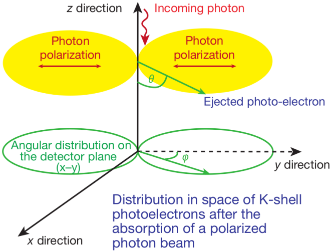
Photoelectric X-Ray Polarimetry for e-XTP

Luca Baldini
Università and INFN–Pisa
luca.baldini@pi.infn.it

Roma, December 11, 2019



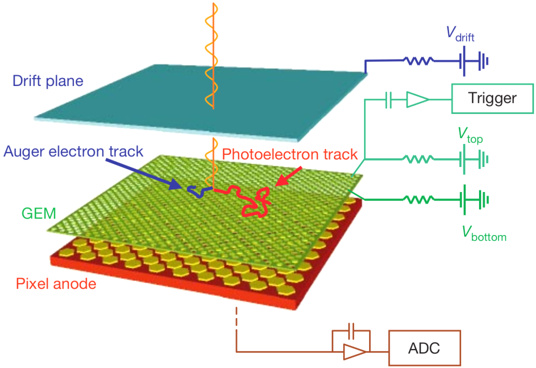
- Dominant interaction process at low energy.
- The distribution of the direction of emission of a K-shell photoelectron is 100% modulated if the incident radiation is 100% linearly polarized:

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

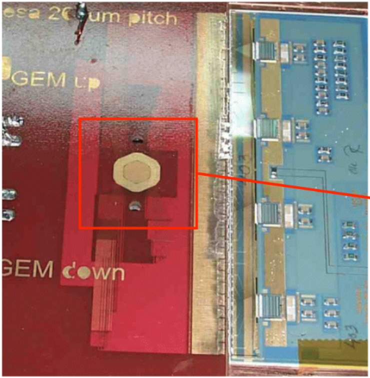
- In principle this is the perfect polarization analyzer, but. . .
  - Need to reconstruct the direction of emission of the photoelectron, i.e., a granularity significantly smaller than the typical range.
  - The range for a 5 keV photoelectron is a few μm in a solid—main driver for choosing a gaseous detection medium.

The Gas Pixel Detector (GPD) as a polarimeter

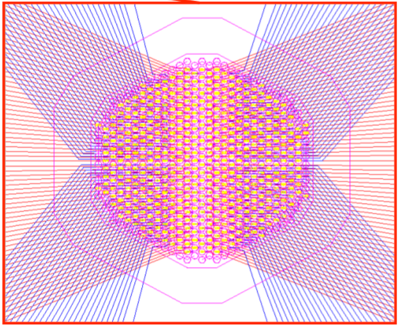
- Basic components: absorption gap, Gas Electron Multiplier (GEM), finely pixelized readout anode.



- ✓ Sensitive down to very low energy (~ 1 keV).
- ✓ Fully two-dimensional (imaging).
- ✓ Highly azimuthally symmetric (no need of rotation to control systematics).
- ✘ Coupling between the efficiency and the modulation factor.
  - Track blurring due to the transverse diffusion of the ionization.



- Main technical challenge: fan-out from the readout anode to the front-end electronics.



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

letters to nature

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

Enrico Costa*, Paolo Soffitta*, Ronaldo Bellazzini†, Alessandro Brez†, Nicholas Lumb† & Gloria Spandre†

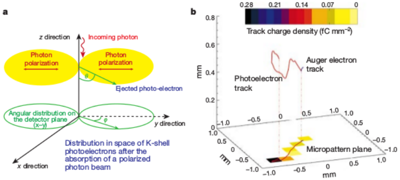
** Istituto di Astrofisica Spaziale del CNR, Via Fosso del Cavaliere 100, 1-00133, Rome, Italy*
† Istituto Nazionale di Fisica Nucleare-Sezione di Pisa, Via Livornese 1291, I-56010 San Piero a Grado, Pisa, Italy

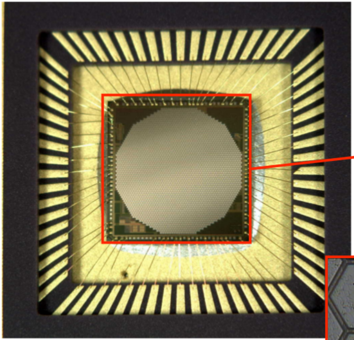
The study of astronomical objects using electromagnetic radiation involves four basic observational approaches: imaging, spectroscopy, photometry (accurate counting of the photons received) and polarimetry (measurement of the polarizations of the observed photons). In contrast to observations at other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

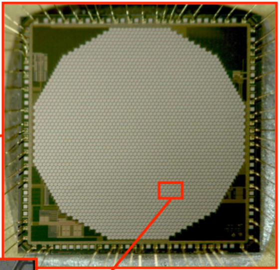
The main advantage of the proposed polarimeter is its capability of investigating active galactic nuclei (quasars, blazars and Seyfert galaxies) for which polarization measurements have been suggested, crucial to understand the geometry and physics of emitting regions. We can separate synchrotron X-rays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

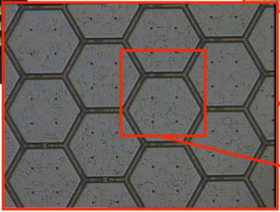
In spite of this wealth of expectations, the important but only positive result until now is the measurement, by the Bragg technique, of the polarization of the Crab nebula[18,19]. The Stellar X-ray Polarimeter[20] (SXRP) represents the state of the art for conventional methods based on Bragg diffraction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

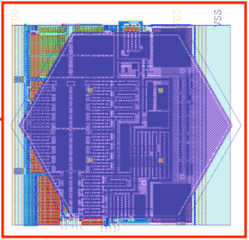
The photoelectric effect is very sensitive to polarization. The electron is ejected from an inner shell with a kinetic energy which is the difference between the photon energy and the binding energy. The direction of emission is not uniform but is peaked around that of the electric field of the photons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



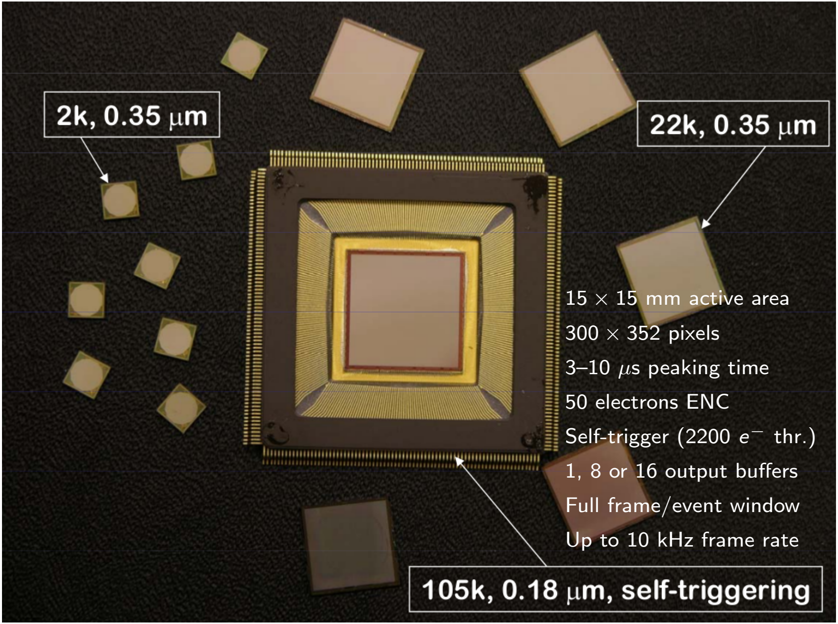


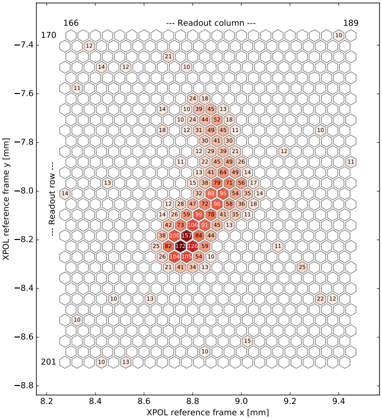




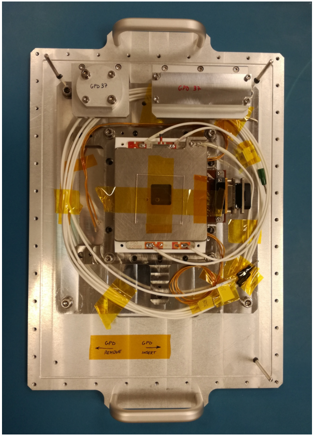


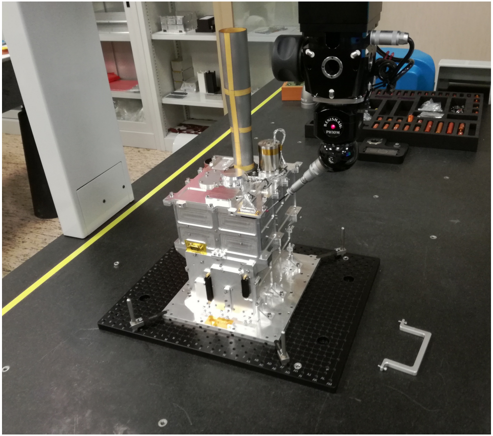
- 2101 hexagonal pixels.
- 80 μm pitch.
- Metal top layer acting as a charge collecting anode.
- Integrating preamplifier, shaper, S/H, multiplexer.
- Serial readout via external ADC.


2k, 0.35 μm
22k, 0.35 μm
15 × 15 mm active area
300 × 352 pixels
3–10 μs peaking time
50 electrons ENC
Self-trigger (2200 e^- thr.)
1, 8 or 16 output buffers
Full frame/event window
Up to 10 kHz frame rate
105k, 0.18 μm, self-triggering



- Serial readout on (up to) 16 parallel buses, clocked up to 10 MHz.
- Self-triggering, based on 2×2 mini-clusters with fast shaper.
- Internal definition of the region of interest for the event readout.
  - All mini-clusters above threshold plus some padding (10 or 20 pixels).
  - Typical window size < 1 k pixels.
  - Multiple window readout for event-by-event pedestal subtraction.





- 3 (+ 1 spare) flight Detector Units assembled and tested
  - Each including the GPD, FE and BE electronics, a filter and calibration wheel and a stray-light collimator
  - Qualification completed
  - Calibration ongoing
- Integration with the SC due to begin in spring 2020

Is all of this ready off the shelf for e-XTP?

- The IXPE instrument design is now tested and qualified for space
  - The overall architecture is fairly similar to the e-XTP baseline
  - IXPE readout ASIC successfully flown on a cubesat (lead: Hua Feng)
- e-XTP effective area per telescope significantly larger than IXPE
  - Readout throughput does not scale well for bright sources
  - Need to cut down the dead-time by an order of magnitude
  - Feasible with specific modifications of the readout ASIC
- Systematic effects connected to the GEM manufacturing for IXPE
  - Low-energy spurious modulation
  - Rate-dependent gain variations due to charge build up
- We have convincingly demonstrated that all the systematics can be calibrated to meet the IXPE Science requirements. . .
  - (via a dithering of the observatory and suitable time-dependent calibrations)
- . . . but we do have a clear path to fix (or at least mitigate) them at the hardware level
  - "Diagnostic" R&D on the GEM successfully started in the IXPE framework
- (And we now have a much more profound understanding of the detector to base the optimization of the gas cell upon)

- The e-XTP PFA will largely build upon (and benefit from) the IXPE experience
  - We have a full design working and qualified for space
- New generation of the readout ASIC needed to cope with the larger effective area
- In practice: natural chance to design a full GPD "2.0" overcoming the difficulties encountered through the IXPE development
  - The ASIC development does not happen in vacuum (needs a full end-to-end test in a full GPD assembly)
  - Clear path forward from the technical standpoint
- Can be realistically achieved through a focused R&D in the e-XTP phase B