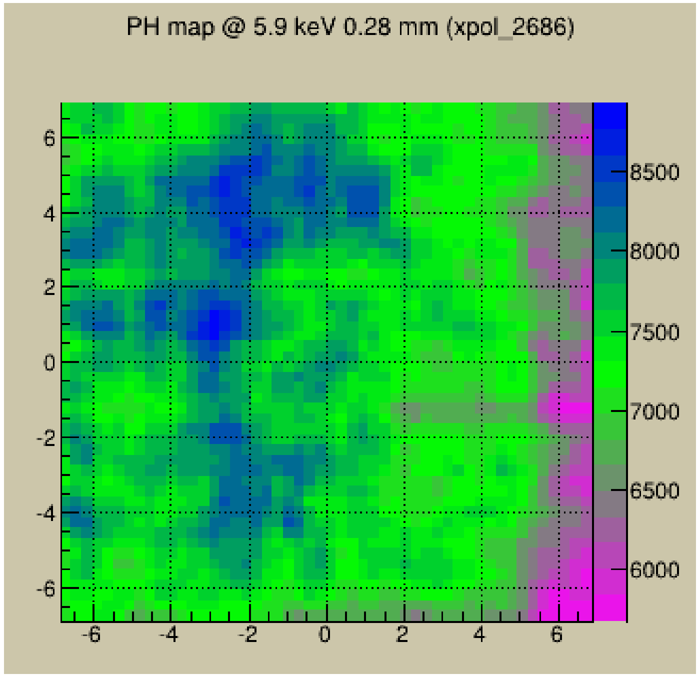


12 angle values + 3 control positions at 2 energies (3.7 and 4.5 keV) in one point

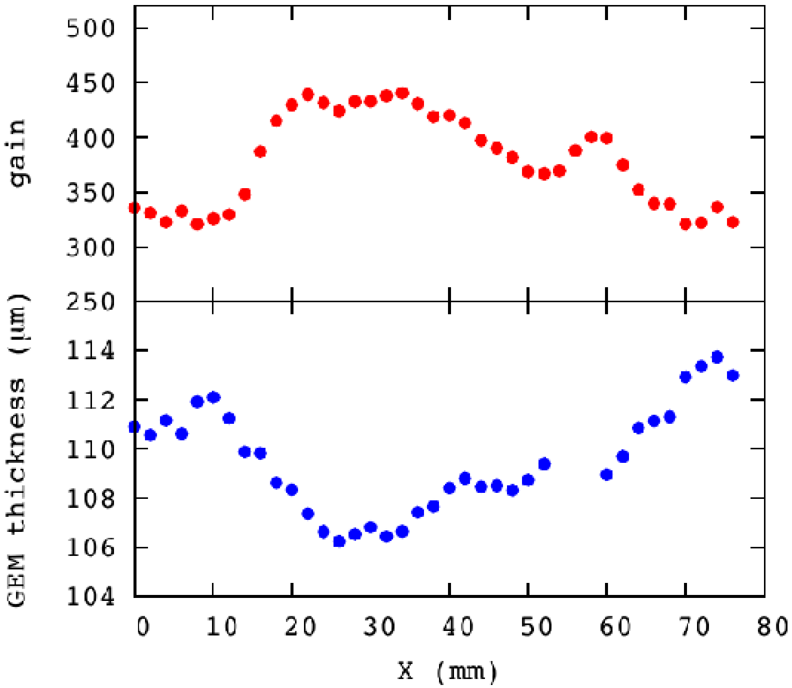
DU stand-alone calibration

To map (and correct) the gain disuniformities all over the sensitive area

- Gain disuniformities spoil the energy resolution (and, ultimately, the measurement of the polarization degree)
- The pattern should be constant with time and energy
- T hey are related to few-µm-scale differences in the GEM thickness (Takeuchi et al. 2014)



GEM gain map of the GPD at 5.9 keV
(0.28 mm spatial resolution)



Takeuchi et al. 2014

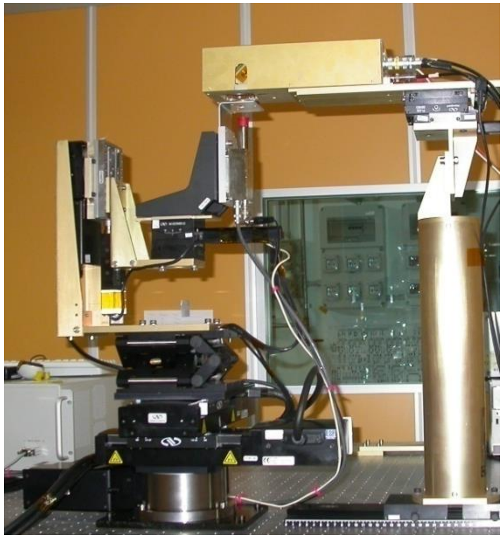
Flat field illumination at 2 energies (3.7 and 5.9 keV)

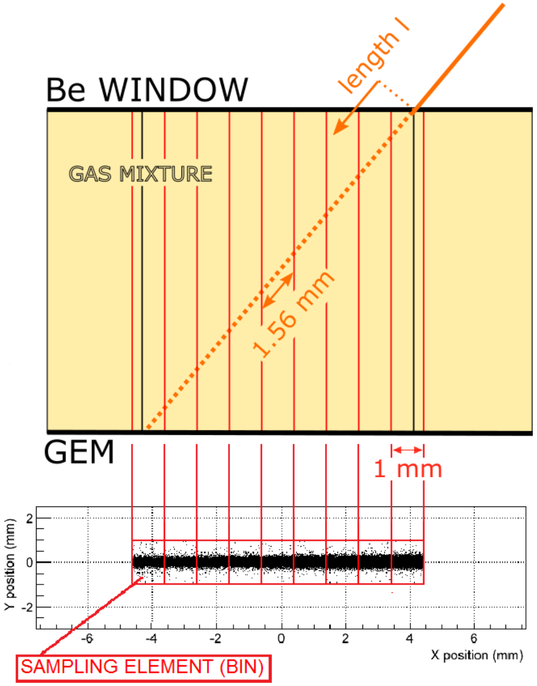
Efficiency measurements

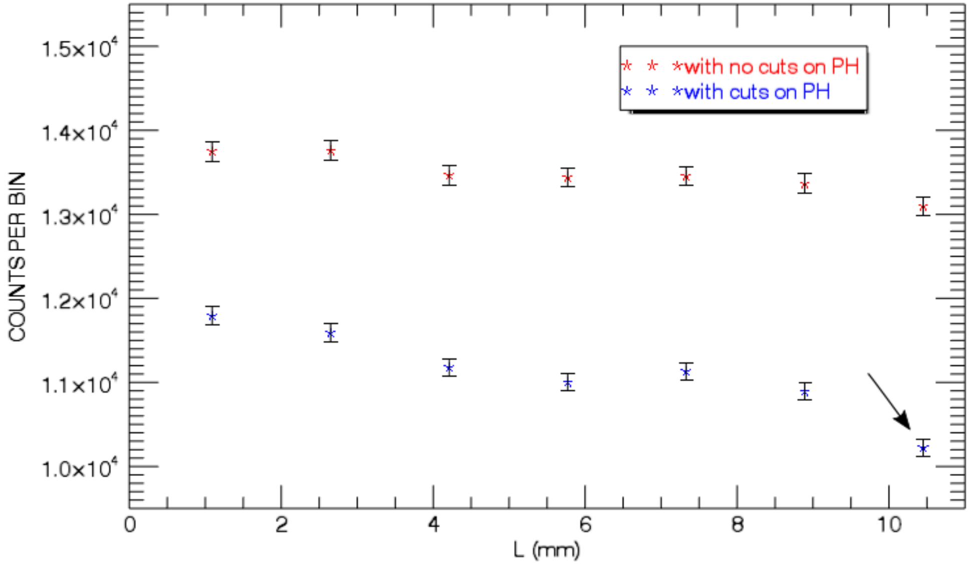
DU stand-alone calibration

Efficiency of the GPD will be measured by:

- comparing the counting rate with that of a detector of known efficiency
  - Error may be of the order of 10%
  - also foreseen during End-To-End calibrations
- studying the differential absorption along the path of the photons (*inclined-measurement setup*)
  - path length derived by the absorption point
  - measurement of the absolute efficiency, errors <15%





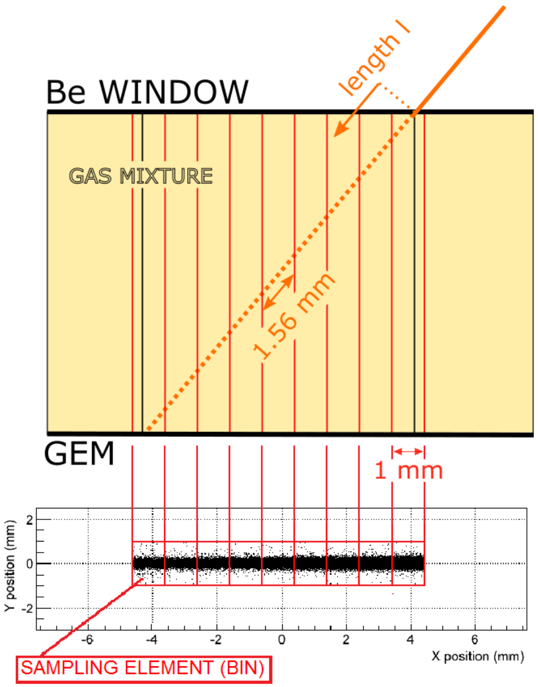


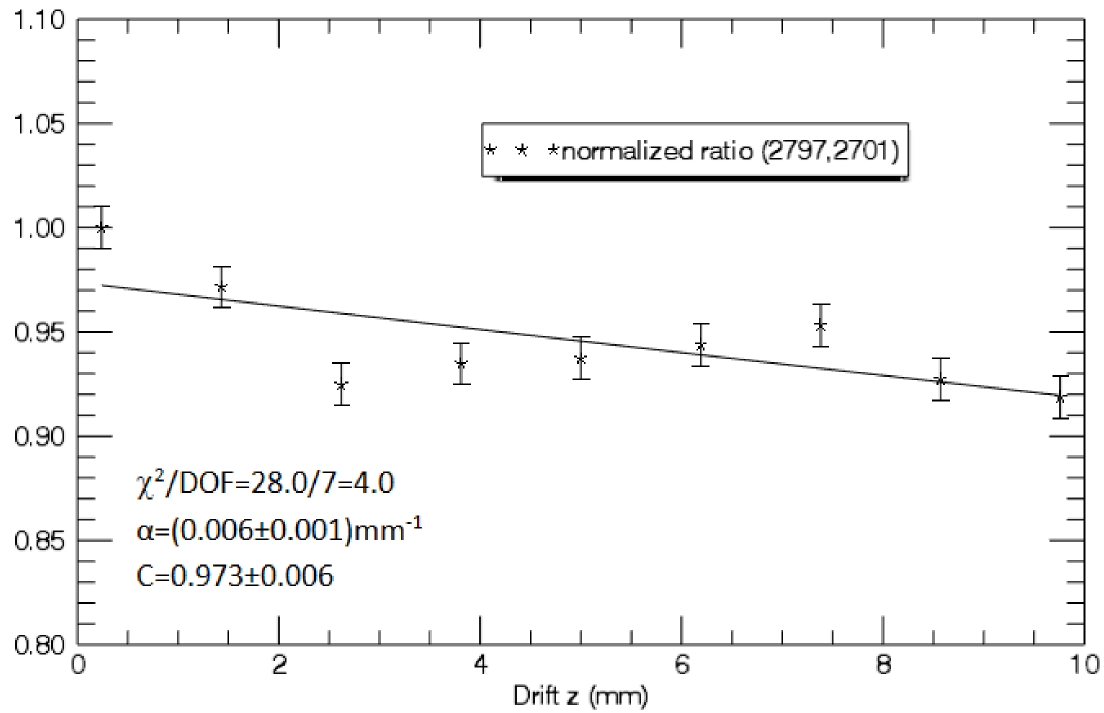
Credit: D. Buongiorno

DU stand-alone calibration

The same inclined measurement can be used to derive the attachment coefficient.

In this case, we are interested in the peak position as a function of the drift





Credit: D. Buongiorno

Quantify the pollution of the gas mixture.

Independent indication of the energy resolution behavior Vs time

DU stand-alone calibration

Calibration	Energy (keV)	XY Positions	Angle of polarization	Time for each position (ks)	Live total time (ks)	Live total time (days)
Modulation factor/ Energy resolution	1.7, 2.0, 2.6, 3.7, 4.5, 5.2, 6.4, 8.0, 9.7	2x2	1	15	540	6.3
Modulation factor/ Energy resolution	4.5	5x5+5	1	10	300	3.5
Spatial resolution	2.3, 4.5, 9.7	3x3+2	1	5	165	1.9
Spurious modulation	2.3, 3.7, 5.9	3x3+2	1	25	825	9.5
Angle of polarization	3.7, 4.5	1	12+3	15	450	5.2
Gain mapping	3.7, 5.9	1	1	100	200	2.3
Efficiency	3.7, 4.5, 6.4	1	1	10	30	0.3
Inclined measurement	3.7, 4.5, 6.4, 8.0	1	1	10	40	0.5
					TOT	29.5
Contingency+Set-up mounting/unmounting						60

MU & Telescope calibration

Picking the right direction

The source is 123 m far from the experimental chamber.

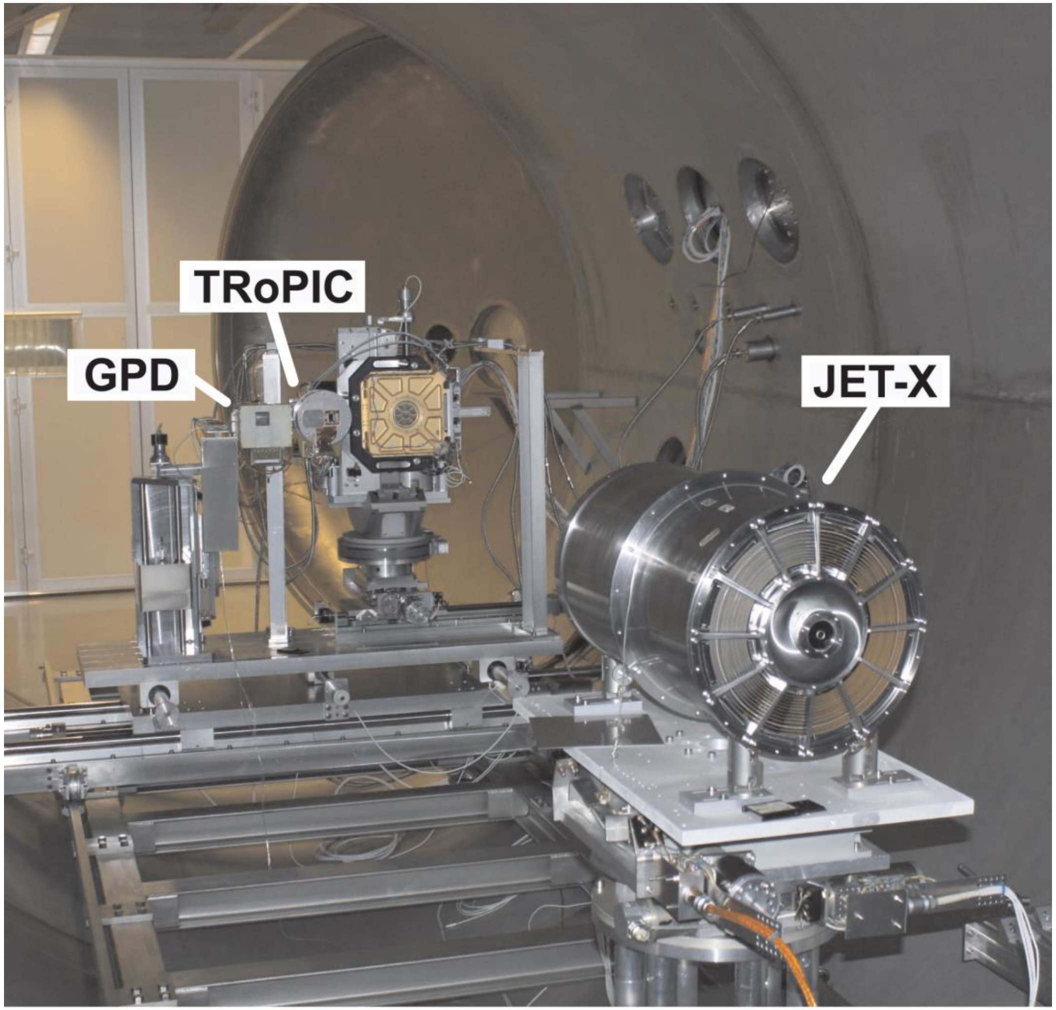
The X-ray optics and the detector can be moved to account for the finite distance of the source and the alignment.

Different energies available in the energy range 0.18-8.4 keV.

Filters can be used to select nearly monochromatic photons

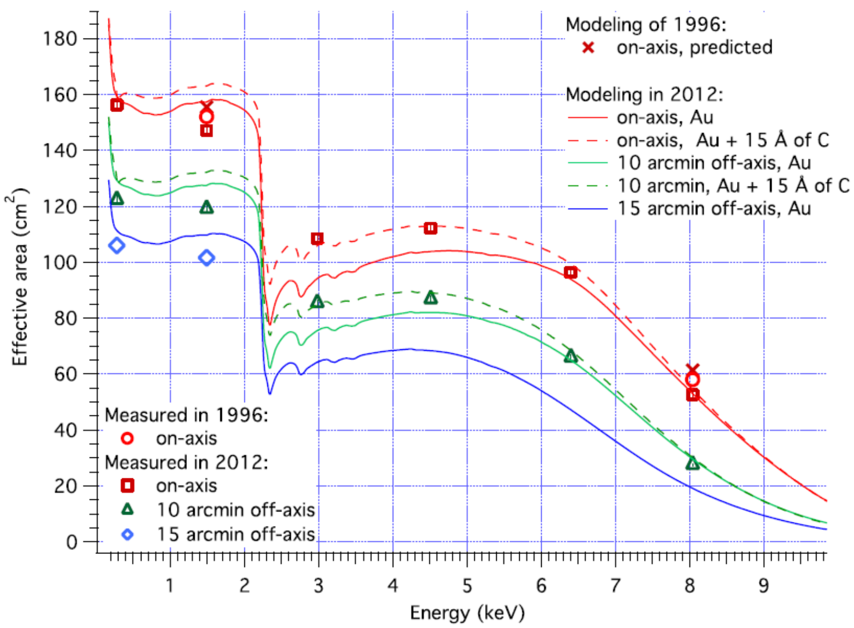
Unpolarized and polarized (through Bragg diffraction) radiation available

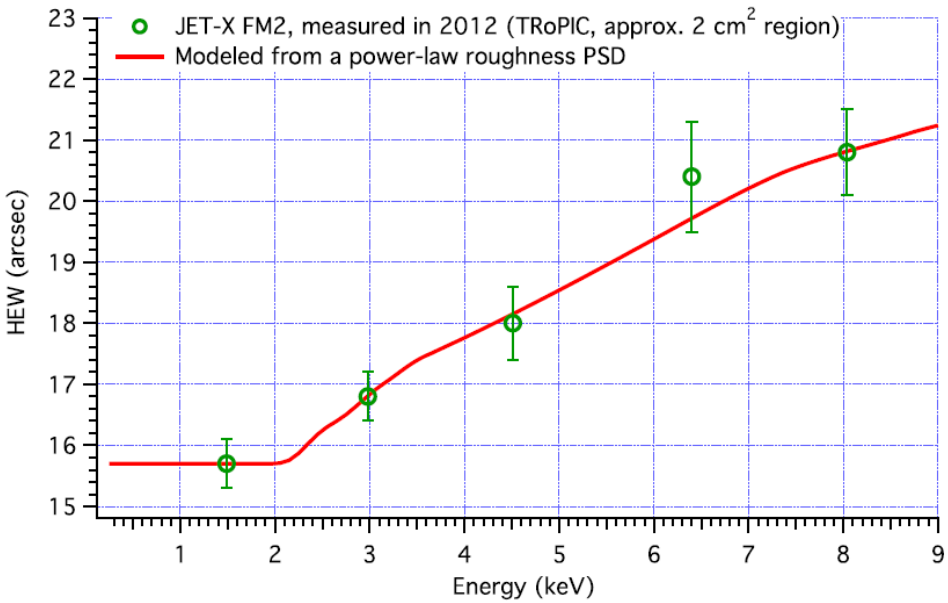
A gas detector (PSPC) and a CCD (TRoPIC) can be used as reference detectors



Freyberg et al. (2005); Burwitz et al. (2013).

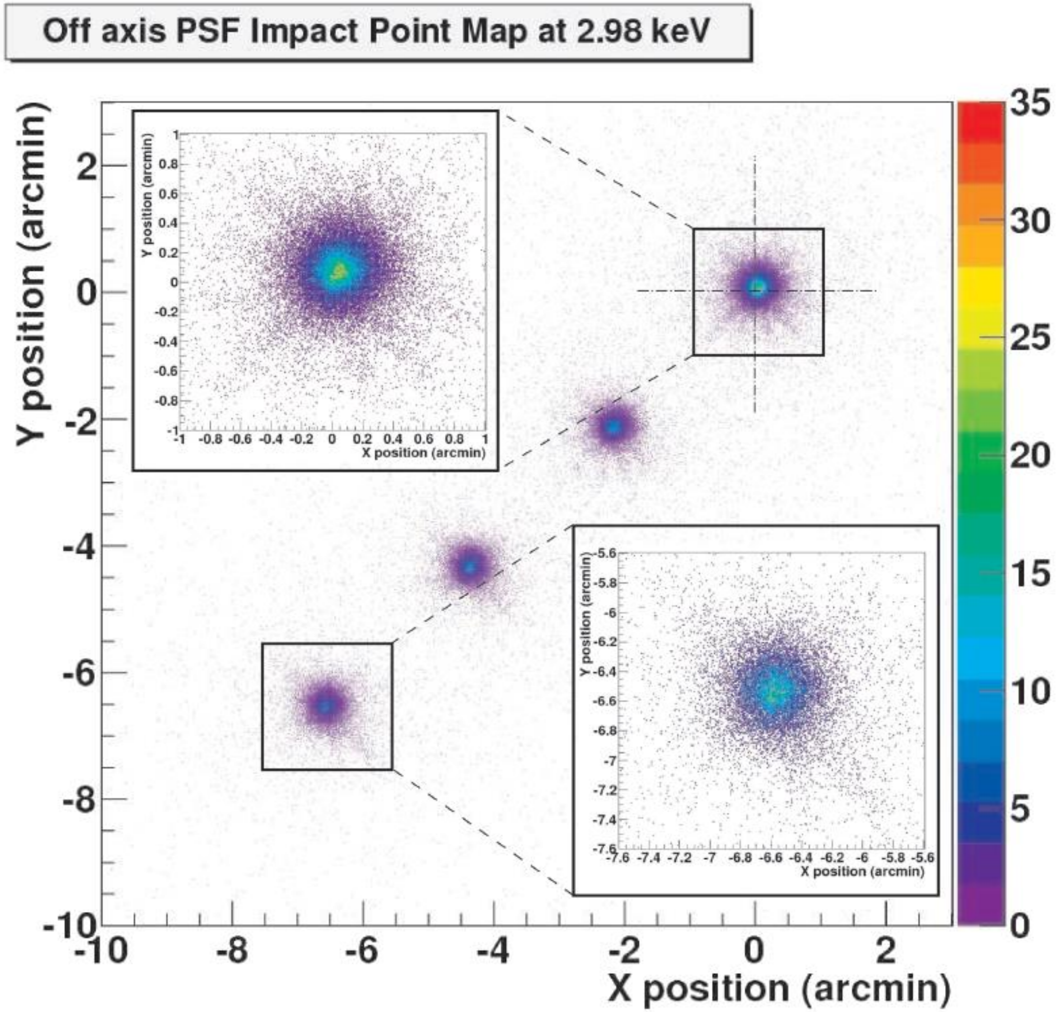
- measuring the mirror effective area as a function of energy and off-axis direction;
- measuring the Point Spread Function (PSF) of the mirror as a function of energy and off-axis direction;
- …





Verification of the operation of the assembly DU/MU with known sources in conditions equivalent to the observation of celestial objects:

- characterize any effect on the polarization state of radiation due to the grazing-incidence reflection on and off-axis up to the systematic limit in sensitivity;
- measure the effective area of the telescope to relate the measured counting rate to the absolute flux of the observed source;
- measure the angular resolution of the telescope as a function of energy and off-axis direction;
- …



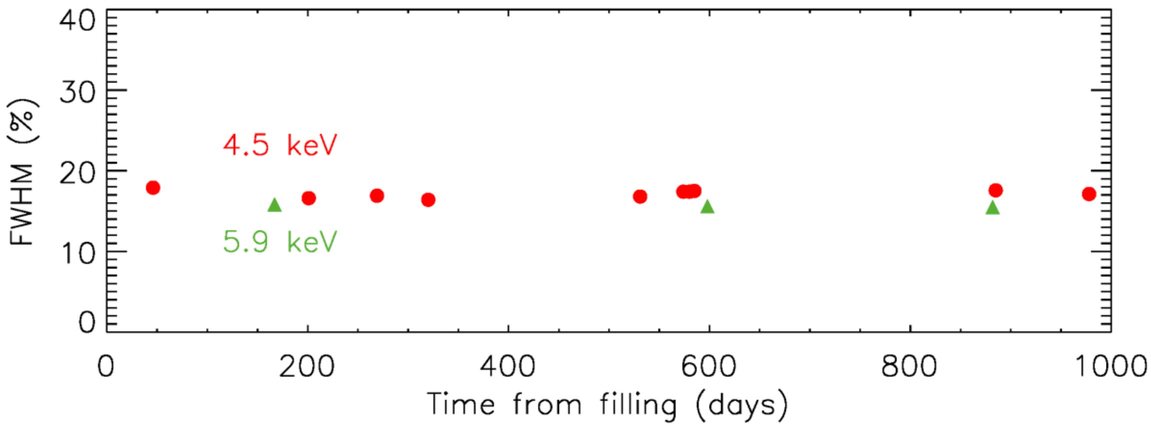
In-flight calibration

Picking the right direction

Xipe

Rationale

The operation of the Gas Pixel Detector has proved rather stable.



Notwithstanding, we need to check:

- **GEM gain & energy calibration**, which may vary with environmental conditions (e.g. temperature and time);
  >> This is important to correctly derive the polarization degree of the source
- **response to polarization**, because we do not have any indications whether stable astrophysical source for calibration does exist or not.
- **alignment**

Philosophy

DU calibration:

- **Phys**: Calibration with on-board sources located in the filter wheel.
- **Ele**: Electrical calibration (TBV)

Telescope calibrations:

- **Astrometric**: Observation of sources with known coordinates for calibrating in celestial coordinates the coordinates in the detector frame.
- **Astro**: Calibration with astrophysical sources, having (allegedly) constant and known polarization.

DU stand-alone in-flight calibration

Picking the right direction

DU stand-alone in-flight calibration

Phys calibrations

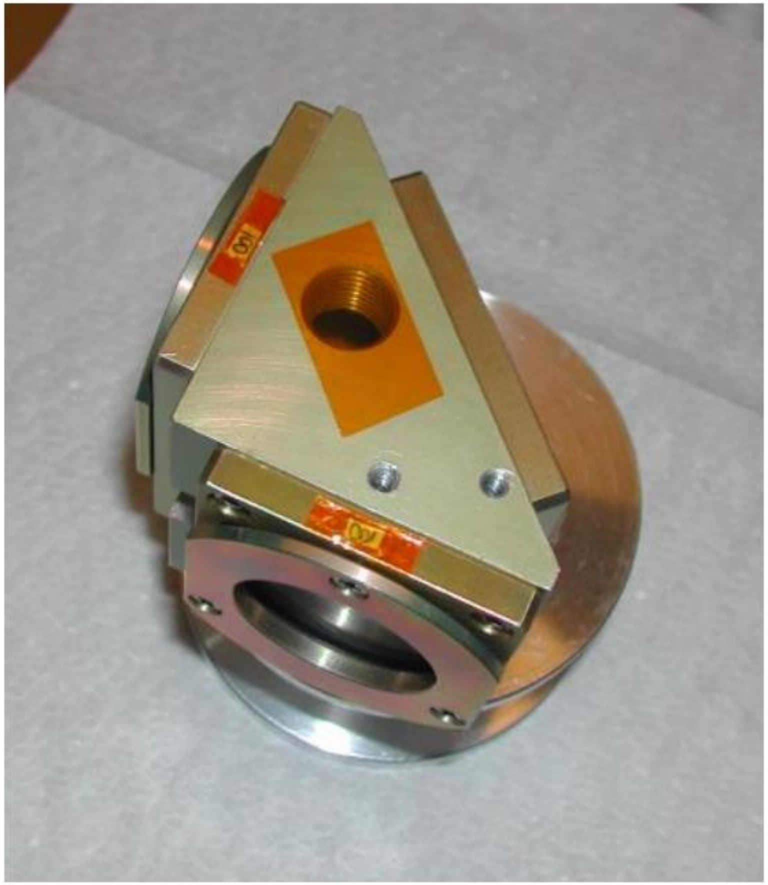
- Different modes, corresponding to different positions of the filter wheel;
- Only one GPD calibrated a time; the other two in scientific observation.

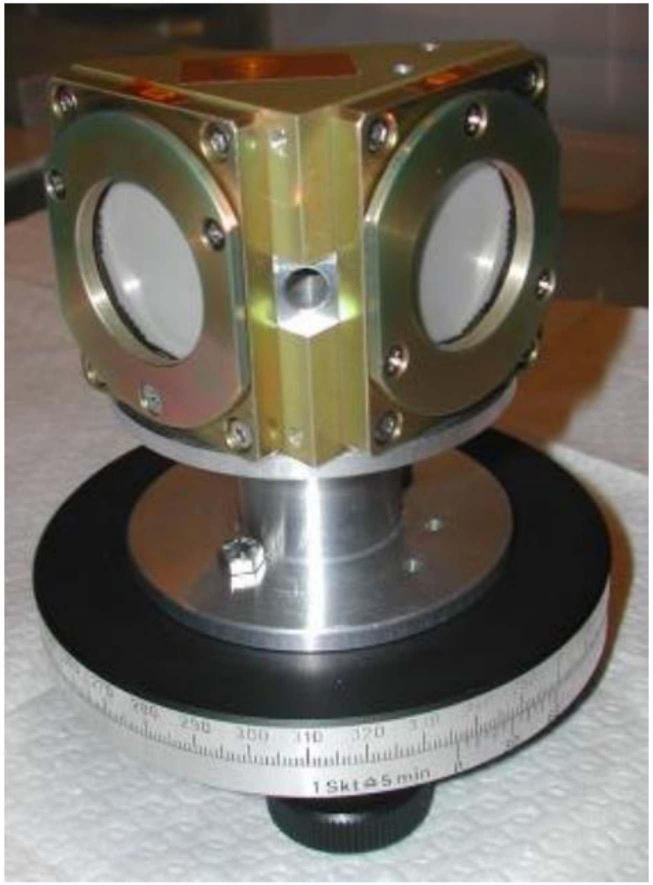
Calibration type	Description	Length (ks)	When
Phys-Pol	Calibration with a polarized source (Calibration Source A), to measure the modulation factor for monochromatic photons at two energies, 2.6 and 5.9 keV. The eventual energy values will be set by the study (radioactive or produced by a modulated calibration source, MCS)	5.0 (x3)	Every month
Phys-UnPol	Calibration with a collimated ^{55}Fe source to measure the absence of spurious modulation (Calibration Source B)	20.0 (x3)	Every 3 months
Phys-FlatField1	Full illumination of the instrument with a radioactive source (Calibration source C, 55Fe) to map the gain at 5.9 keV in all of the sensitive area.	15.0 (x3)	Every 3 months
Phys-FlatField2	Full illumination of the instrument with a source of fluorescence at 8.0 keV (Calibration source D, 109Cd illuminating a Cu target) to map the gain at 8.0 keV in all of the sensitive area.	20.0 (x3)	Every 6 months

Polarized on-board calibration source

The laboratory version:

- 47x47x50 mm^3
- 150 g (aluminum body)

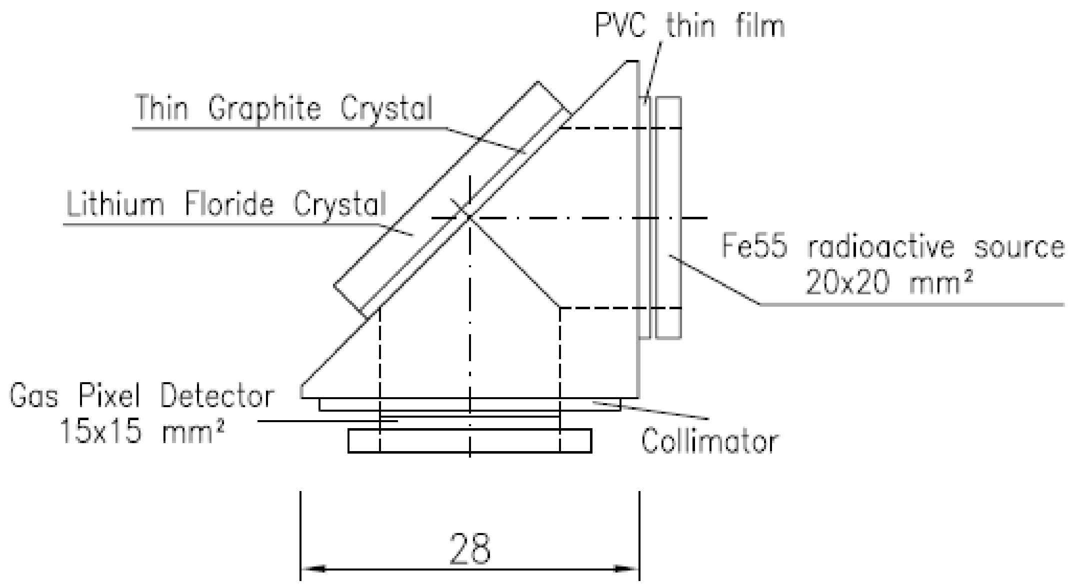




Polarized on-board calibration source

We need:
- a compact source of X-ray photons, possibly with an energy in the range of maximum sensitivity of the polarimeter (2-4 keV)
- a crystal able to diffract the photons at nearly 45° degrees

Baseline:
- A single ^{55}Fe radioactive source emitting at 5.9 keV (activity about 10 mCi, half-time period 2.7 yr)
- A thin PVC film in front of the ^{55}Fe, to extract 2.62 keV Kα fluorescence photons from Chlorine
- A thin Graphite crystal, to diffract at 45° 2.62 keV photons
- A thick LiF crystal to diffract 5.9 keV from ^{55}Fe
- A collimator to constrain the diffraction angle for reducing the contribution from scattered photons

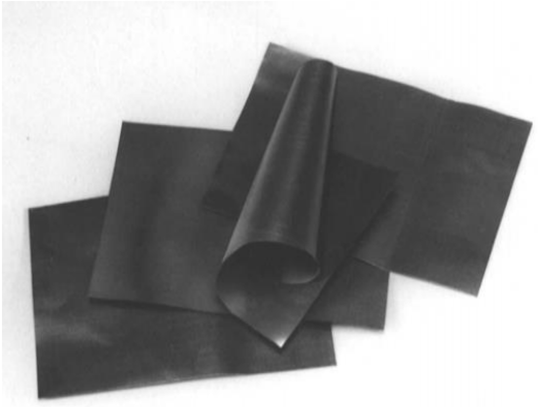


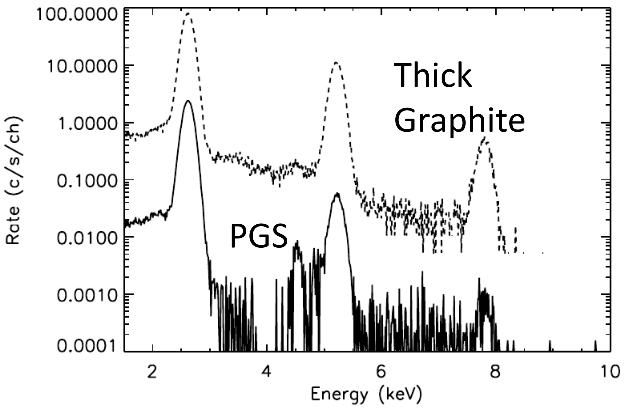
Muleri et al. 2007 Proc. of SPIE

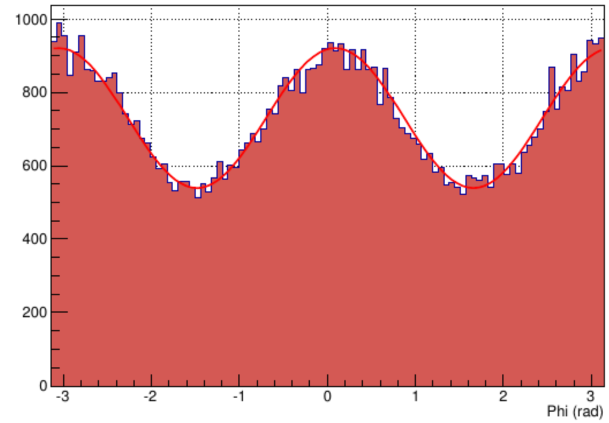
2.62 keV (100% polarized) + 5.9 keV (88% polarized) photons distributed over the entire active surface

Polarized on-board calibration source

Diffraction on 25 µm thick Pyrolytic Graphite Sheets (PGS) manufactured by Panasonic

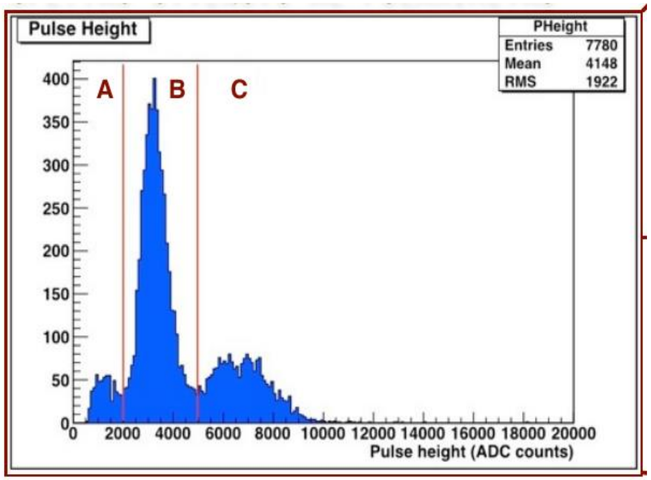


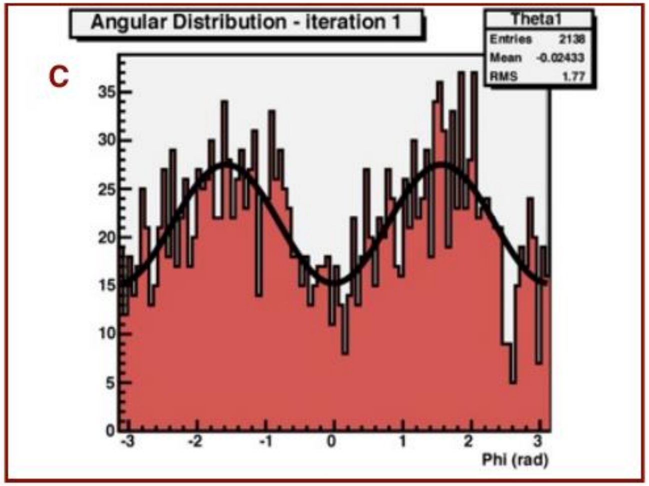




Modulation curve measured with the GPD for photons at 2.62 keV diffracted on PGS (Muleri et al. 2012)

Diffraction of 5.9 keV photons on LiF verified as well

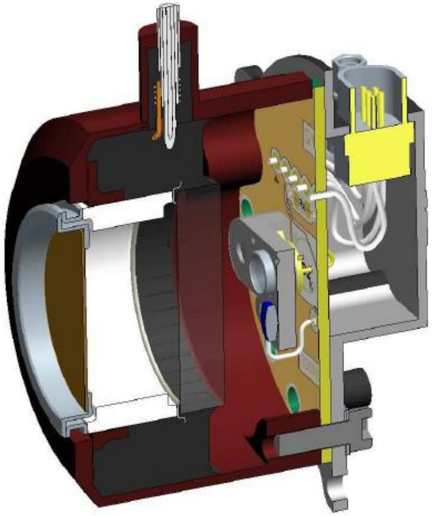


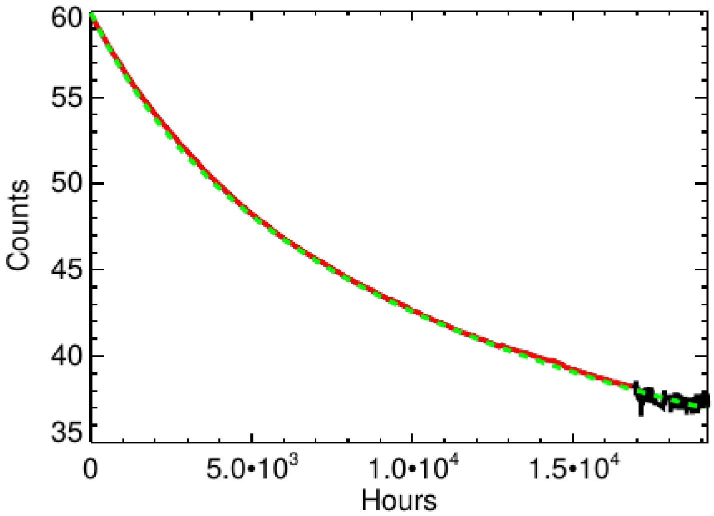


Polarized on-board calibration source

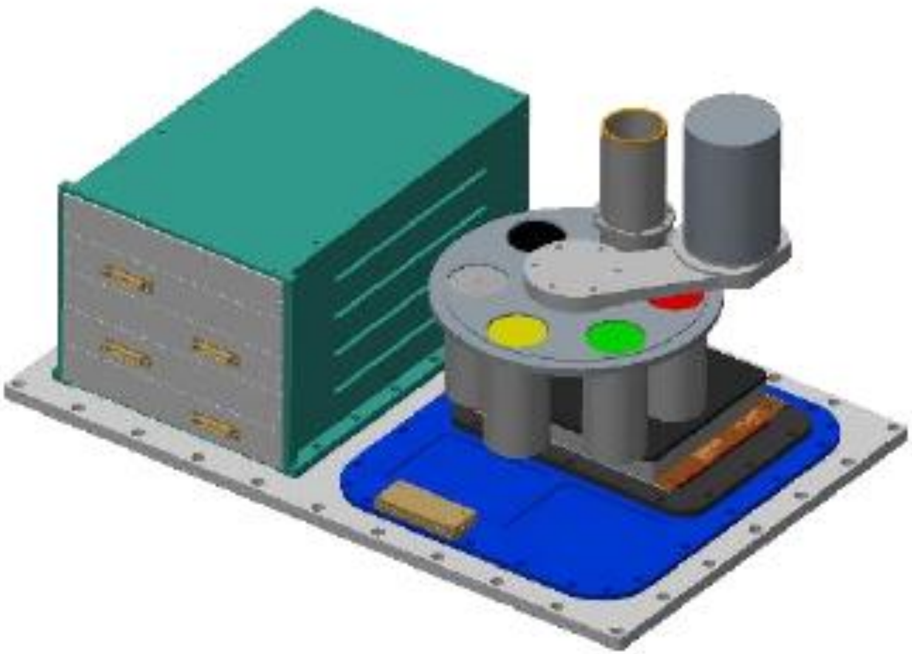
Baseline source:
• principle verified in the laboratory;
• compact and passive;
• good match of energies with the GPD energy range;
• flux much lower than estimated, further studies needed.

Alternative design based on the Modulated X-ray Source (MXS) design (de Vries et al. 2012):
• more choice of energies
• it may provide higher flux in some configurations
• flown on-board Astro-H (and foreseen on Athena)
• lines + bremsstrahlung continuum
• decay of the flux with time
  • about half of the flux after >900 ks, expected use on-board XIPE: 60ks/yr)
  • LED intensity can be increased over time
• compact but active (requires HV)





Polarized on-board calibration source



Baseline:
Polarizer and X-ray source mounted in one of the filter wheel position

Alternative design with the MXS:

- Polarizer and MXS mounted on a fix location
  - Off-axis illumination of the detector
  - Redundancy possible

- Polarizer mounted on the FW, MXS mounted on a fix position
  - Maybe a higher requirement on the FW positioning

Unpolarized calibration source B

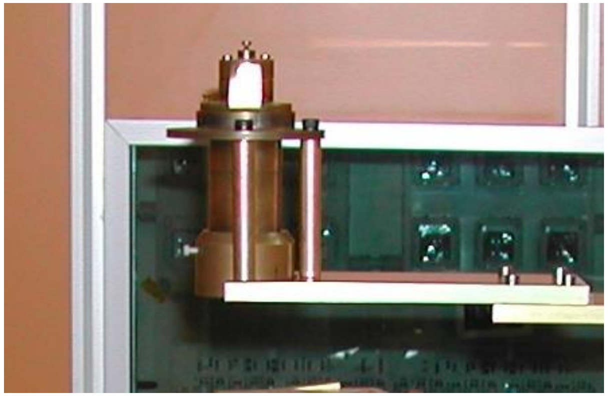
- To check that polarimeter is not introducing spurious polarization.

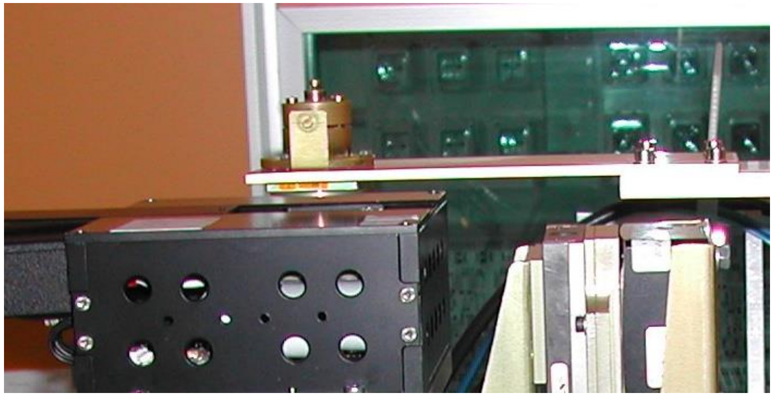
- Demanding measurements:
  - about 600k counts required to reach 1% sensitivity
  - the spot should be small, preferentially comparable to the point spread function (about 400 μm)

- Baseline design:
  - 10 mCi of ^{55}Fe
  - x2 3 mm diaphragm at 8 cm
  - about 50 c/s
  - decreasing during the mission life, half life period of ^{55}Fe 2.7 yr

  >12 ks required per detector (20 ks allocated in the Calibration Plan)

Two possible designs of calibration B: pinhole or based on capillary plate





Calibration sources C e D

Two energies to derive the (linear) calibration all over the sensitive area

Calibration source C
- ^{55}Fe, 5.9 keV
- easy to reach a high flux

Calibration source D
- ^{109}Cd + Cu target, 8.0 keV
- we need to evaluate the flux

Electrical calibrations

DU stand-alone in-flight calibration

Calibration type	Description	Length (ks)	When
Ele-Pedestals	Electrical calibration for measuring the pedestal of the ASIC pixels. Pedestal calibration is meaningful only for the improved version of the ASIC, which use will be assessed during the study. With the baseline ASIC the pedestals are read on the fly for each event and subtracted automatically by the BEE.	0.1 (x3)	Every 6 months
Ele-Gain (diagnostic)	The gain calibration is not viable. A charge can be injected only for diagnostic.	TBD	TBD

In-flight Telescope calibration

Picking the right direction

Xipe

In-flight Telescope calibrations

Observation of sources with known coordinates for calibrating in celestial coordinates the coordinates in the detector frame. All detectors calibrated at the same time.

Calibration type	Description	Length (ks)	When
Astrometic Raster	Observation of a point source with known coordinates in 5x5 pointings covering the FoV.	3.0	Every 1 year
Astrometic Multiple	Observation of a field containing two or more point sources.	TBD	TBD
Astrometic Extended	Cross calibrating the image of the Crab, Cas A or other extended sources with the corresponding Chandra image. This can be a corollary of the Astro-Pol calibration.	TBD	TBD

Astrometric calibrations

Observation of sources with (allegedly) known and constant polarization.

Calibration type	Description	Length (ks)	When
Astro-Pol	Observation of a polarized source (e.g. the Crab Nebula, when in visibility), to check the response of the instruments to continuum and polarized radiation.	10.0	Every 6 months
Astro-UnPol	Observation of an unpolarized source, to verify the absence of spurious signals with continuum radiation and a low – possibly negligible- polarization. Candidates sources are Sco X-1, whose average polarization was measured to be <1% (3-s) by OSO-8, but this is expected to change with the spectral state, Capella or clusters of galaxy. The ascertainment of the presence of truly unpolarized astrophysical sources is an action of different scientific WGs.	10.0	Every 6 months

In-flight calibration plan

Day	Detector unit	Calibration mode	Energy (keV)	Real time (ks)	Average rate (c/s)	Peak rate (c/s)	Average data load (kbit/s)	On-board memory usage (Mbit)	Notes
1	#1+#2+#3	Astrometric-Raster	Cont.	3,0	48	96,8	51	76	100 mCrab source assumed. Real time includes 1.5 ks for operation
	#1+#2+#3	Astro-Pol	Cont.	10,0	484	968	511	5111	For all of the three detector units
	#1+#2+#3	Astro-UnPol	Cont.	10,0	500	1000	528	5280	For all of the three detector units
	#1	Phys-Pol	2.6 + 5.9	5,0	10	10	11	53	Units #2 and #3 in scientific obs.
	#2	Phys-Pol	2.6 + 5.9	5,0	10	10	11	53	Units #1 and #3 in scientific obs.
	#3	Phys-Pol	2.6 + 5.9	5,0	10	10	11	53	Units #1 and #2 in scientific obs.
	#1	Phys-UnPol	5,9	20,0	50	50	105	2096	Units #2 and #3 in scientific obs.
	#2	Phys-UnPol	5,9	20,0	50	50	105	2096	Units #1 and #3 in scientific obs.
	#3	Phys-UnPol	5,9	20,0	50	50	105	2096	Units #1 and #2 in scientific obs.
	#1	Phys-FlatField1	5,9	15,0	200	200	419	6288	Units #2 and #3 in scientific obs.
	#2	Phys-FlatField1	5,9	15,0	200	200	419	6288	Units #1 and #3 in scientific obs.
	#3	Phys-FlatField1	5,9	15,0	200	200	419	6288	Units #1 and #2 in scientific obs.
	#1	Phys -FlatField2	8,0	20,0	100	100	314	6272	Units #2 and #3 in scientific obs.
	#2	Phys-FlatField2	8,0	20,0	100	100	314	6272	Units #1 and #3 in scientific obs.
	#3	Phys-FlatField2	8,0	20,0	100	100	314	6272	Units #1 and #2 in scientific obs.
	#1	Ele-Pedestals		0,1				8,4	Assuming 10 values per pixel
	#2	Ele-Pedestals		0,1				8,4	Assuming 10 values per pixel
	#3	Ele-Pedestals		0,1				8,4	Assuming 10 values per pixel
2,6	SCIENTIFIC OBSERVATIONS								
⋮									
31	#1, #2, #3	Phys -Pol		15,0					
	SCIENTIFIC OBSERVATIONS								
61	#1, #2, #3	Phys -Pol		15,0					
	SCIENTIFIC OBSERVATIONS								
91	#1, #2, #3	Phys -Pol		15,0					
	#1, #2, #3	Phys-UnPol		60,0					
	#1, #2, #3	Phys-FlatField1		45,0					
			TOTAL (1 year)	760,6	ks				
				8,8	days				

6 months

Calibrations takes 9 days/yr (2.5%).

>> For XMM is 3.5%