X-ray Polarimeter for IXO

By **Enrico Costa,** *IASF – Roma, INAF*

& **Ronaldo Bellazzini,** *INFN , Pisa*

the Gas Pixel Polarimeter Team

Enrico Costa[a], Ronaldo Bellazzini [c], Luca Baldini[c], Johan Bregeon[c], Alessandro Brez[c], Massimo Frutti[a], Francesco Lazzarotto[a], Giorgio Matt[d], Massimo Minuti[c], Fabio Muleri[a,b], Michele Pinchera[c], Alda Rubini[a], Carmelo Sgro[c], Paolo Soffitta[a], Gloria Spandre[c]

a)Istituto di Astrofisica Spaziale e Fisica Cosmica, INAF, Roma, Italy;
b)Universita' di Roma Tor Vergata, Dipartimento di Fisica, Roma, Italy;
c)Istituto Nazionale di Fisica Nucleare, Pisa, Italy;
d)Universita' di Roma Tre, Dipartimento di Fisica, Roma , Italy

E.Costa – Exploring the Hot Universe with IXO Polarimeter – MPE 17-19 sept 2008

What can Polarimetry Test?

Astrophysics:

Emission processes and geometry of the emitting regions in a variety of situations and classes of sources: jets, accretion, reflection, archeoastronomy, etc.

Fundamental Physics:

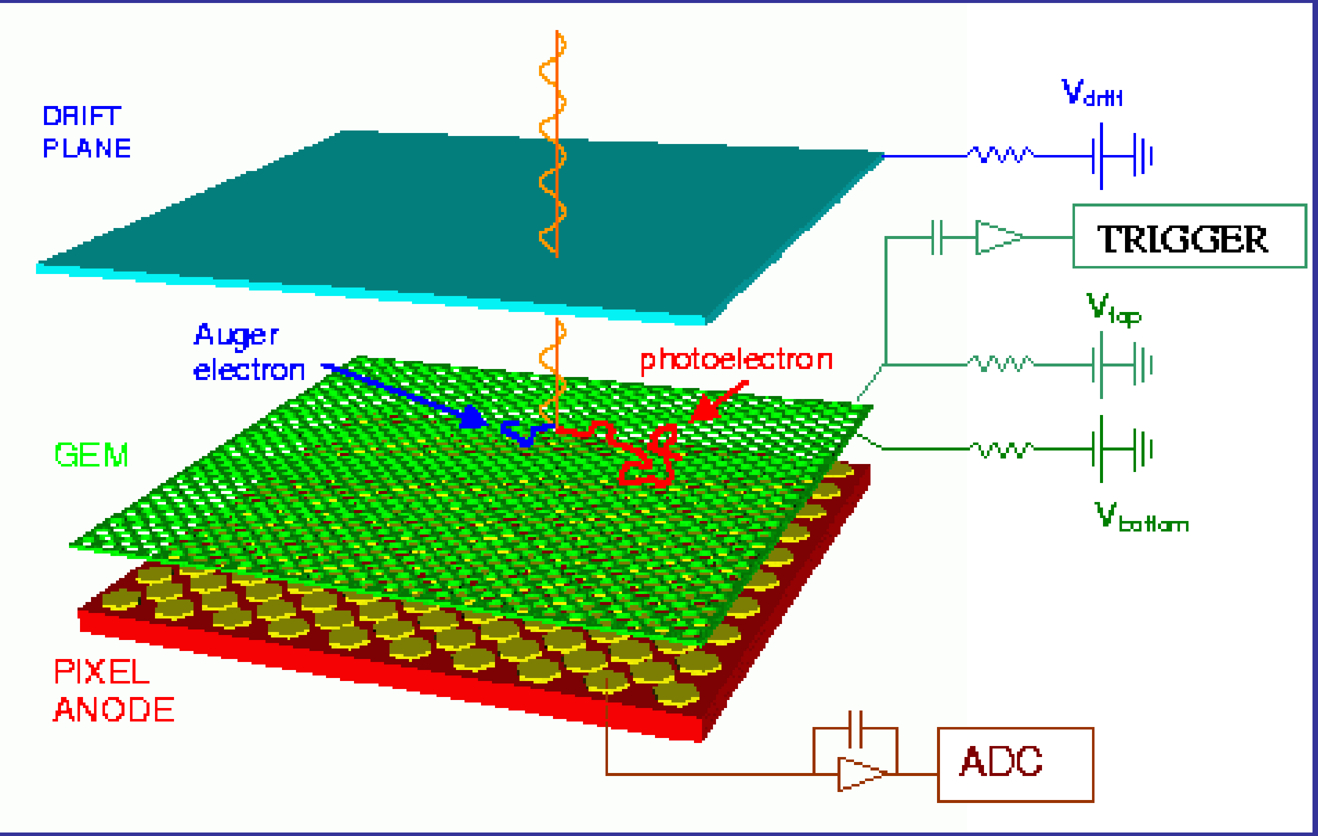
*** Matter in extreme magnetic fields**

*** Matter in strong gravity fields**

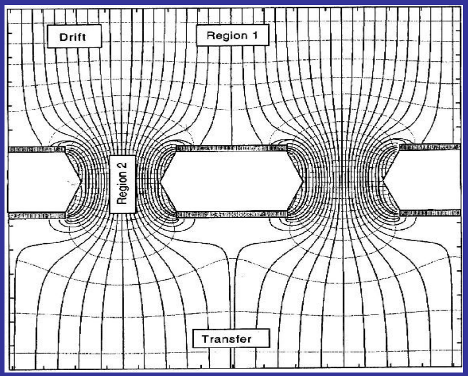
*** Quantum gravity effects**

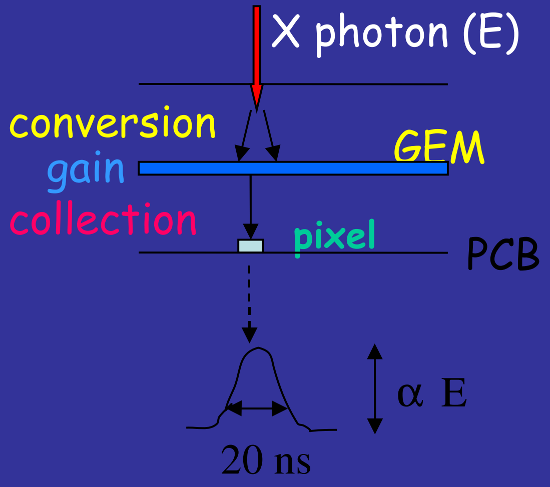
Listen to the talk by Giorgio Matt on Thursday afternoon

The Gas Pixel Detector developed at INFN-Pisa



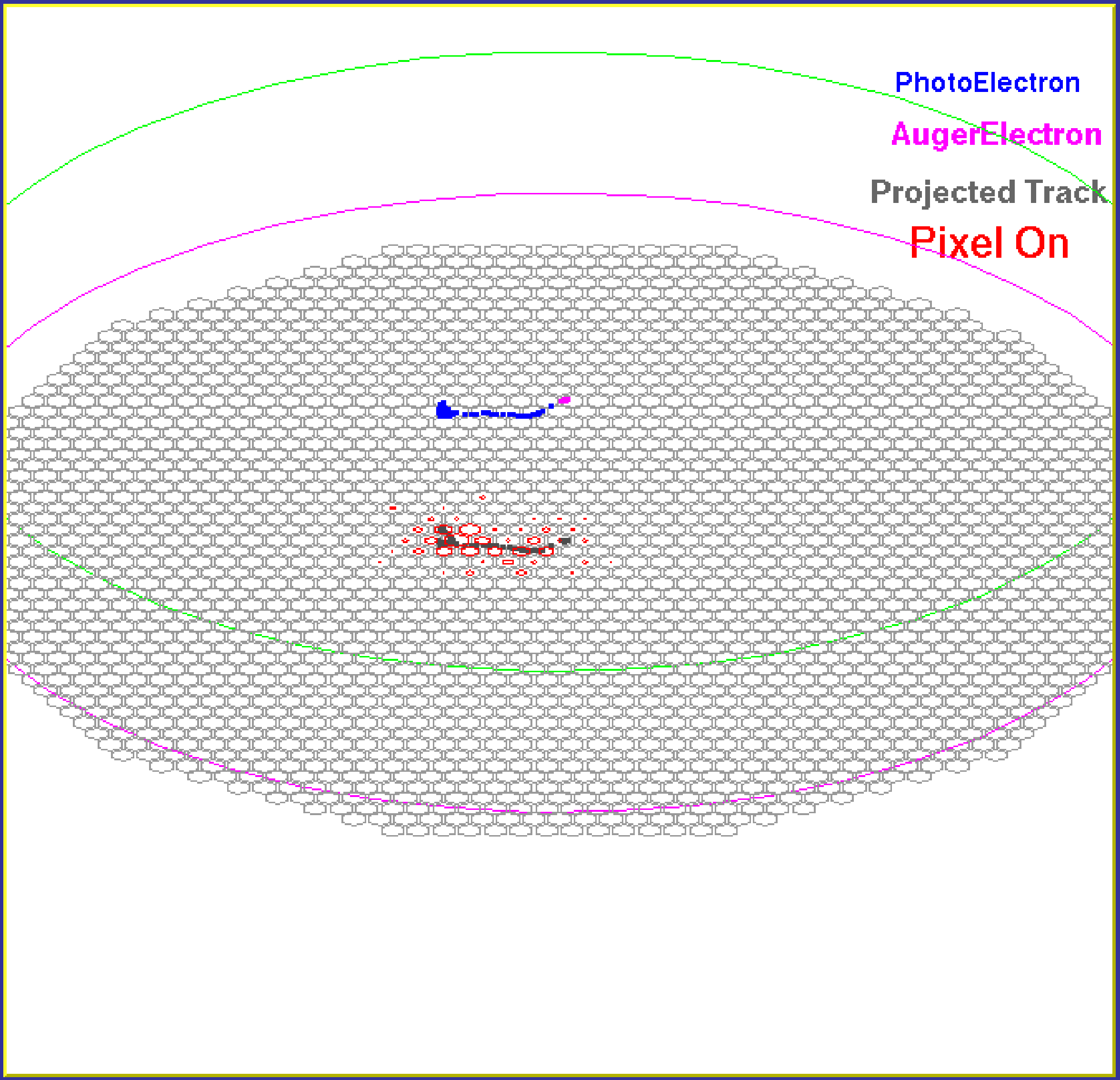
GEM electric field





Polarization information is derived from the tracks of the photoelectron, imaged by a finely subdivided gas detector.

The photoelectrons create tracks in the gas



- Generation (photoelectron + Auger)
- Propagation (SS_MOTT)
- Creation and diffusion of primary ionization (Maxwell, Garfield, Magboltz)
- Gas multiplication
- Digitization
- Pixel Representation

Tracks reconstruction

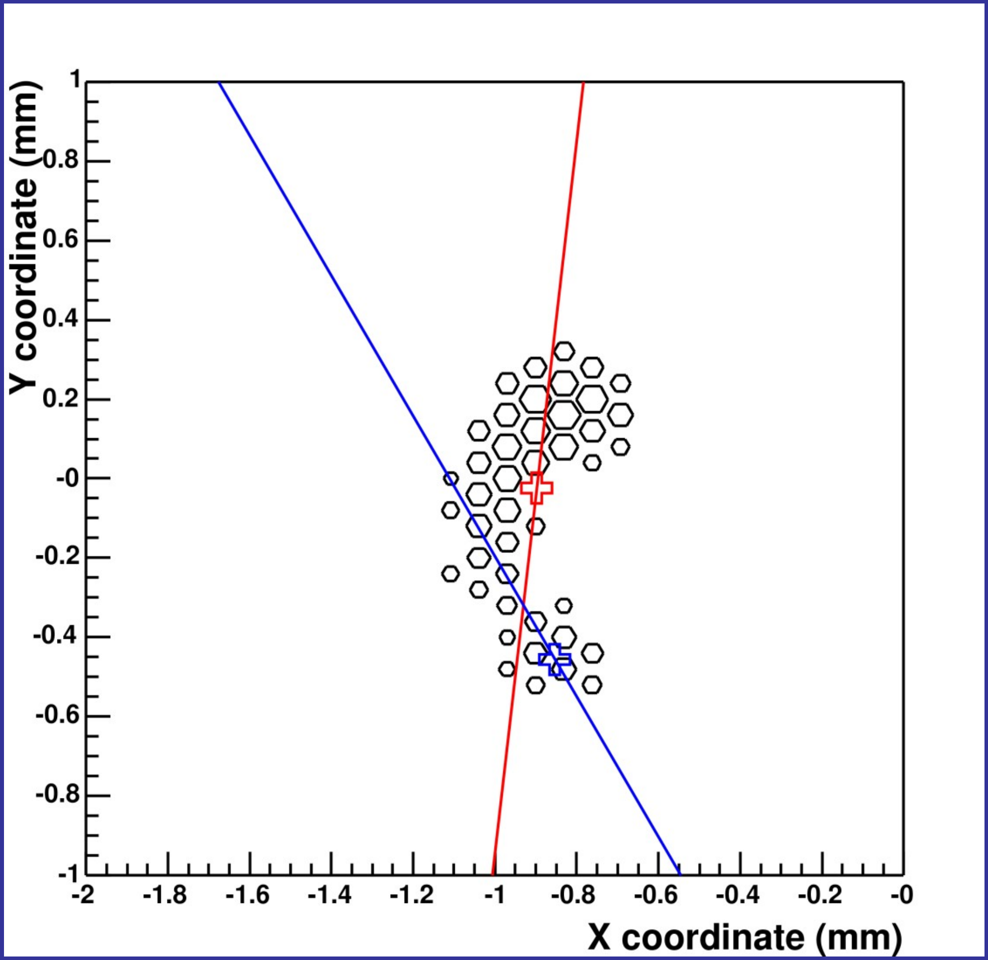
1) The track is recorded by the PIXel Imager

2) Baricenter evaluation

3) Reconstruction of the principal axis of the track: maximization of the second moment of charge distribution

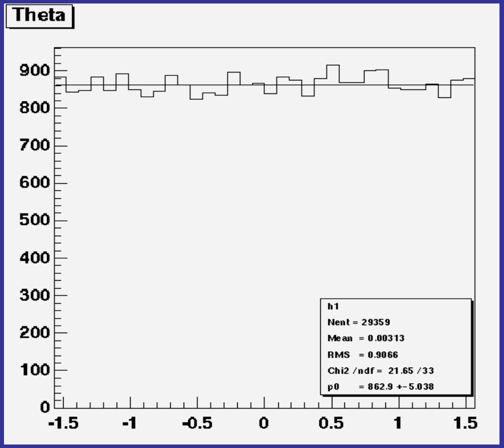
4) Reconstruction of the conversion point: major second moment (track length) + third moment along the principal axis (asymmetry of charge release)

5) Reconstruction of emission direction: pixels are weighted according to the distance from conversion point.

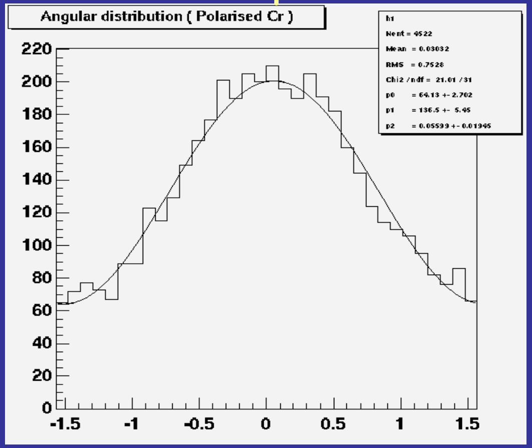


The angular distribution of photoelectron tracks gives polarization degree and angle

5.9 KeV unpolarized source



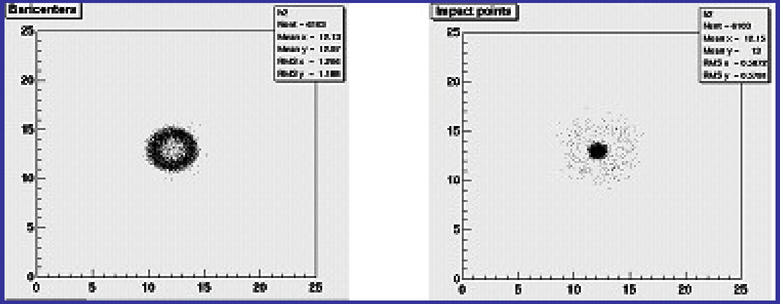
5.4 KeV polarized source



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

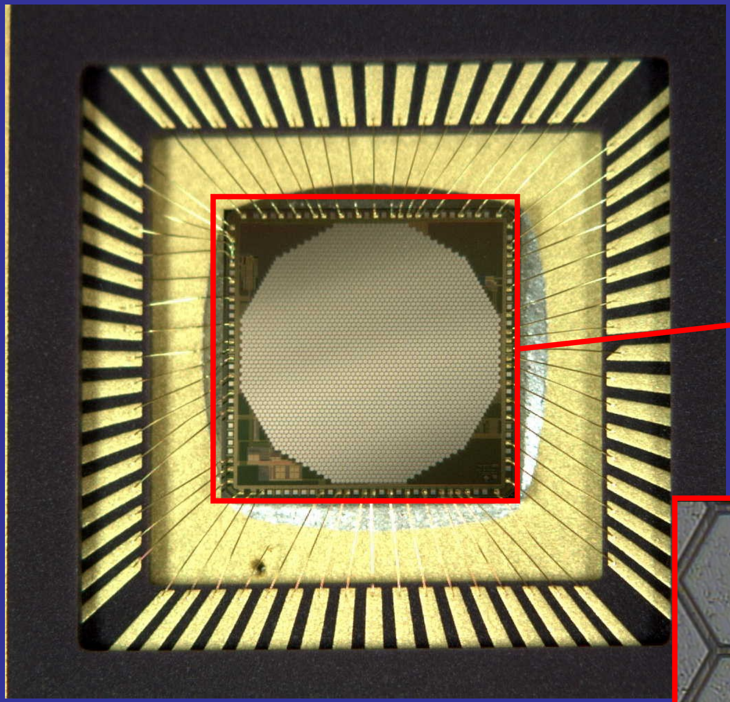
$$MDP(n_\sigma) = \frac{1}{\varepsilon} \cdot \frac{n_\sigma}{\mu} \cdot \frac{1}{S} \cdot \sqrt{2\frac{\varepsilon S + B}{AT}}$$

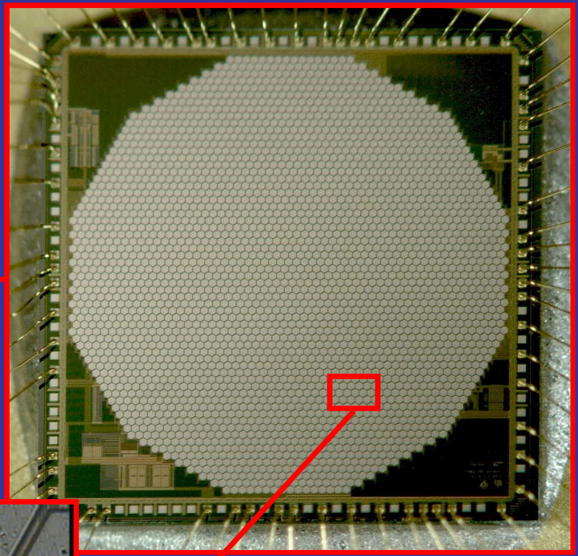
Modulation factor = (Cmax – Cmin)/ (Cmax + Cmin) ~ 50% at 5.4 KeV

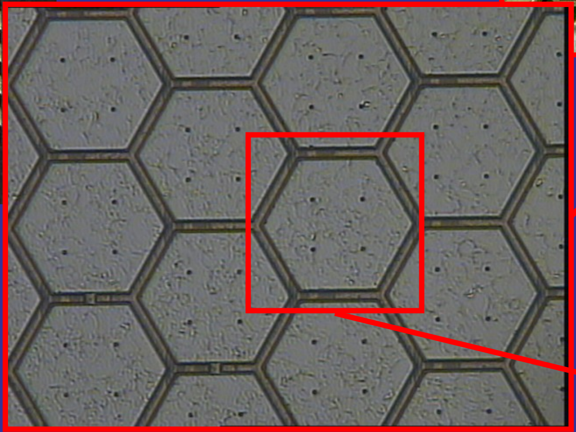


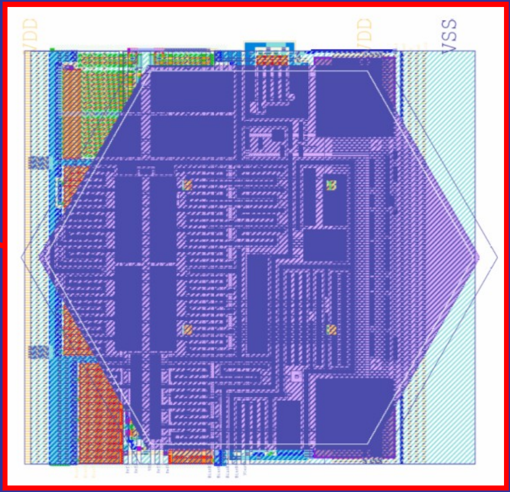
Using the impact point instead than the centroid the resolution is much improved

The collecting anode/read-out VLSI chip



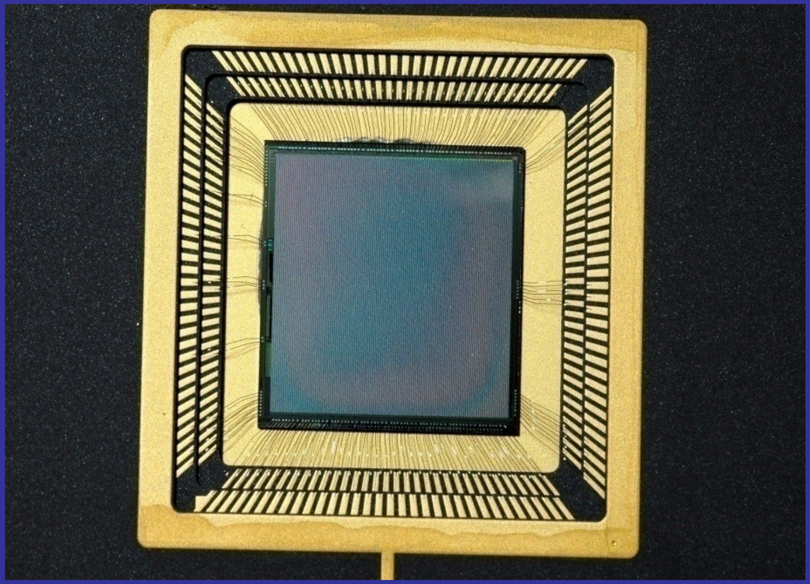


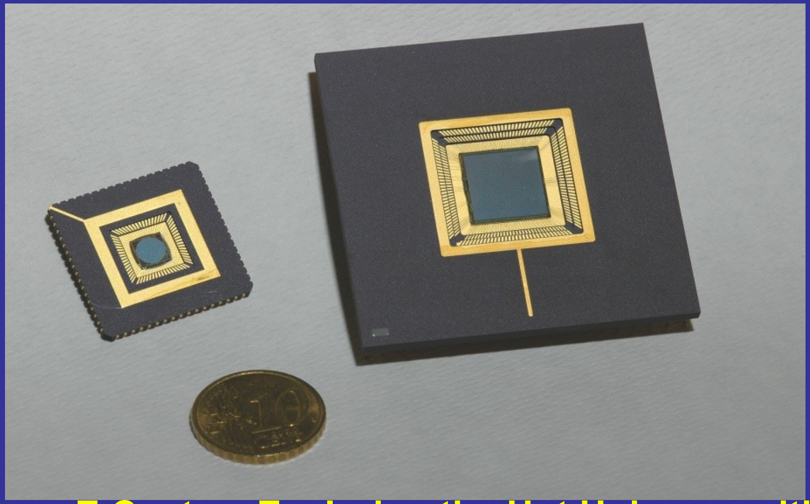


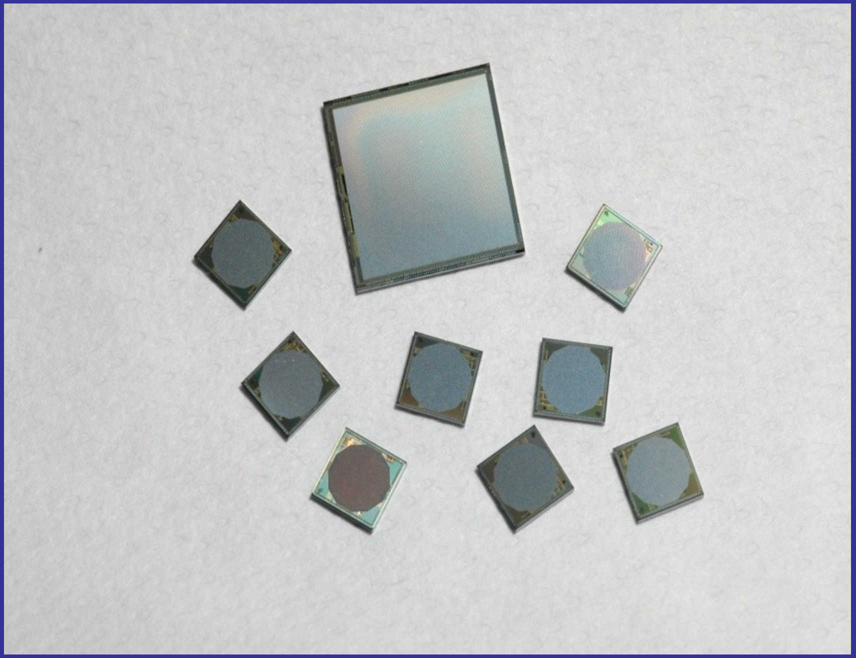


pixel electronics dimension:
80 μ m x 80 μ m in an hexagonal array, <u>comprehensive</u> of preamplifier/shaper, S/H and routing (serial read-out) for each pixel
number of pixels: 2101

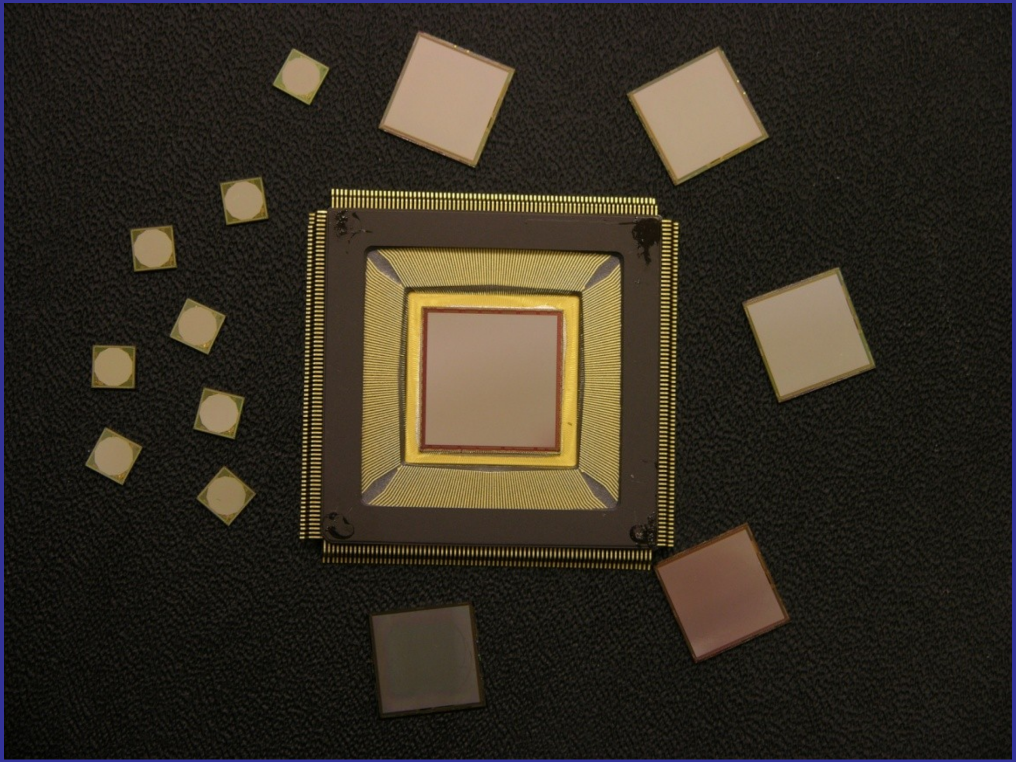
From 2k to 22k pixels







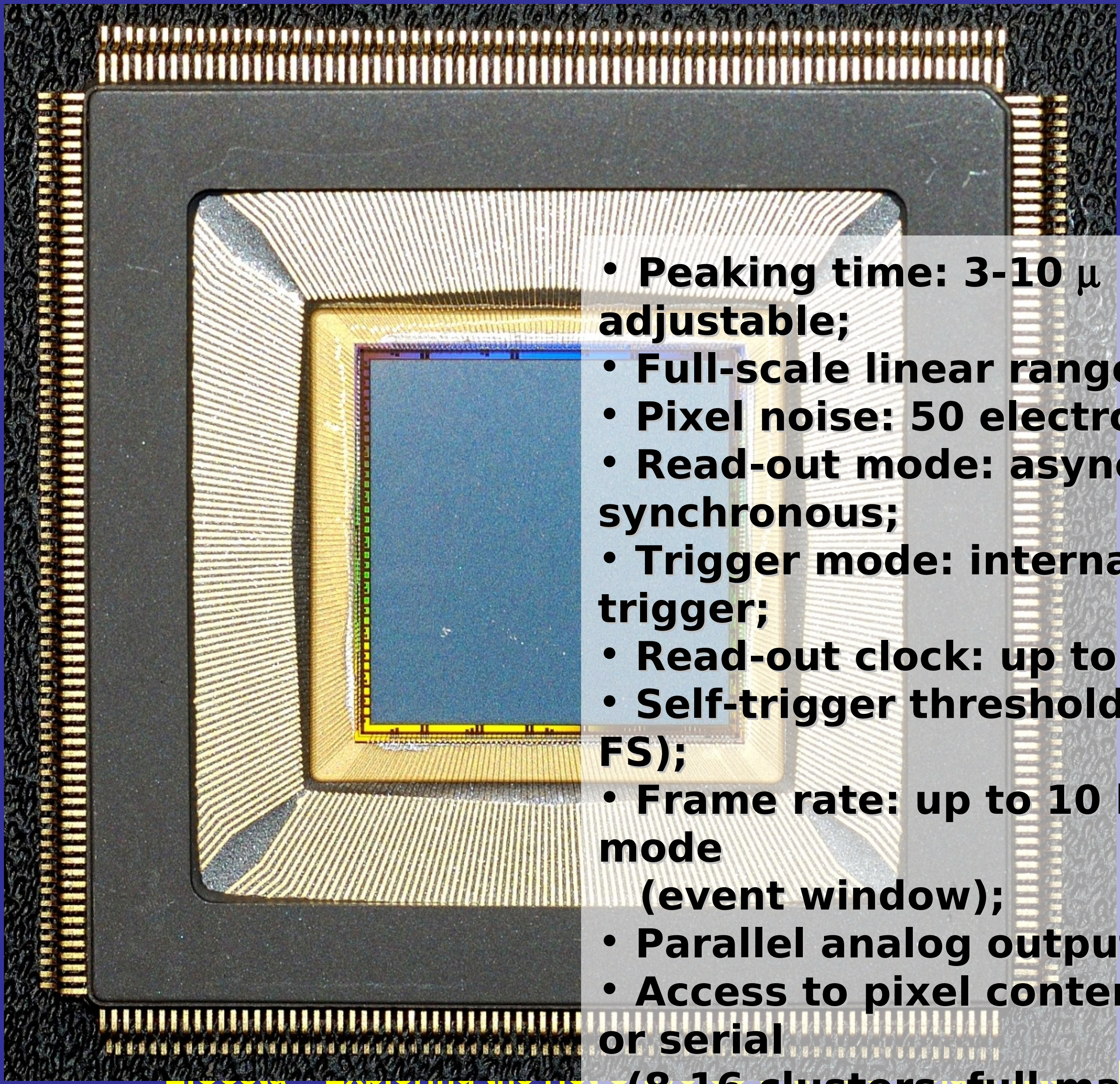
Further technological step:
a 0.18 μ m CMOS VLSI



The chip integrates more than 16.5 million transistors.
It has a15mm x 15mm active area of 105’600 pixels organized in a honeycomb matrix

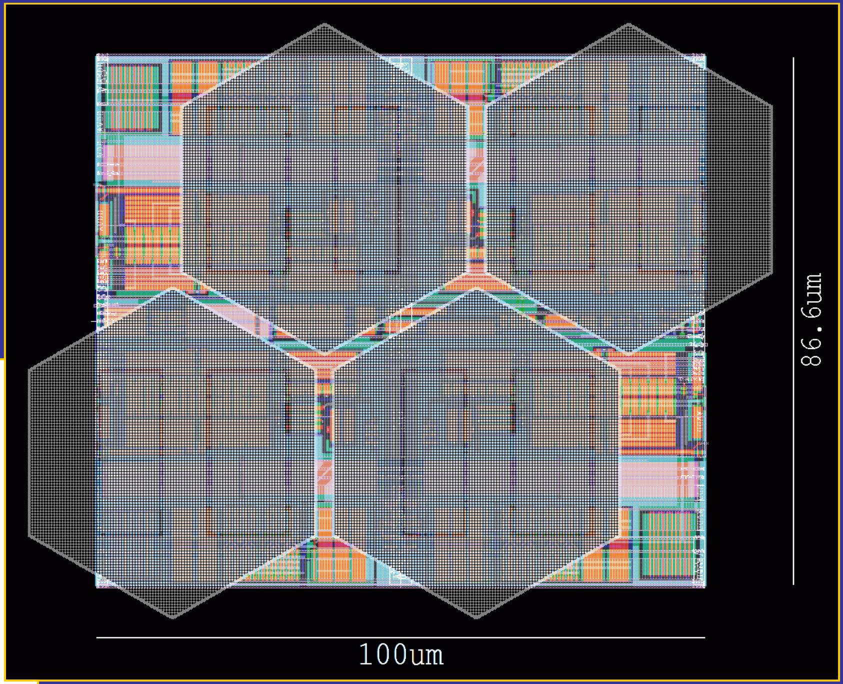
Matrix organization
300 (width=300x50μ m=15mm) x 352 (height=352x43.3μ m=15.24mm) pixels
16 clusters of 300 x 22 = 6600 pixels each or
8 clusters of 300 x 44 = 13200 pixels each

ASIC features



- Peaking time: 3-10 μ s, externally adjustable;
- Full-scale linear range: 30000 electrons;
- Pixel noise: 50 electrons ENC;
- Read-out mode: asynchronous or synchronous;
- Trigger mode: internal, external or self-trigger;
- Read-out clock: up to 10MHz;
- Self-trigger threshold: 2200 electrons (10% FS);
- Frame rate: up to 10 kHz in self-trigger mode
  (event window);
- Parallel analog output buffers: 1, 8 or 16;
- Access to pixel content: direct (single pixel) or serial
  (8-16 clusters, full matrix, region of interest);
- Fill fraction (ratio of metal area to active

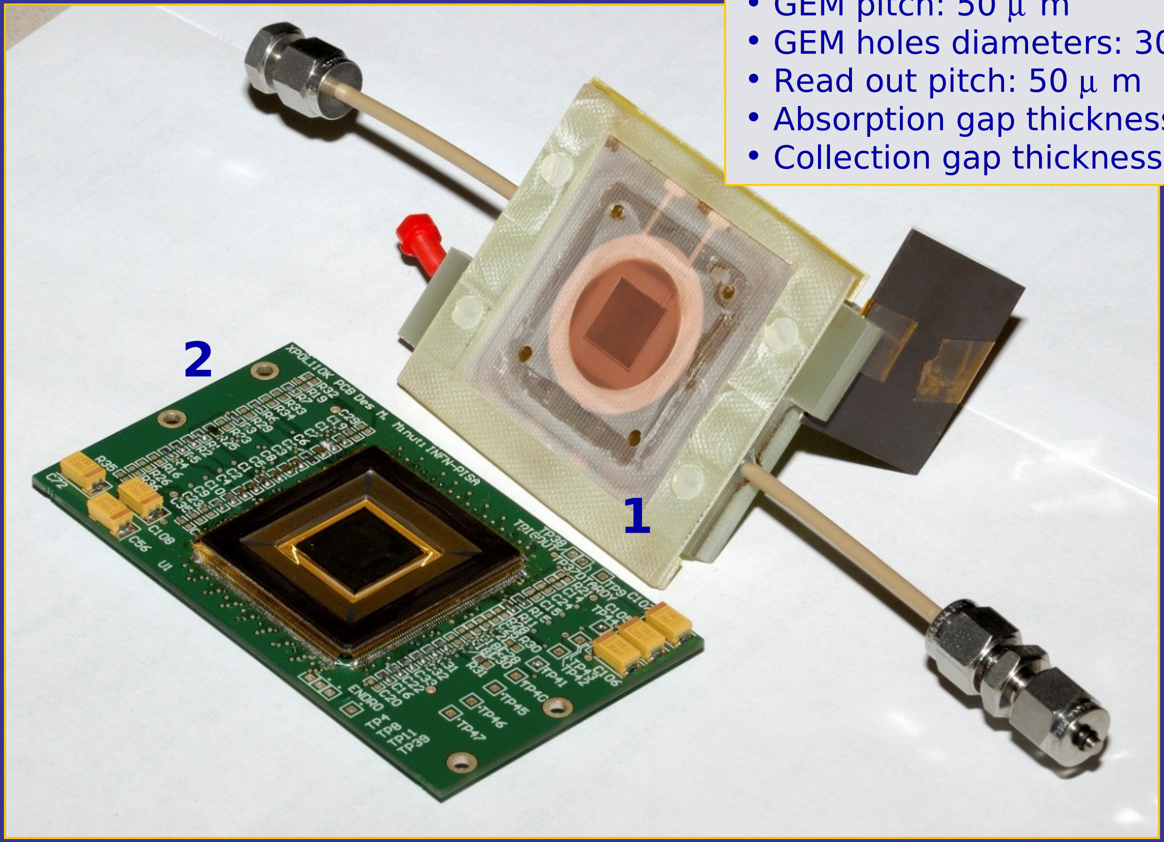
Internal trigger functionality



✓ **mini-clusters of 4 pixels contribute to a local trigger with dedicated shaping amplifier**
✓ **threshold < 3000 e^{-} (10% FS)**
✓**individual pixel trigger mask**
✓**independent trigger level for each 16 clusters**
✓**event localization in rectangle containing all triggered mini-clusters + user selectable region of 10 or 20 pixels**
✓**the chip calculates the event ROI (X_{min},Y_{min} – X_{max},Y_{max}) for subsequent**

Detector assembly

- GEM pitch: 50 μm
- GEM holes diameters: 30 μm, 23 μm
- Read out pitch: 50 μm
- Absorption gap thickness: 10 mm
- Collection gap thickness: 1 mm

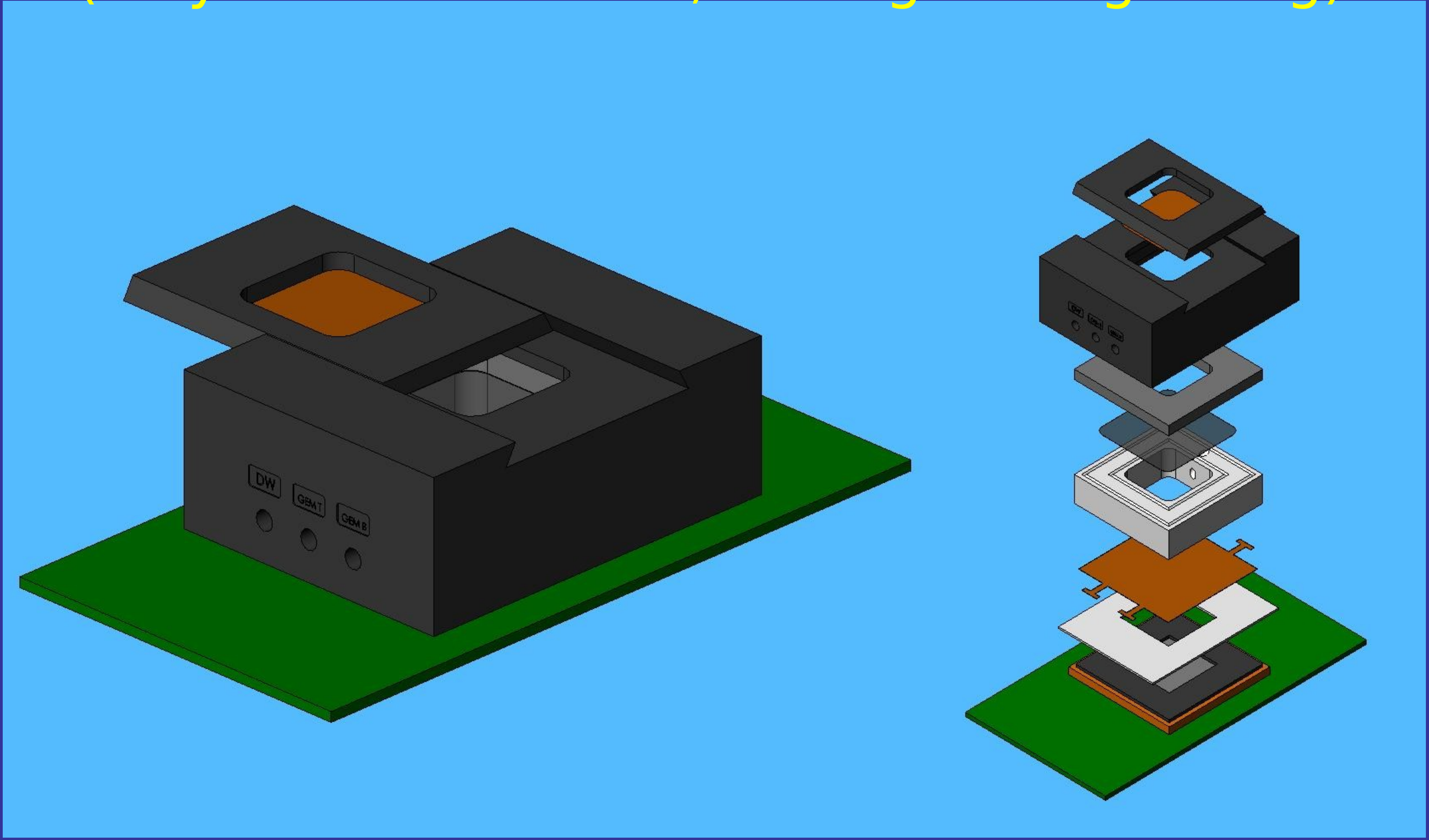


1 - The GEM glued to the bottom of the gas-tight enclosure

2 - The large area ASIC mounted on the control motherboard

The matching of readout and gas amplification (GEM) pitch allows getting optimal results and to fully exploit the very high granularity of the device

Sealed device
(only clean materials, baking & outgassing)



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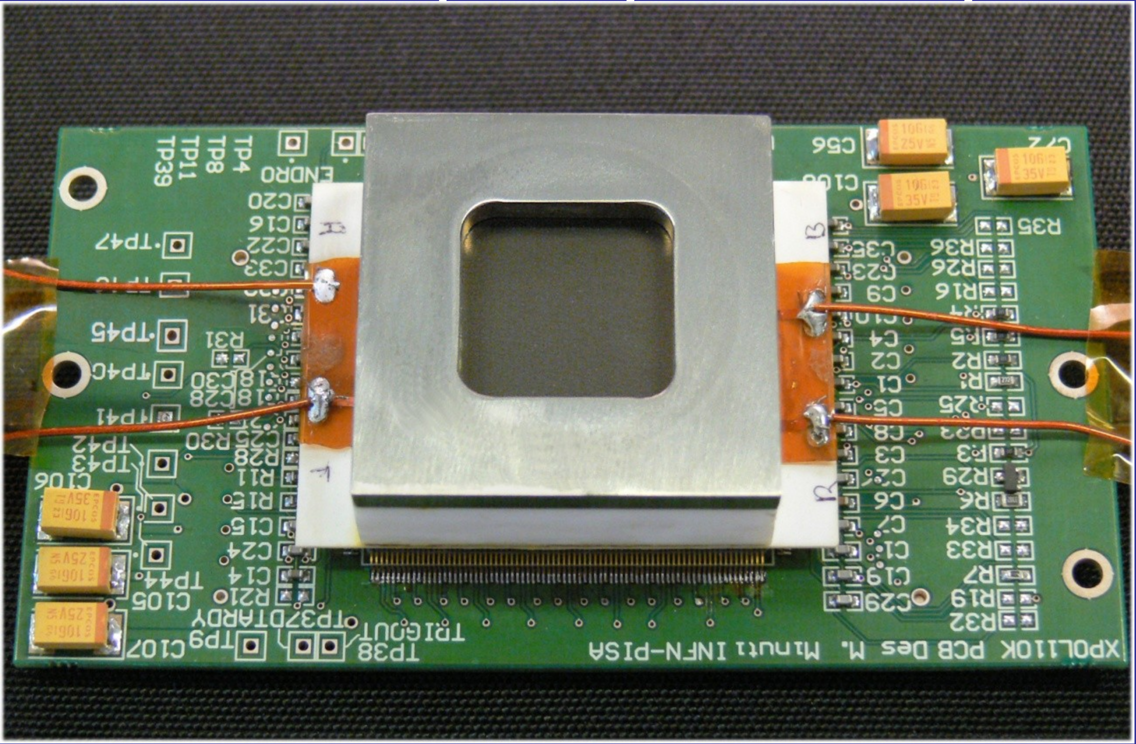
From the laboratory to a flight prototype

Body, window, gas handling, HV etc. are conventional well established technology. A prototype sealed detector is already built and first testing is very satisfactory.



The first prototype of a sealed detector, built with low desorption materials and processes. The window is 50μ m Be. (Bellazzini et al. astro-ph/0611512)

Has been tested for 40 days showing excellent stability.

It weights 50 g + 30 g of PCB!

A contract has been given from ASI to the Polarimeter Team (INFN-Pisa and INAF-IASF Roma with a subcontract to Alcatel Alenia Space – LABEN)-to assess the technology to evolve the prototypes toward flight compatible models

Readiness

• Stability. Many sealed prototypes have been integrated. They do not show evidence of desorption. One detector has been tested systematically for two months and seredipitously for more than one year and does not show any decay of performance.

• A sealed prototype has passed mechanical tests

• The same has passed thermal cycling tests.

•The same has passed thermal-vacuum tests.

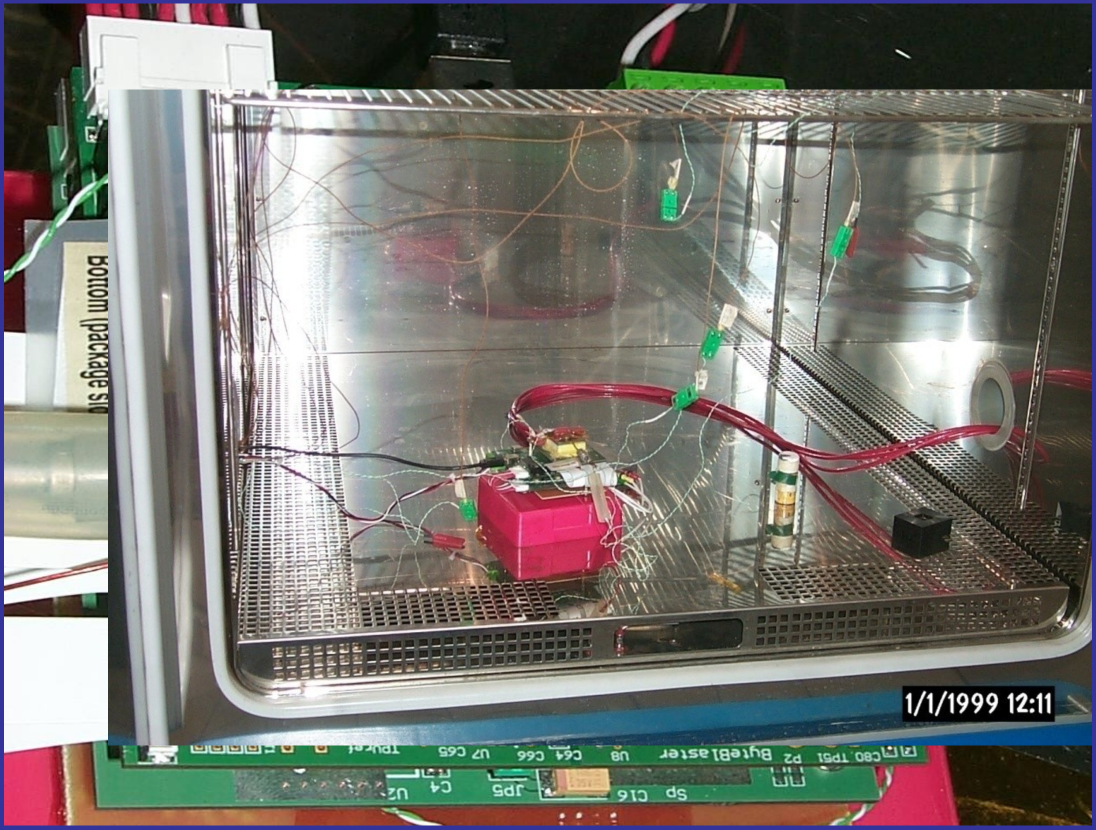
• Radiation tests with X-rays have been performed successfully

• Radiaton tests with ions, aimed to ascertain the survival in space environment have been performed in May

Environmental tests: thermal cycles and thermo-vacuum

Test temperature range: between -15°C and +45°C

8 thermal cycles in a climatic chamber at atmospheric pressure with reduced humidity (<10% RH) and 1 thermo-vacuum cycle ($P<10^{-4}$Torr) in the same temperature range.

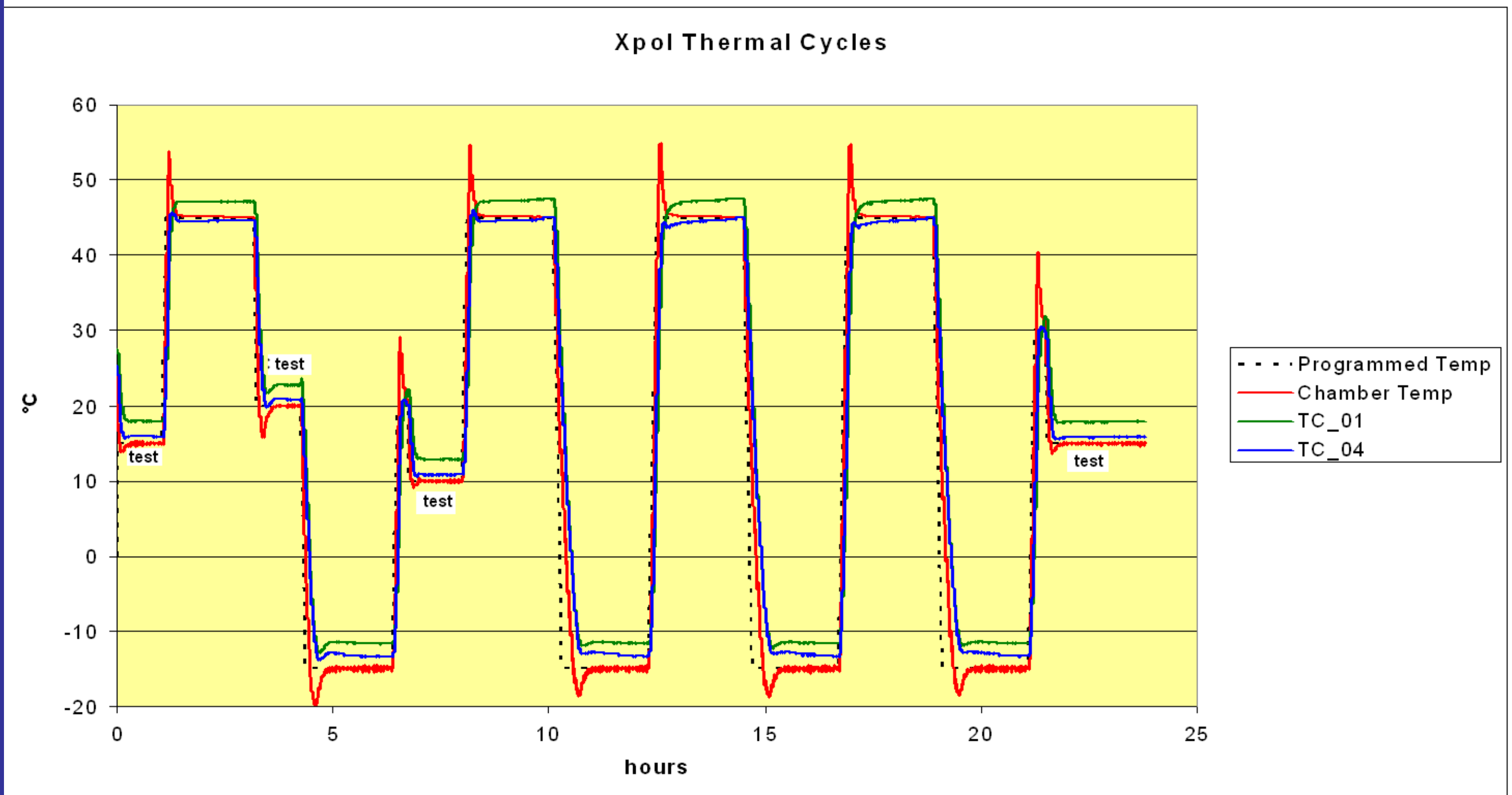


XPOL inside the climatic chamber (Angelantoni Challenge 1200)

2 thermocouples: TC_01 (on the readout board) and TC_04 (on top of the drift window Titanium frame)

During test a Fe^{55} (Ø~ 1cm) illuminated the whole detector sensitive area

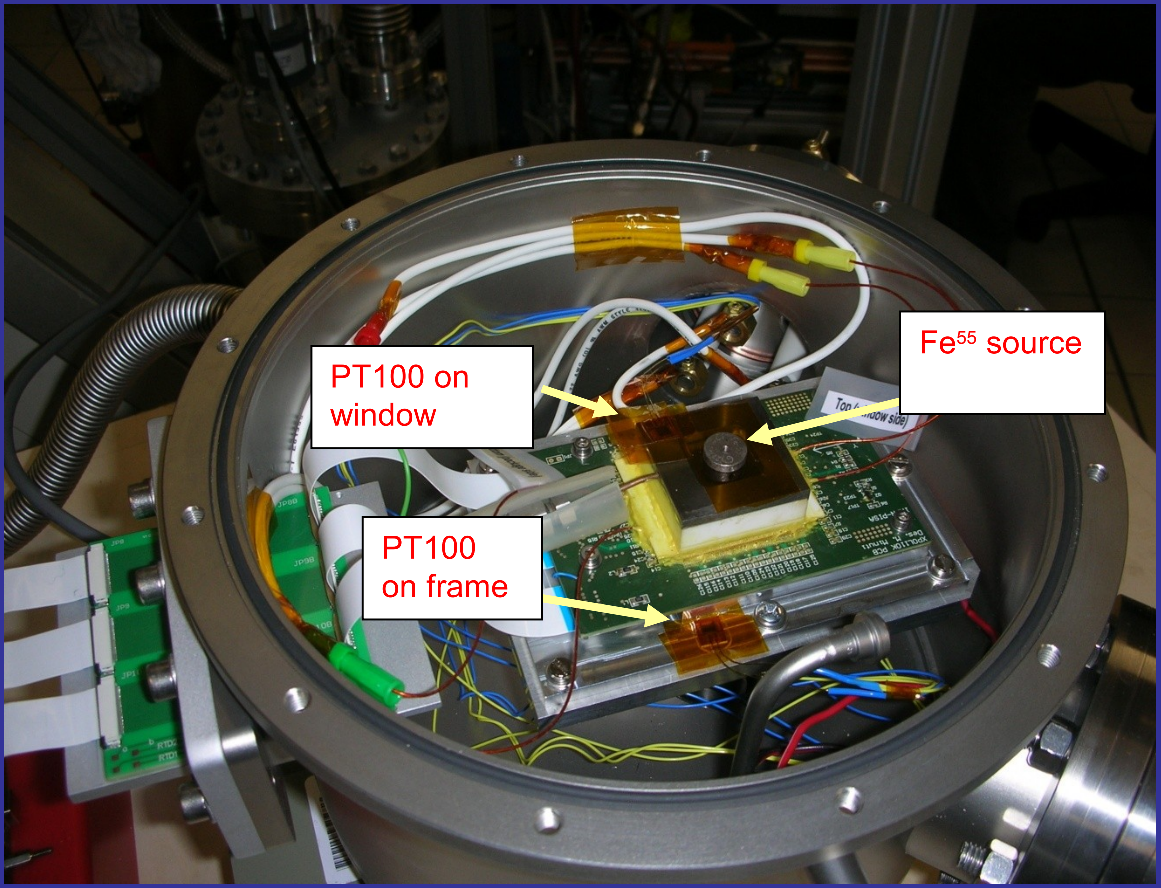
Thermal cycles



Test point temperature	Peak amplitue (ADC counts)	Relative gain
15∞C reference test	3200±150	1
20∞C higher operative temp.	2870±150	0.90±0.06
10∞C lower operative temp.	3583±150	1.12±0.06
15∞C last reference test	3296±150	1.03±0.06

Tests at 15°C at the beginning and at the end of the cycles (reference tests) and at +20°C and +10°C (maximum and mimimum operating temperatures)
The hot and cold data taking tests show a ~-2%/°C gain dependence.

Thermo-vacuum

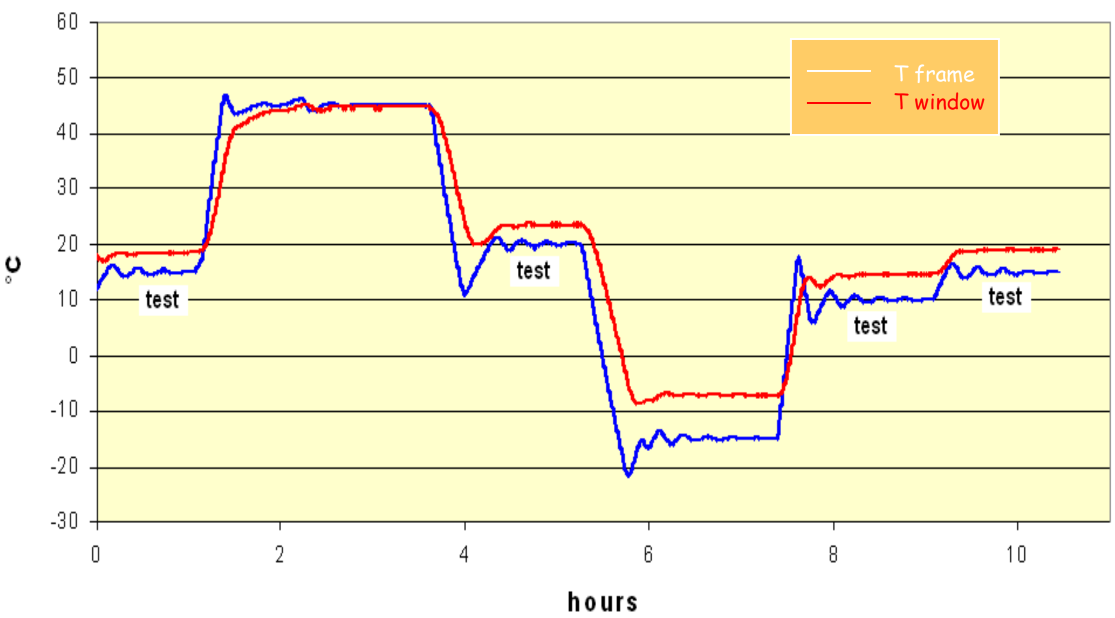


A vacuum vessel (Ø~250mm) is mounted around the cold head of a CRYODINE cryostat and connected to a Varian 979 leak test system that can easily reach a vacuum pressure $<10^{-4}$ Torr.

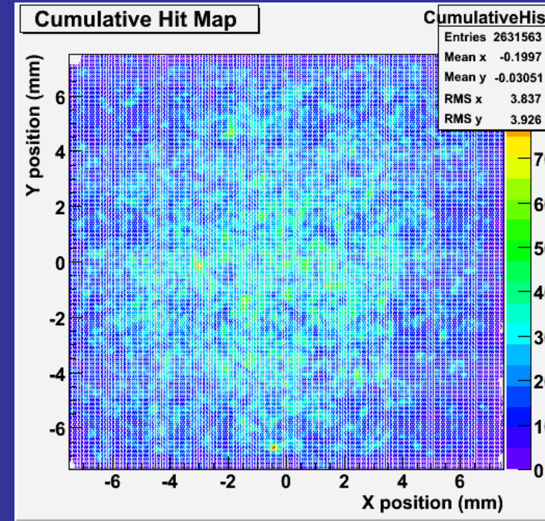
The detector is mounted on the aluminum flange screwed on top of the cryostat. A series of 6 x18W resistors is glued to the lower face of this flange. The resistors heat, in competition with the cryostat freezing, allows the system to reach a large range of temperatures.

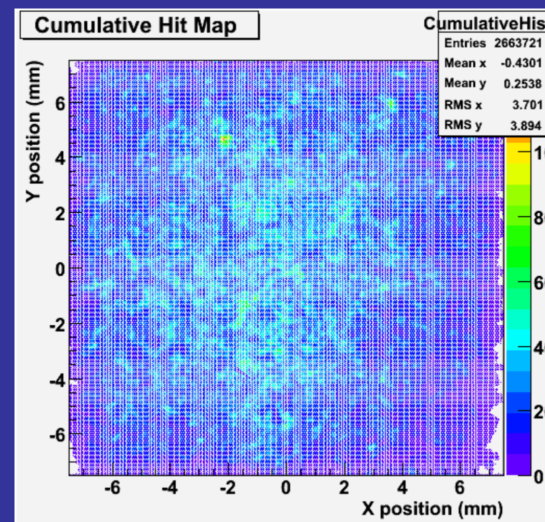
Thermo-vacuum

A single +45°C, -15°C cycle at P<10-4Torr was performed



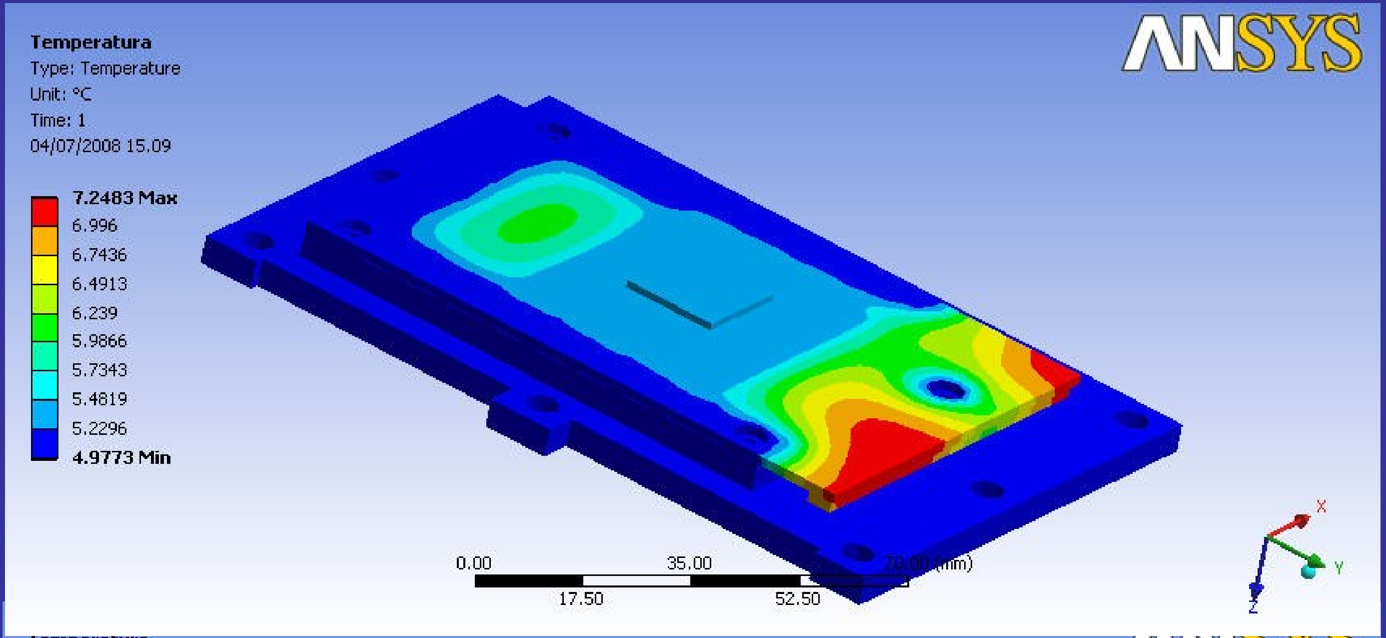
Test point temperature	Peak value (ADC counts)	Relative gain
15∞C reference test	3200±150	1
20∞C higher operative temp.	2900±150	0.91±0.06
10∞C lower operative temp.	3620±150	1.13±0.06
15∞C last reference test	3190±150	0.99±0.06



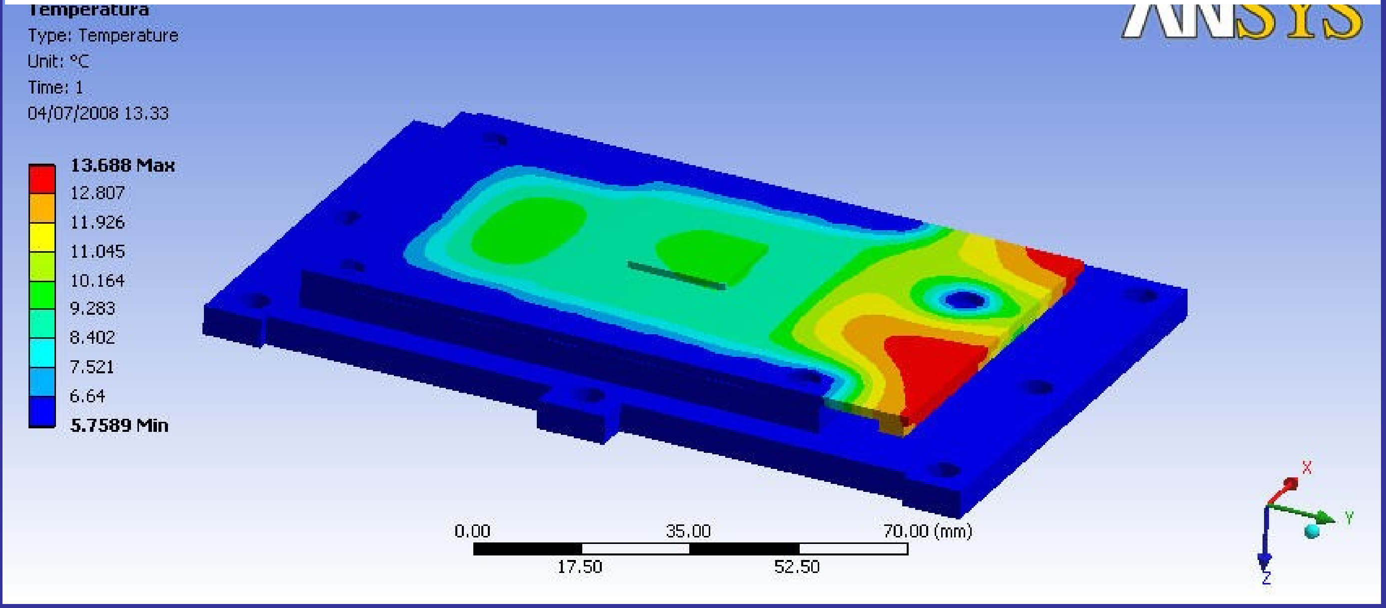


Fe^{55} source image at the beginning (top) and at the end of the thermo-vacuum cycle

Analisi termiche preliminari



- Detector OFF
- Peltier (+0.1W)
- GPD Temp=7.1°C



- Detector ON (Q=0.5W)
- Peltier (-0.4W)
- GPD Temp=9.4°C

3D models and Analysis

Preliminary structural and modal FEM analyses have been performed to design the XPOL board interface frame and the vibration vertical fixture (the plate fixture was supplied with the test equipment).

CAD software: UGS I-Deas NX12

FEM software: ANSYS V11

The results, see below, show that neither the equipment nor the board with the interface frame have frequency modes below 2000Hz. These results have been confirmed by the vibration tests.

Modes	Frequence [Hz]
1.	2838.7
2.	3268.2
3.	3817.6
4.	3899.
5.	4090.4
6.	4296.5

Mesh data:

Nodes=17557

Tetrahedral Elements=6738

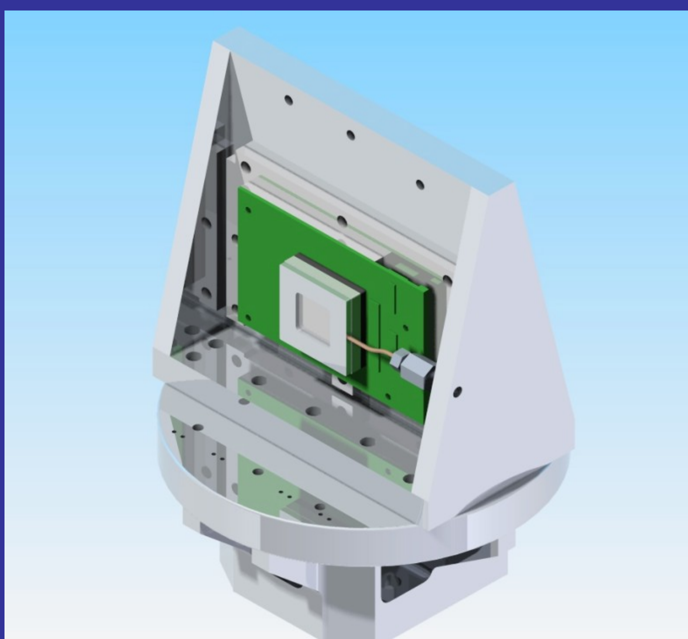
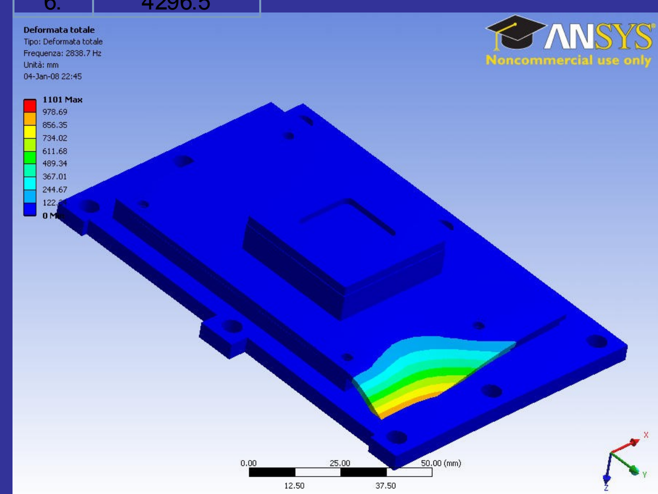


Fig. Vibration Test XPOL Board and Fixture Assembly 3D model



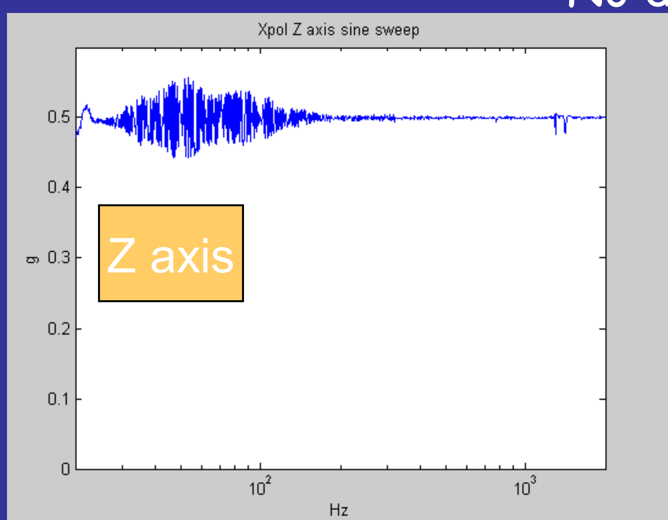
XPOL Board and Interface Frame Assembly - Modal Analysis, 1st Mode, 2839Hz

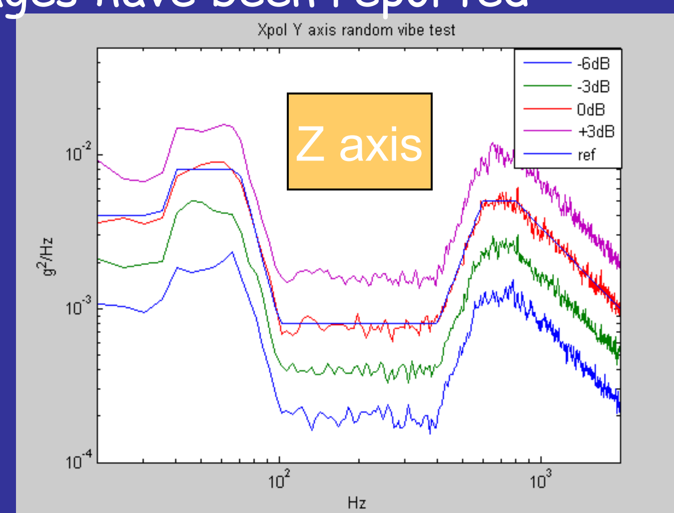
Sine sweep test

For each axis we have performed a sine sweep between 20 and 2000Hz at 2oct/min and a random test 3dB for 75s over the predicted random vibration environment of the Pegasus rocket. In all the random tests the item was vibrated to an overall $3g_{rms}$

As foreseen by the FEM analysis no resonances are present in the 20-2000Hz range.

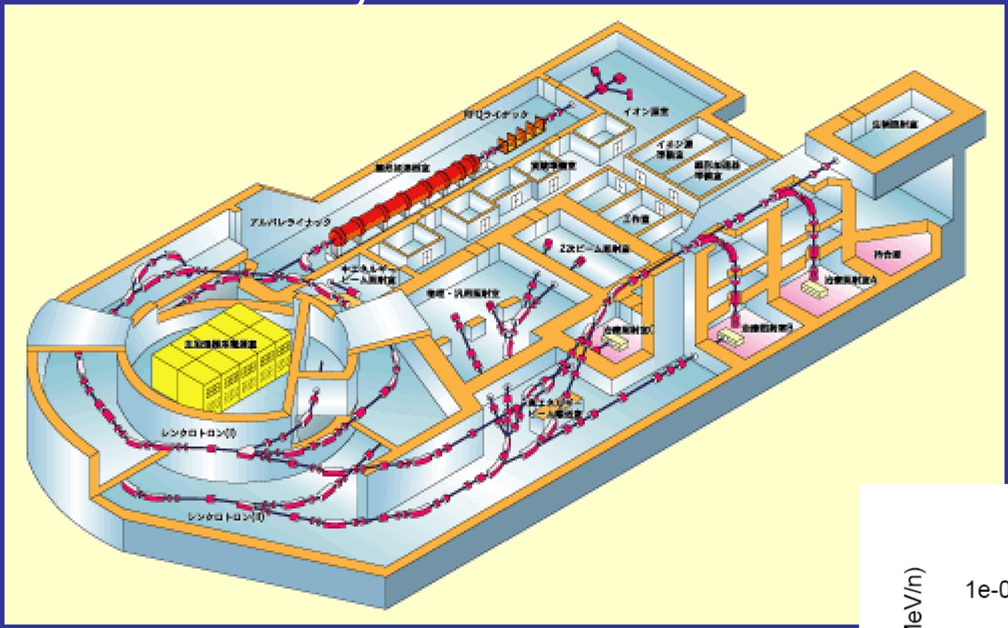
No damages have been reported



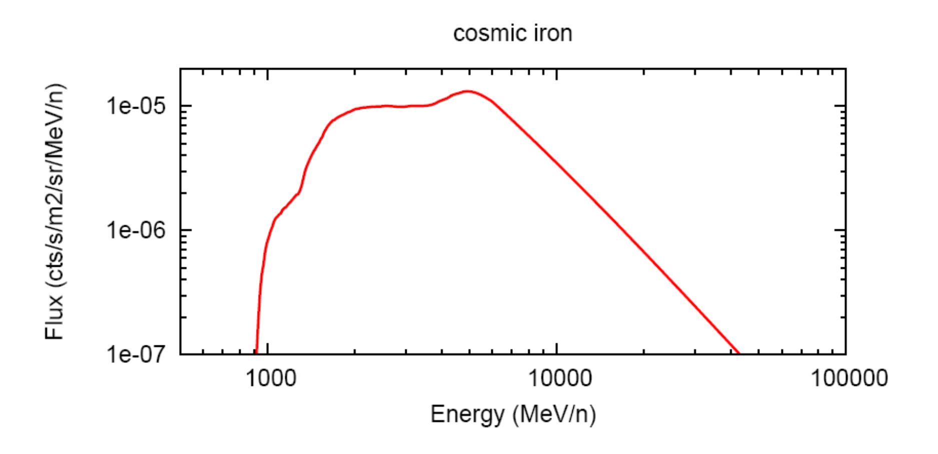


Testing with ions!

Heavy Ion Medical Accelerator in Chiba (HIMAC)



P < 160 MeV
He
C
N
O
Ne
Si
Ar
Fe
Xe



500 MeV/n Fe beam
100-150 c/cm^2/spill
Spill = 3.3s repetition and 1.7s flat top
5 x 5 cm^2 or σ =5mm Gaussian shape b
At 50Hz, 1min of beam ~ 1year of exposure in space
$R = \int F \cos\theta \, d\Omega \, dE = 6\times 10^{-5}$ cts/s/cm^2

This is the best answer to an FAQ

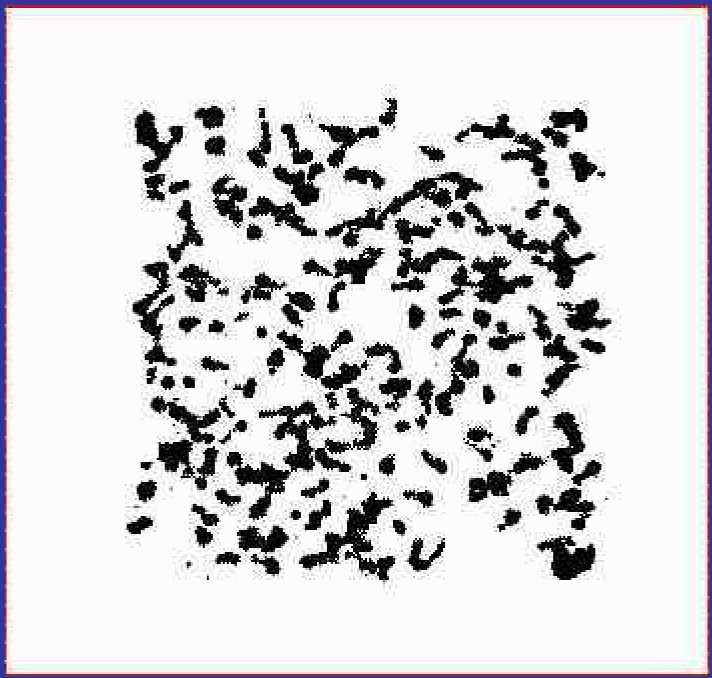
Readiness II

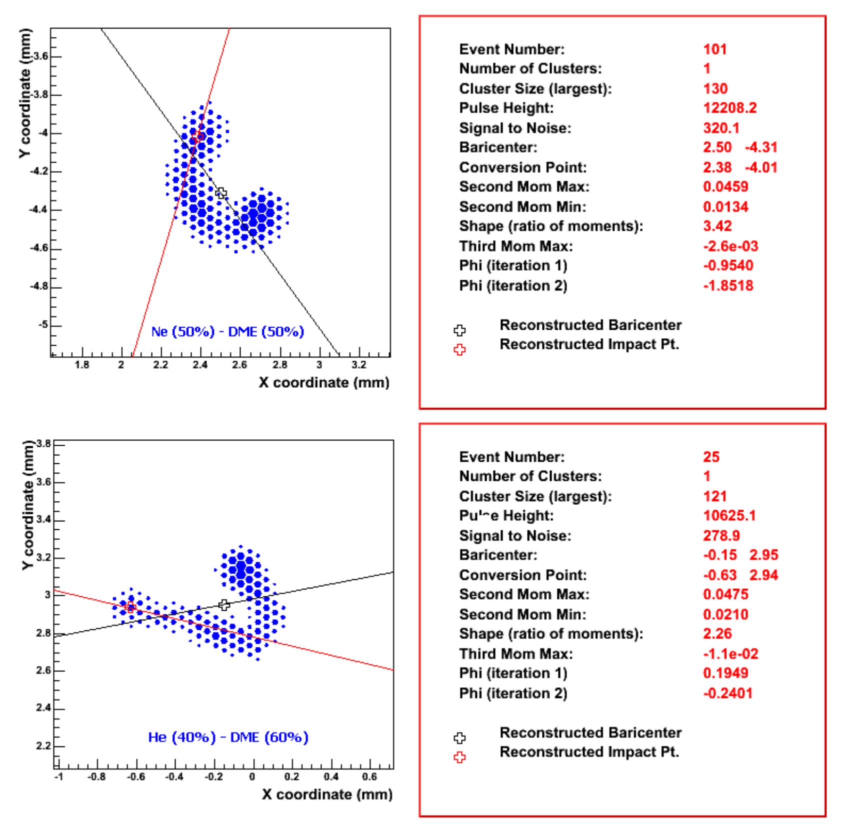
The present ASIC is likely not capable to support the data flow (of the order of 20 kevents/s expected with the XEUS telescope and a source like Crab, wihout high dead time.

A new version of the chip will be designed in order to decrease the space window around the trigger channels (now overdimensioned) and an improved timing allowing for an A/D conversion at 20MHz (compared with the present 10MHz).

A study is in progress to dimension a PDHU capable to peform onboard the analysis of the track. This will afford for a reduction of the data rate of a factor 20, useful for the most bright sources.

Track morphology and angle reconstruction



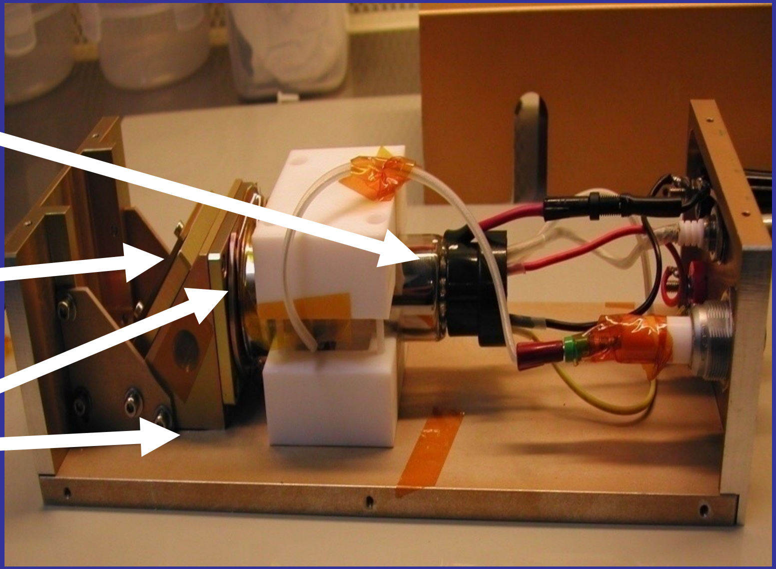


Measure of Low Energy X-ray sensitivity of XPOL and comparison with Montecarlo estimates

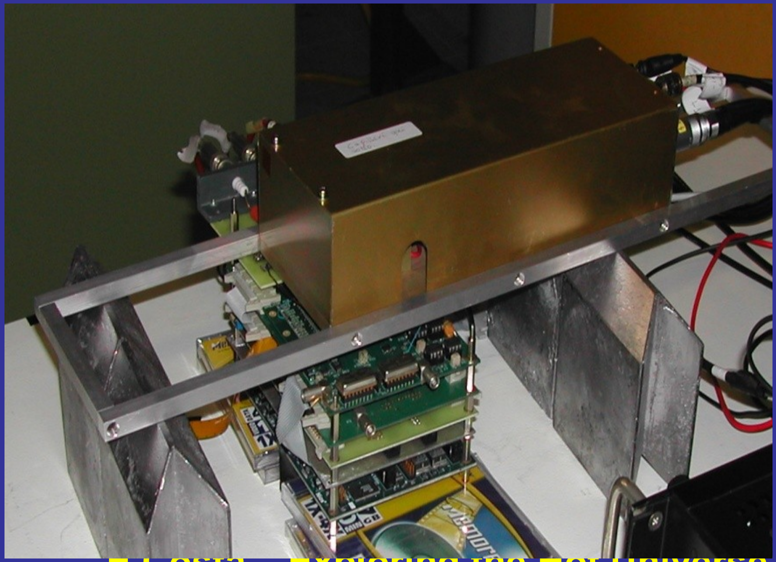
X-ray generator

Bragg Crystal

Collimators

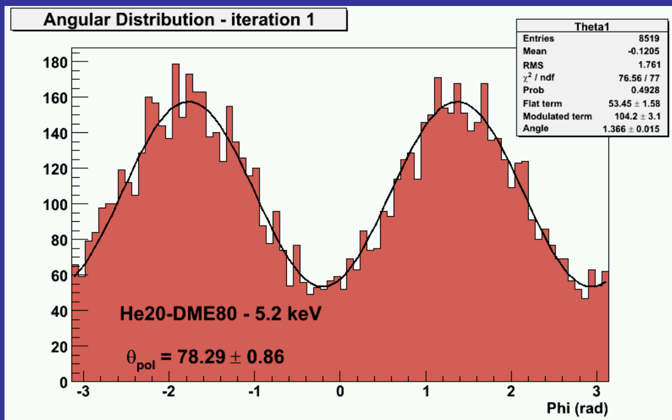


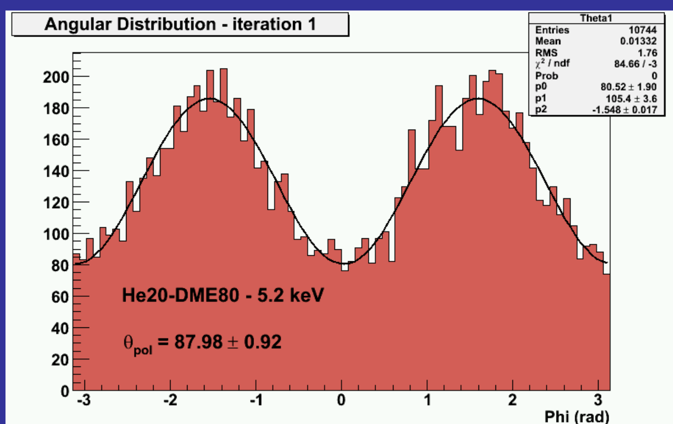
An X-ray polarizer based on selectable low energies Bragg diffraction crystals has been devised and built. (At 45o only one plane of polarization is reflected)



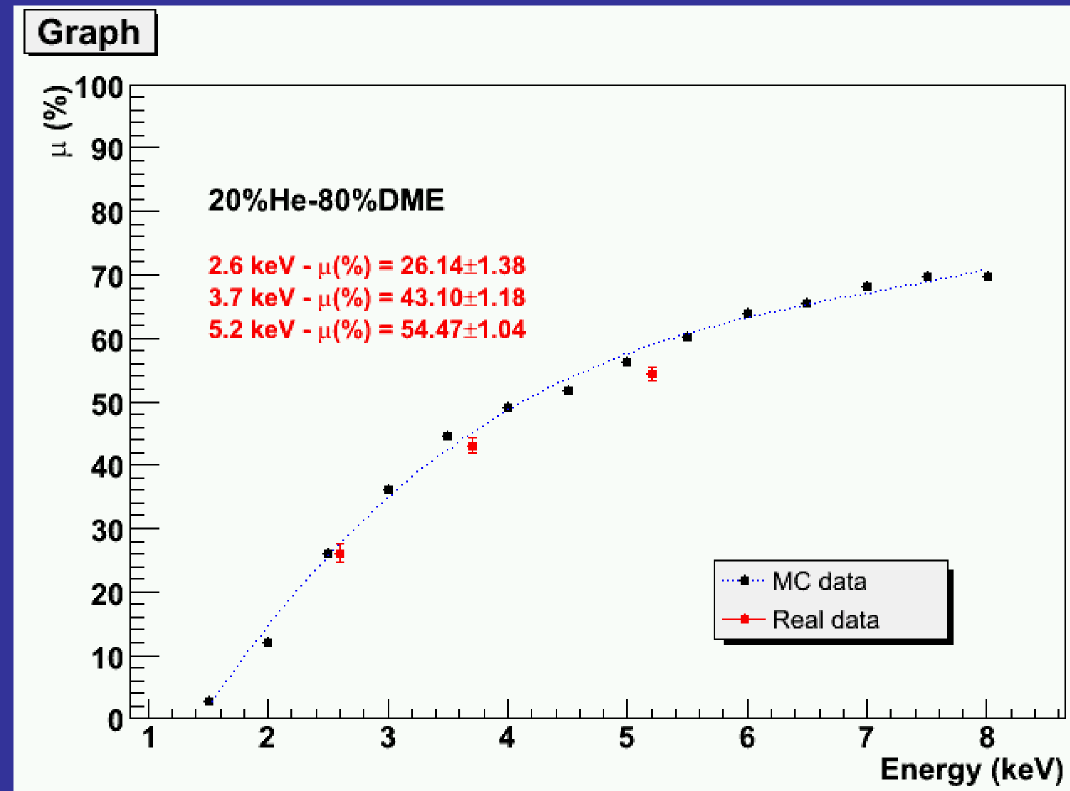
The measurement set-up.

Results of the first measurement campaign (march 2007)



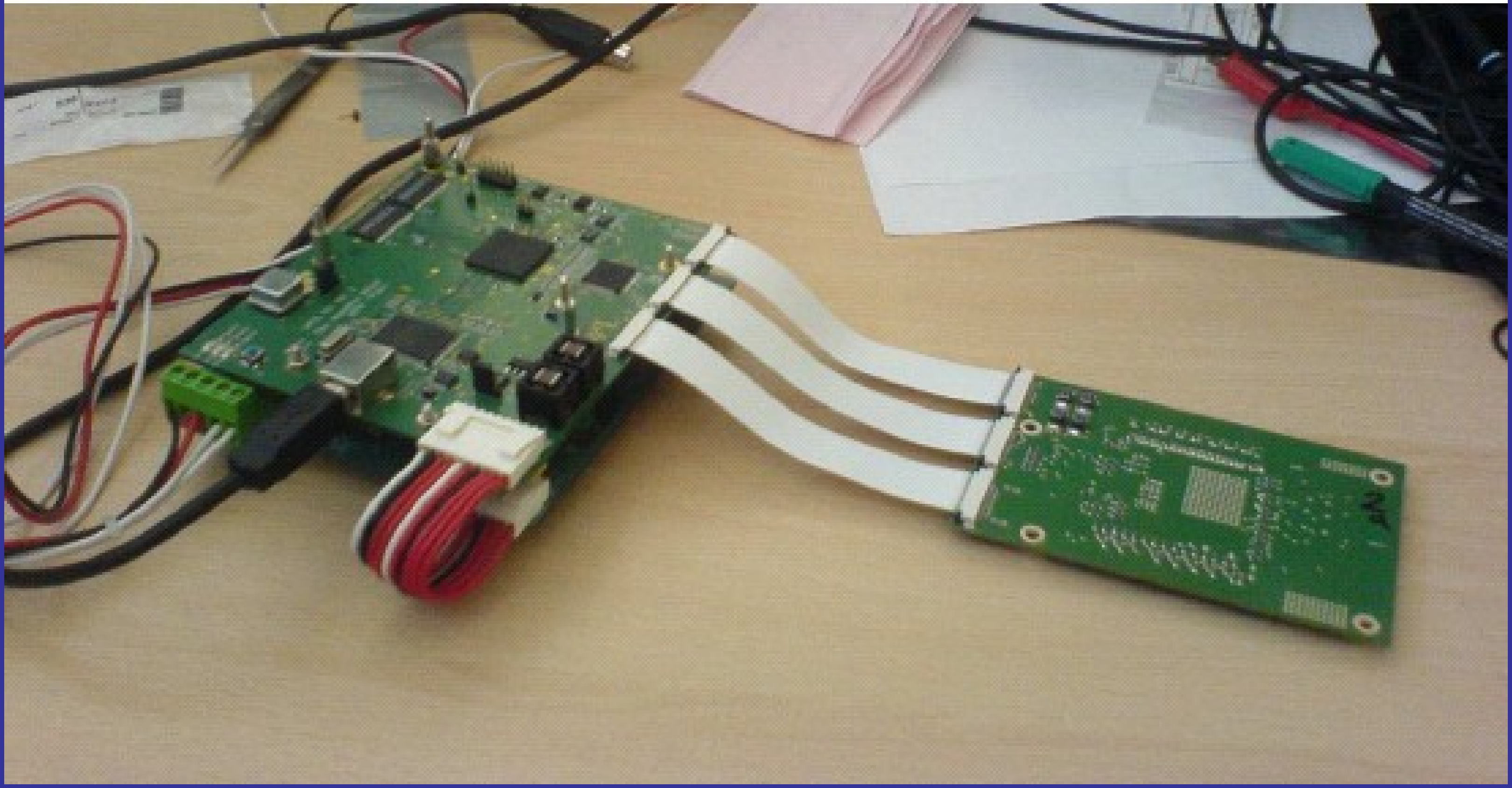


5.2 keV polarized photons for two angular rotatio of the polarizer showing the good angular sensitivity.



The modulation factor measured at 2.6 keV, 3.7 keV and 5.2 keV with XPOL has been compared with the Monte Carlo previsions. The agreement is very satisfying.

Focal plane flexibility



Detector and interface electronics are connected via flexi-cable

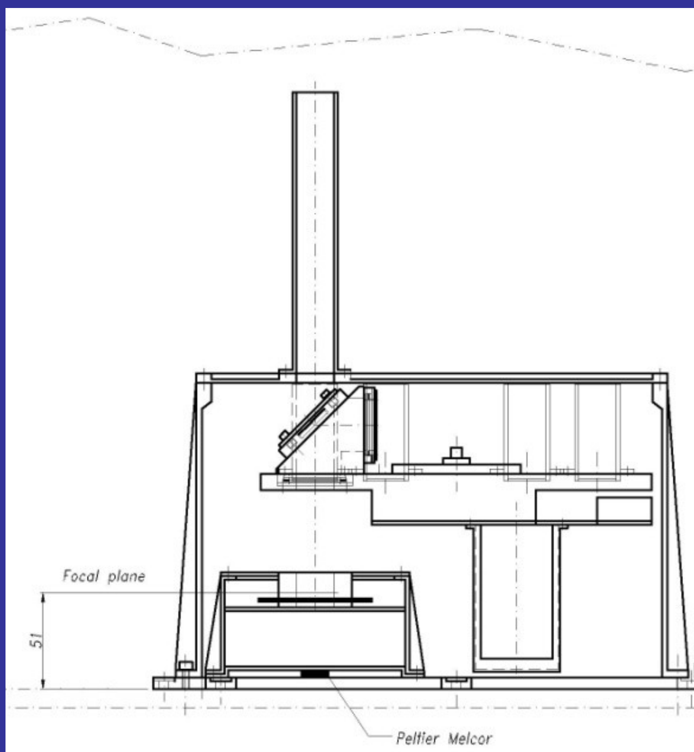
A Pathfinder Mission will likely fly before IXO:
3 possibilities on the table

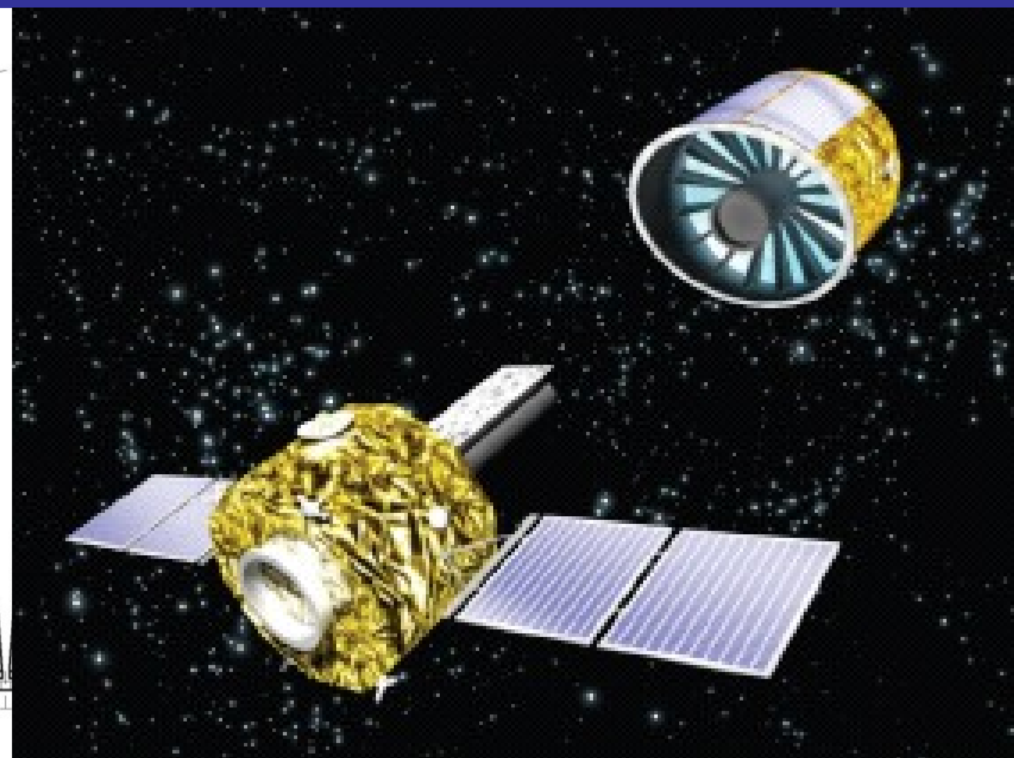
- An italian national mission POLARIX (selected for A phase): 3 to 5 telescopes like JET-X/SWIFT (total area 500 to 1000 cm^2)

- Two telescopes onboard the Chinese Mission HXMT (total area 600 cm^2): under negotiation

- GEM: a mission proposed at NASA SMEX AOO (total area 600 cm^2) and selected for phase A study

XPOL in the Focal Plane of XEUS





A telescope of 5 m^2. The baseline includes a polarimeter in the focus

Full exploitation of this technique with XEUS

A f.o.v. of 1.6×1.6 arcminutes

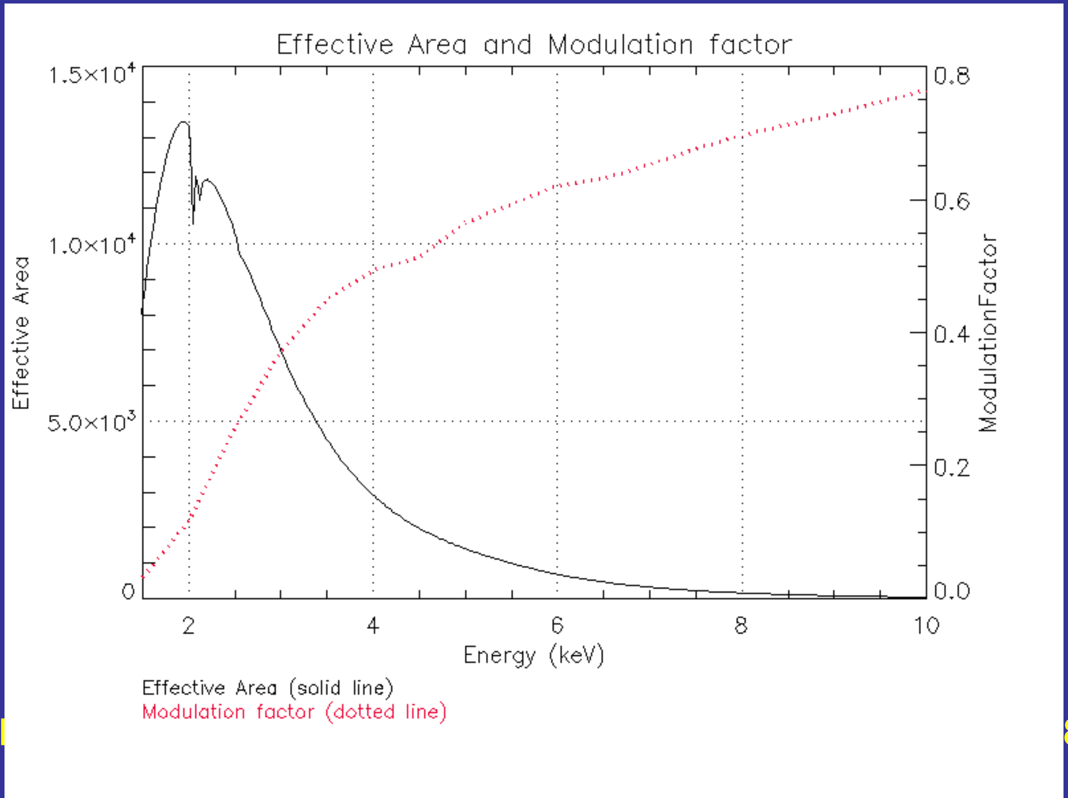
An angular resolution of 5 arcseconds

An effective area above 1 m^2

A timing capability of the order of a few μ sec

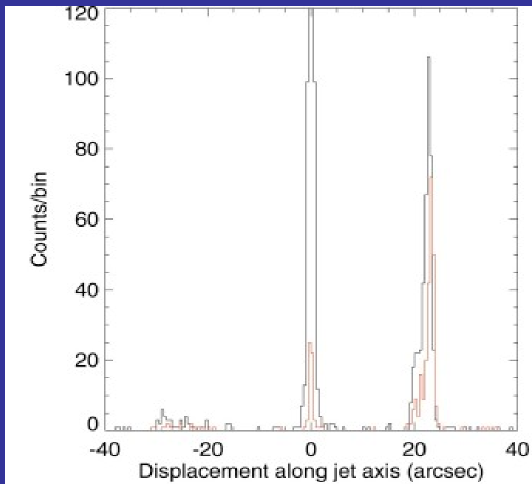
A moderate energy resoluton

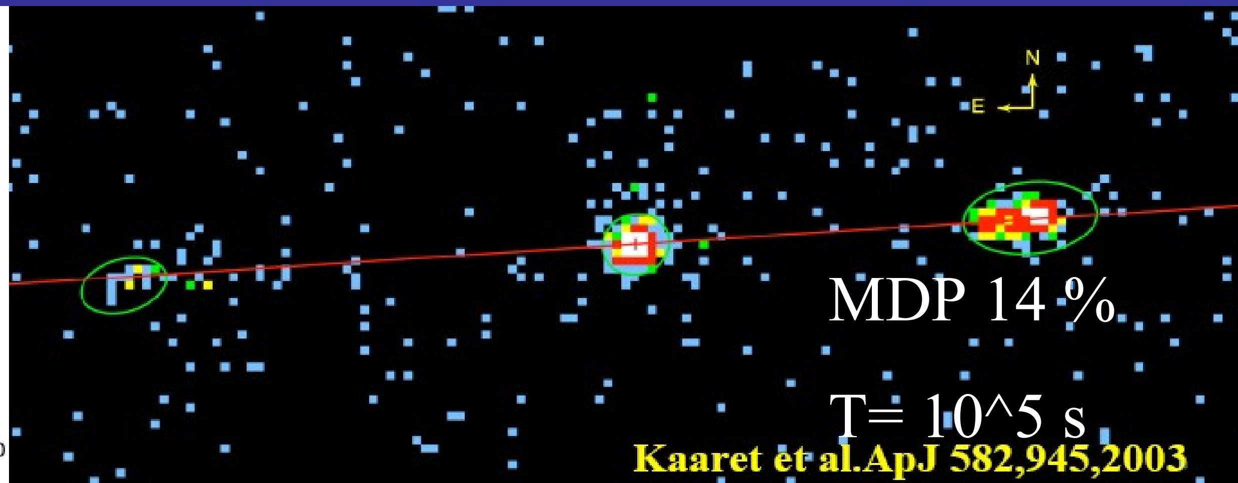
The capability to measure polarization of 1% on 1mCrab source in 10^5 seconds



IMAGING X-RAY JETS

XTE J1550-564



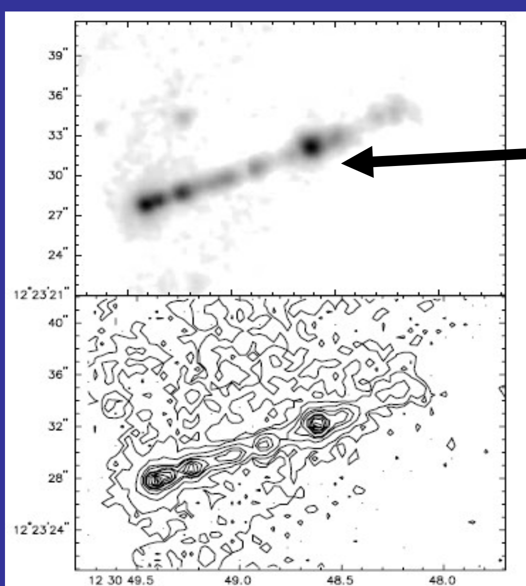


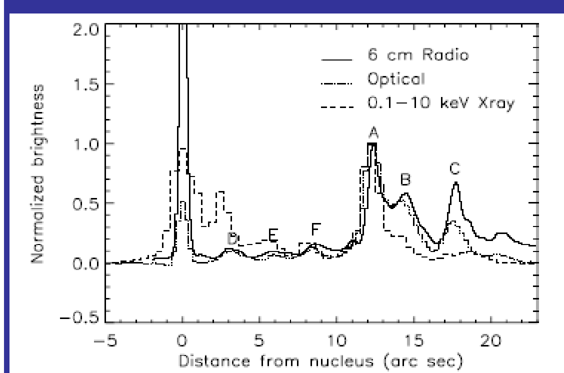
Syncrotron or External Compton ?

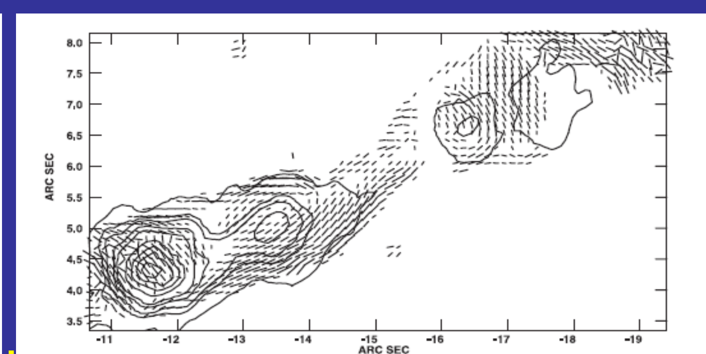
M87

Knot A

MDP Knot A 5.3% in 10^5 s

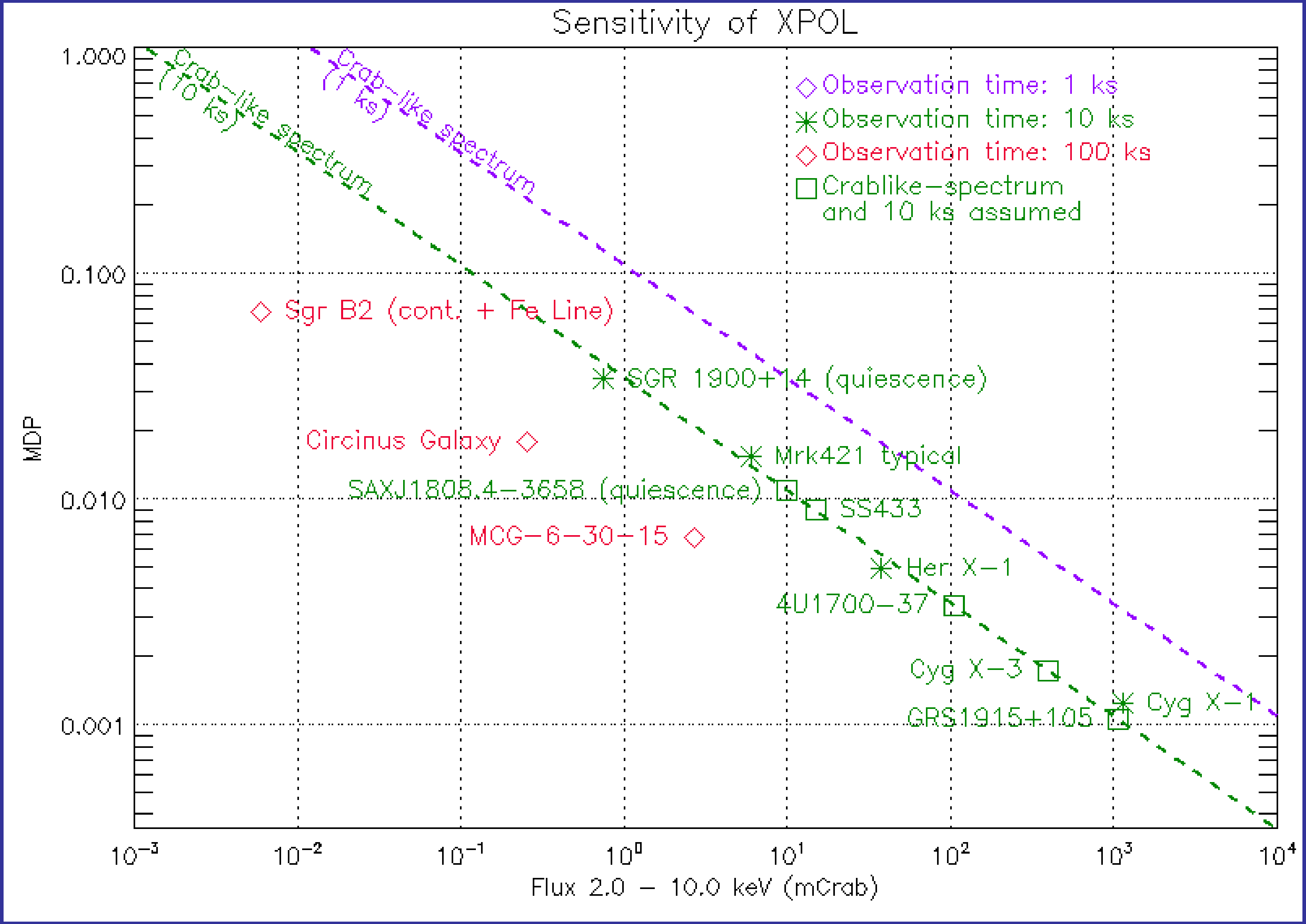






Perlman & Wilson Ap.J. 2005

XEUS XPOL Sensitivity



1 mcrab (2-10 keV) = 2.4 10^{-11} erg s^{-1} cm^{-2}

Characteristics	X-Ray Polarimeter
Detector Type	Gas Pixel Detector
Pixel size	50 µ m (on hexagonal pattern)
Number of pixels	105600
Array Size (mm^2)	15 × 15
Field of View	**1.5 × 1.5 $arcmin^2$**
Energy range	**1.9 - 6.0 keV (2% efficiency 10 % Mfactor)** **1.7 – 10.0 keV (5% Mfactor, 0.5% efficiency)**
Energy Resolution	**Δ E /E = 0.2 × (6 KeV/E)$^{1/2}$**
Non X-Ray detector Background	1 x 10^{-2} counts/cm^2 s roughly flat
Angular Resolution: Telescope :5'' Detector : (150 um = 1'') Inclined penetration (400 um = 2.7 '')	**5.8''**
Count rate/source with 10% pile-up	20k independent on the position with 10% dead time (no pile-up)
Timing accuracy	**10 µ s**
Typical/ Max telemetry	**15kbs^{-1}/1.5 Mbs^{-1}**
Operating Temperature	Detector 10 ± 2 °C Electronics 20± 20 °C
Cooling Requirements at operating temperature	0.5 W
Type of coolers	peltier
Cooler Mass	100 g
Instrument Mass, excl coolers	14.3
Instrument Power excl coolers	33 W
Total Mass	14.4 kg
Total Power	33.5 W(in operation)

Fom XEUS to IXO

How the polarimetric capabilities are affected moving from XEUS to IXO?

The reduction of the area will decrease the overall sensitivity.
The reduction of the band will enhance this effect.
The reduction of the focal is not effective down to 20m.

Which impacts on the XPOL design?

Change the gas filling mixture moving to lower energies?
Two polarimeters tuned to different energy bands?
Possibly no need to move to more powerful pdhu.

Decreasing the Area

A decrease of collecting surface Rs

Results in a proportional increase of the observing time: t→t/Rs

Or

In a reduction of MDP as $Rs^{1/2}$ for the same observing time

e.g. this would result in:

•a reduced sample of AGN, with a poorer coverage of parameter space

•a significant loss of sensitivity to variability of polarization angle with time (namely on testing strong gravity in extragalactic BHs)

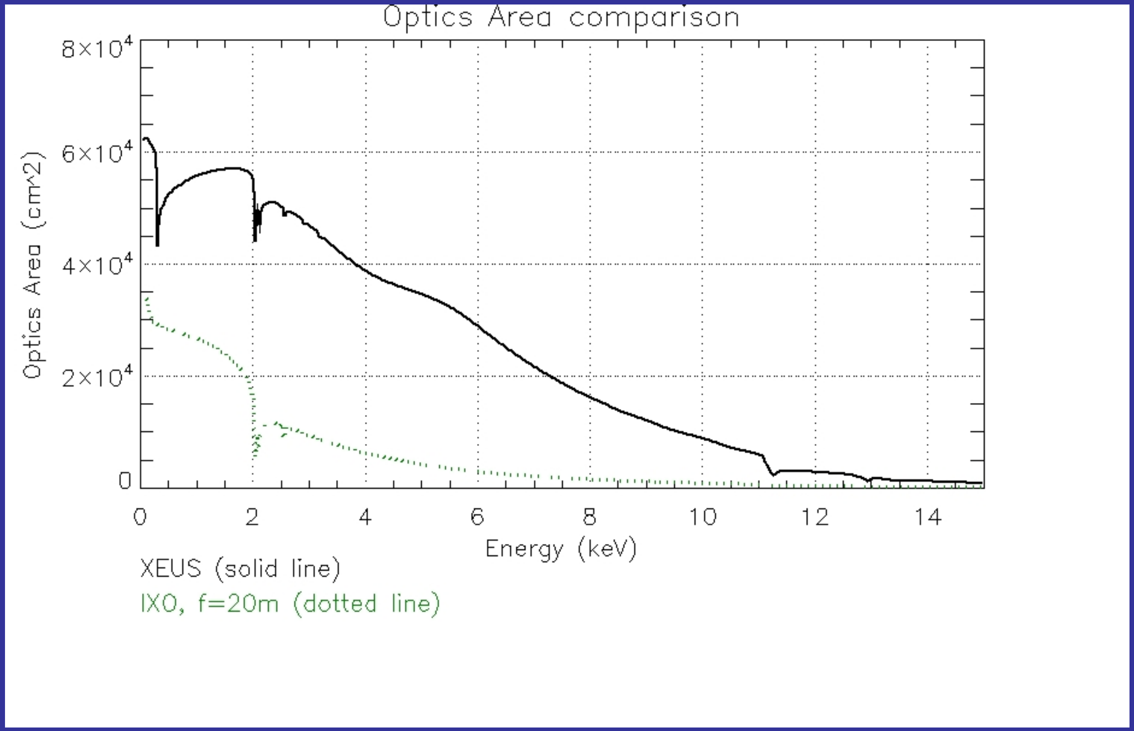
How it would compare with pathfinder missions?

IXO could reasonably dedicate to polarimetry only a fraction of its time (let us say 1/10) while a pathifinder could perform full time polarimetry.

The step in surface to have a significant improvement with respect to pathfinders for deep pointing is of two orders of magnitude.(≈5m^2)

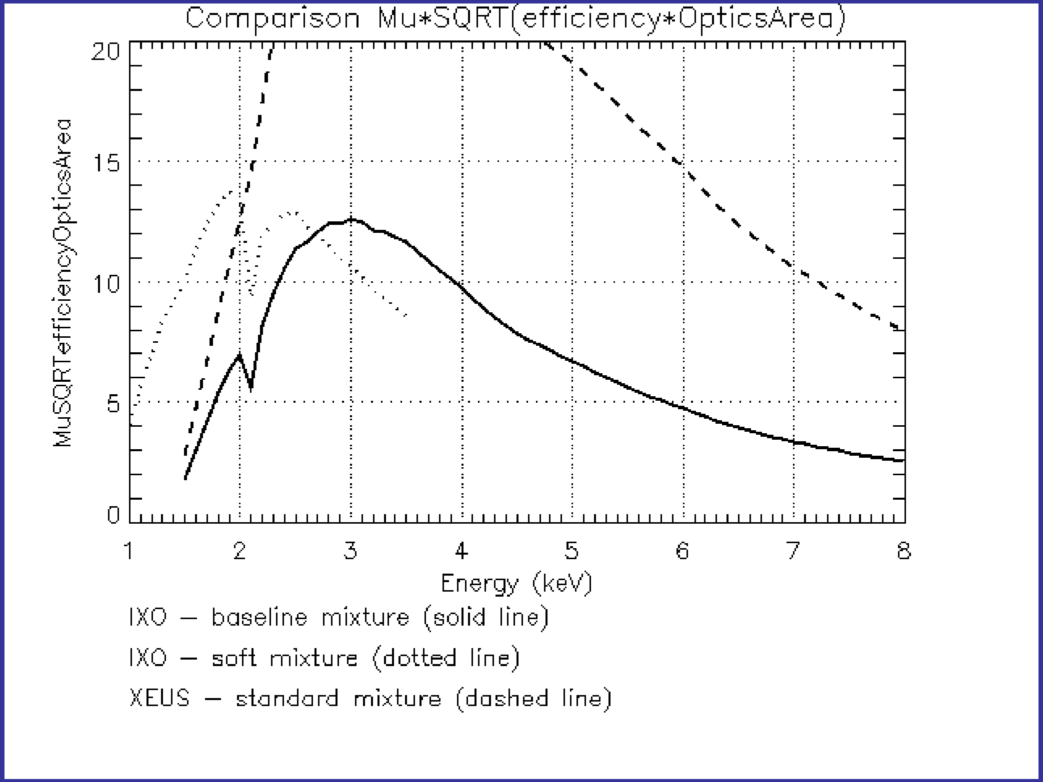
The change of the band

The GPD is nominally a large band device but actually not that large! The present baseline gas mixture is tuned on a larger band-pass telescope and gives the best performance from 2.5 to 4 keV.
The designs under study have a band-pass significantly softer than XEUS. Where the polarimeter is more sensitive the improvement with respect to pathfinders is more one order of magnitude than two.



Possible approach

A possible approach is to change the filling gas mixture to increase the sensitivity to lower energies where the telescope throughput is high.



Another approach could be to put two detectors: one with a mixture harder than the baseline and one with thin window with a mixture softer than the baseline. It would be more performant with equivalent time. The additional resources are nominally a few but a study is needed.

The reduction of the focal

Is positive for the field of view:

50m → 20 m

1.1 arcminute × 1.1 arcminute → 2.7 arcminute × 2.7 arcminute

e.g. Cas A could be imaged with 4 pointings only, Crab with a single pointing.

Implies an increase of the contribution to the angular resolution of the blurring due to the inclined penetration of photons in the gas.

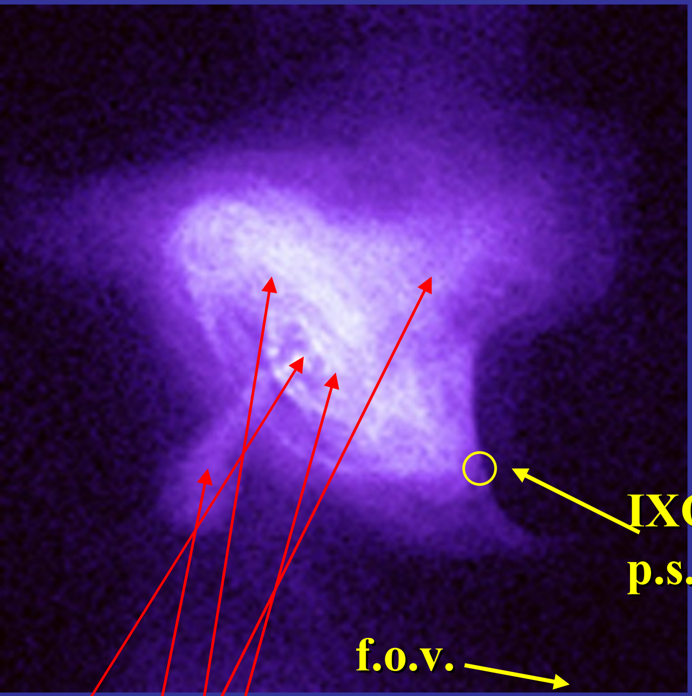
With a focal length of 20 m and a resolution of 5 arcseconds (50%) this term is still almost negligible.

5 arcseconds → 6 arcseconds

This is computed with ray-tracing and corrects previous evaluation based on worst case considerations.

IXO would have [almost] the same angular resolution of XEUS and a much larger f.o.v. (nice for extended sources)

The only polarized source already known



IXO p.s.f.

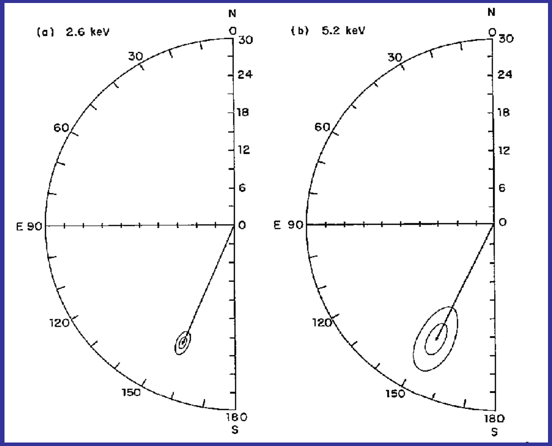
PSR

NW jet

SE jet

Inner torus

Outer torus



Positive measurement: of X-ray polarization of the Crab Nebula without pulsar contamination (by lunar occultation, Weisskopf et al., 1978). **P = 19.2 ± 1.0 %**

θ = 156.4° ± 1.4°

But this is only the average measurement
The structure is much more complex!

Also the recent measurements by INTEGAL SPI and IBIS are integrated on the whole source.

With XPOL we can perform the separate polarimetry of details of the major structures

How turbulent is the field?

How polarized is the PSR?

This is much better than any pathfinder!

The coming of age of x-ray polarimetry

Rome, April 27th - 30th, 2009

Centro Studi Americani
Via Michelangelo Caetani 32
00186 Roma

http://projects.iasf-roma.inaf.it/xraypol/

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