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ABSTRACT

XIPE, the X-ray Imaging Polarimetry Explorer, is a mission dedicated to X-ray Astronomy. At the time of writing XIPE is in a competitive phase A as fourth medium size mission of ESA (M4). It promises to reopen the polarimetry window in high energy Astrophysics after more than 4 decades thanks to a detector that efficiently exploits the photoelectric effect and to X-ray optics with large effective area. XIPE uniqueness is time-spectrally-spatially-resolved X-ray polarimetry as a breakthrough in high energy astrophysics and fundamental physics. Indeed the payload consists of three Gas Pixel Detectors at the focus of three X-ray optics with a total effective area larger than one XMM mirror but with a low weight. The payload is compatible with the fairing of the Vega launcher. XIPE is designed as an observatory for X-ray astronomers with 75 % of the time dedicated to a Guest Observer competitive program and it is organized as a consortium across Europe with main contributions from Italy, Germany, Spain, United Kingdom, Poland, Sweden.

Keywords: X-ray Astronomy, Polarimetry, X-ray optics, Gas Pixel Detector

1. INTRODUCTION

X-ray polarimetry promises to provide a wealth of information. Indeed emission processes in this energy band are expected to provide polarized radiation. However, even if the radiation is emitted thermally, and therefore intrinsically not polarized, the scattering in a-spherical plasma which are common in X-ray Astronomy provide polarized radiation. Also X-ray polarimetry probes environment with magnetic fields much larger than that obtainable on the Earth allowing for detecting phenomena of birefringence not yet discovered in ground experiments. Here below we provide some early bibliography on these topics.

1. Emission processes themselves: cyclotron, synchrotron, non-thermal bremsstrahlung[1–3]

2. Scattering on aspherical accreting plasmas: disks, blobs, columns[3–5]

3. Vacuum polarization and birefringence through extreme magnetic fields[6–8]

Polarimetry would allow for determining the geometry of sources on angular scales not accessible with current or planned X-ray astronomy imaging missions. A positive measurement will remove geometrical degeneracies in X-ray binaries, in isolated pulsar and magnetars. Indeed, nowadays, geometry is still a parameter in a fit of a light-curve or of a spectrum and it is not the result of a direct measurement.

2. MODULATION CURVE AND MINIMUM DETECTABLE POLARIZATION

An X-ray polarimeter measures a modulation curve, that is the response of a polarization sensitive device to an angle related to the polarization angle of the incoming beam. We fit the modulation curve with a $\cos^2$ function. We then normalize the modulation amplitude using the modulation factor, which is the modulation amplitude for 100 % polarized beam, deriving the polarization. From the position of the peaks of the modulation curve we derive the polarization angle. Another important parameter is the Minimum Detectable Polarization (MDP) which is the level over which we can reject the hypothesis of absence of polarization at 99 % confidence level and expressed as in equation 1:

$$MDP(99\%) = \frac{4.29}{\mu S} \sqrt{\frac{S+B}{T}} \qquad (1)$$

where B is the background counting rate (negligible for focal plane experiments as in the case of a GPD at the focus of an X-ray optics), T is the observing time, S is the source counting rate and μ is the modulation factor.[9]

As can be seen in table 1 the total number of counts for reaching an MDP of 1% is three order of magnitude larger than that needed to detect a source or to measure a spectral slope.

Table 1. Different number of counts for different kind of measurements. We assumed μ is 0.5 for the 1 % MDP

Source detection	10 counts
Spectral slope	100 counts
1% MDP	counts > 700000

Therefore X-ray polarimetry deserves a dedicated mission with detectors developed at this aim. Each time polarimetry is tempted as a byproduct of instruments not specifically designed for this, at best, low significance measurements, (if not in contradiction), are produced. So far, the only positive measurement available is indeed the one obtained with the polarimeter on-board OSO-8 based on Bragg diffraction by the group of Robert Novick.[10] We recall that the measurement of the X-ray polarization of the Crab Nebula has a 19-σ significance at 2.6 keV and 10-σ significance at 5.2 keV. Only very coarse upper limits[11] were measured by OSO-8 (except that on Sco X-1[12]). These upper limits are not particularly useful.

3. MODERN X-RAY POLARIMETRY

The modern X-ray polarimeters exploit efficiently the photoelectric effect in gas. The photoelectron from a K-shell is ejected preferentially along the direction of the polarization vector of the incoming beam. If the track is finely resolved and efficiently imaged the emission direction can be reconstructed by applying simple algorithms. We, at this aim, devised and built the Gas Pixel Detector (GPD) to be sensitive in 1-10 keV energy band. In this energy band, basically, all the scientific cases for X-ray polarimetry can be eventually investigated (see table 2), and also conventional X-ray optics are efficient and sources are sufficiently bright.

Polarimeters based on multi-layer mirrors are efficient below 1 keV and, while they may be very sensitive for blazars and isolated pulsars, this energy range suffers of interstellar absorption. Moreover this is not the proper energy band for studying effects of General Relativity in strong gravity regime or phenomena characterized by Compton reflection. The energy band above 10 keV is, instead, particularly suited for studying reflection phenomena and for polarimetry of cyclotron lines in X-ray pulsator. However it does not allow for probing magnetars, including the QED effects of birefringence, or Black Hole X-ray Binaries and general relativistic effects in the strong gravity regime.

Table 2. Scientific goals for X-ray polarimetry. Cyclotron lines are observed above 10 keV except, possibly in one

Scientific goals	Sources	< 1 keV	1-10	> 10 keV
Acceleration phenomena	PWN	yes (but absorp.)	yes	yes
	SNR	no	yes	yes
	jet (μQSO)	yes (but absorp.)	yes	yes
	jet (Blazars)	yes	yes	yes
Emission in strong magnetic fields	WD	difficult	yes	yes (difficult)
	AMS	no	yes	yes
	X-ray pulsator	difficult (absorp.)	yes (no cyclotron ?)	yes
	Magnetar	yes (better)	yes	no
Scattering in a-spherical geometries	Corona in XRB & AGNs	yes (but absorp.)	yes	difficult
	X-ray reflection nebulae	no	yes (long exposure)	yes
Fundamental Physics	QED (magnetar)	yes(better)	yes	no
	GR(BH)	no	yes	no
	QG (Blazars)	difficult	yes	yes
	Axions (Blazars, Clusters)	yes ?	yes	difficult

4. THE DETECTOR CAPABILITY

The detector is designed[13–15] as a sealed gas cell. A 50 μm thick beryllium window is glued on a titanium frame and the latter onto a MACOR spacer. Underneath, the Gas Electron Multiplier and its supporting frame are glued on the KIOCERA package. An ASIC-CMOS, developed at this aim, is internally bonded to the package. The top layer of the multi-layer ASIC is an hexagonally patterned (105400 pixels) collection plane. Below each pixel there is a complete analogue chain. A set of local triggers define the region of interest that surrounds the track. Only a fraction of pixels (600-800) are serially readout reducing dramatically the dead time fraction. Three generation of ASICs were produced. The current ASIC is the first self triggered one with its trigger output signal allowing for time resolved polarimetry. Modulation factor and energy resolution were measured to be basically constant for at least three years of operation so this design is particularly suited for a long term space mission. The modulation factor is found in agreement with the Monte Carlo expectations and a cut on 20 % of data allows for the best sensitivity. The energy resolution is found compliant with the requirement of 20 % (point source) and 25 % extended sources. Some experimental results are shown in figure 1 while details on the performances can be found in this proceedings.[16]
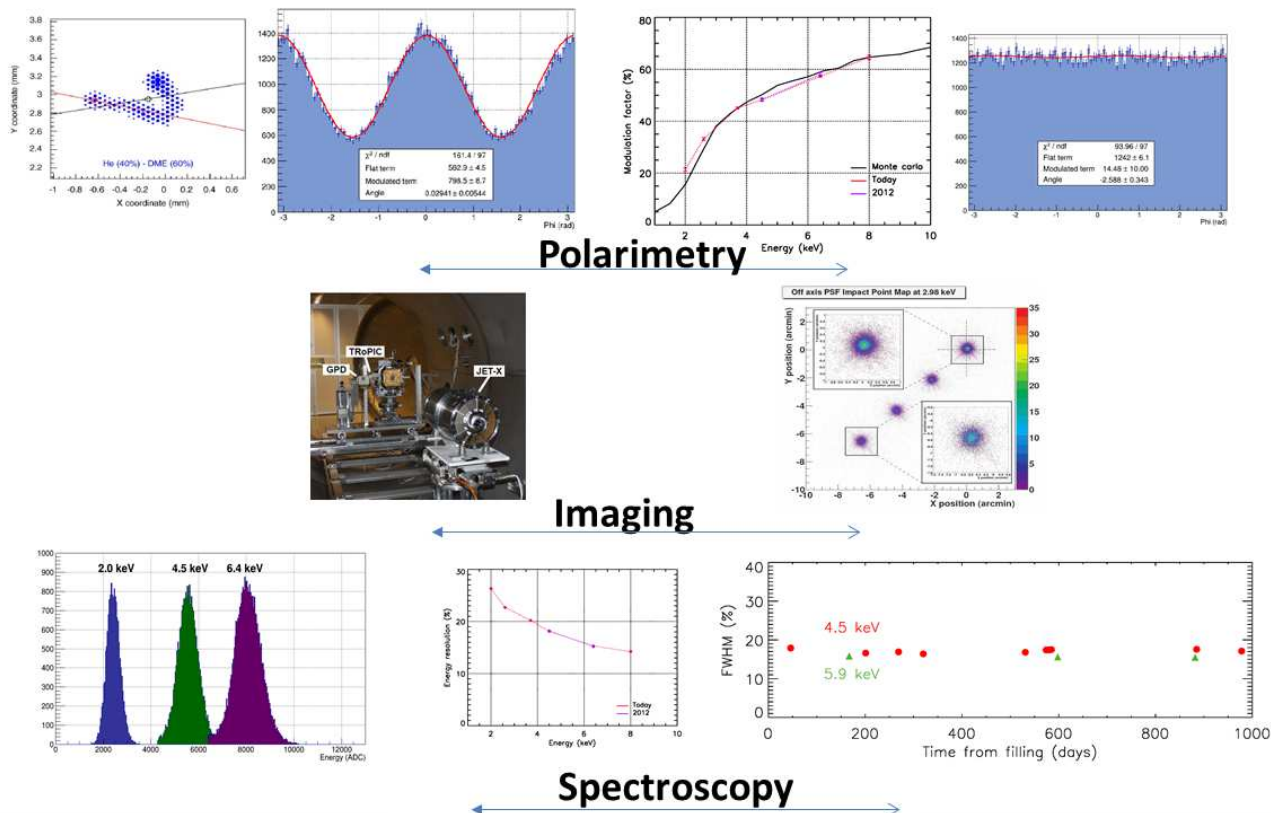
Figure 1. (**Top**) From left: an image of a photoelectron track; a modulation curve at 3.7 keV; the modulation factor as a function of energy; a modulation curve for an unpolarized [55]Fe source. **Middle**. From left: the GPD at the focus of a JET-X optics together with the CCD and the ROSAT PSPC; the on-axis and off-axis images. **Bottom** From left: the spectra of sources at 2.0, 4.5 and 6.4 keV; the behavior of the energy resolution with energy; the behavior of the energy resolution with time.

The imaging capabilities of the detector were measured either in laboratory with a narrow pencil beam[17] and at the PANTER X-ray test facility.[18] We disentangled the various components concurring to the overall angular resolution confirming the expectation[19] that the main contribution is provided by the performances of the optics. The second contribution for importance is given by the inclined penetration of the photons in the 1-cm thick drift region, due to the narrow incidence optics, while the intrinsic position resolution of the detector provides a negligible contribution. We note here that the GPD met the strict requirements for operating in high vacuum and in cleanness environment of the PANTER test facility.

5. THE PATH OF XIPE TO THE 4TH MEDIUM SIZE CALL

Thanks to the invention of the GPD, many missions were proposed answering to call of different international space agencies like ASI, CNSA, NASA and ESA. POLARIX,[20] a missions similar to XIPE but with X-ray optics with much smaller effective area successfully accomplished phase A and it was selected to be one of the two small missions of ASI. Unfortunately the program was then cancelled.

A polarimeter based on GPD technology was foreseen for XEUS/IXO but then Athena, selected as the second large ESA mission, has not a polarimeter on-board. GEMS[21, 22], which uses a technique[23] that privileges the quantum efficiency with respect to imaging, was selected for a flight but then, in 2012, it was discontinued for programmatic reasons. In 2012, after the discontinuation of GEMS, we decided to answer to a call for the 1st small mission of ESA (S1) proposing XIPE[17] (the X-ray Imaging Polarimetry Explorer) a mission consisting of

a payload with two GPDs and two already available JET-X optics. In addition we proposed two GPDs, tuned at higher energies for polarimetry of solar flares, and one X-ray photometer. XIPE was short-listed, it received a good scientific raking, but judged much too costly.

In 2014 ESA issued an Announcement of Opportunity for the 4th Scientific Mission of Medium Size (M4) with a budget of 450 Meuros (plus national contributions). At variance with precedent medium size calls, the budget is reduced by about 20 % reflecting a faster track to launch and no further competition for the instruments. This call requires therefore, a high readiness for the payload. We proposed a larger version of XIPE compared with S1 proposal, increasing either the number of optics, from two to three, and their effective area exploiting the thin shell technologies. XIPE name was maintained. Therefore XIPE for M4 is much more sensitive than XIPE proposed to S1.

At the present time three missions have been selected on 2015 for phase A study:

- XIPE: an X-ray Imaging Polarimeter based on GPD technology.

- ARIEL: a mission for the spectroscopy of Exoplanets.

- THOR: a mission to study turbulence in the Solar Wind.

In the second quarter of 2017 one of these three missions will be selected for the phase B1, and, provided a successful adoption lasting one year, it will fly in 2026. In the following we will describe XIPE the X-ray Imaging Polarimetry Explorer currently in phase A for M4.

6. XIPE MISSION

XIPE is a mission which peculiarity is to perform time-spatially-spectrally resolved X-ray polarimetry as a break-through in high energy astrophysics and fundamental physics. It takes advantage of precedent phase A for POLARIX and XEUS/IXO. XIPE is more similar to POLARIX in terms of configuration but with three new optics made with the technology of replication of nickel electroformed thin-shells. The instrument is composed of three Detector Units (DUs) and three Back End Electronics Units (BEEUs) and of one Instrument Control Unit (ICU). Each DU consists of one GPD surmounted by a Filter Wheel (FW) which hosts the calibration system. In the following we describe the XIPE payload items.

6.1 X-ray optics

Each of the three XIPE Mirror Units (MUs) comprises an optics with 30 mirror shells with diameters from 407 mm to 181 mm. They features a double-cone approximation of the Wolter-I profile with 300 mm of parabolic segment plus 300 mm of hyperbolic segment. The focal length is 4.0 m and it is chosen so that XIPE can fit in the fairing of the Vega launcher. This is an improvement in terms of effective area especially at higher energies with respect to the optics proposed at the M4 call. The precedent baseline had a Mirror Unit of 27 shells and 3.5 meter focal length each. These optics have a ratio between the thickness and the diameter of the shell a factor of 5 smaller than that of JET-X (the optics foreseen for POLARIX) providing a much more favorable performance to mass ratio. The characteristics of the mirror are shown in table 3.

The design has been performed assuming a thickness/radius ratio of 1.7×10^{-3}, 10 arcmin diameter unobstructed Field of View (FoV), 10% structure vignetting. An Half Energy Width (HEW) of 20 arcsec is assumed based on NHXM and eRosita mirror performances and on their integration procedure.[24] The integration procedure allows the assembled optics for basically maintaining the same HEW of the single shells. At this regard we note that the mirrors of eRosita have a better HEW (16 arcsec on-axis[25]), thus we consider the assumed HEW of the XIPE mirrors is conservative.

Table 3. Characteristics of the X-ray optics of XIPE

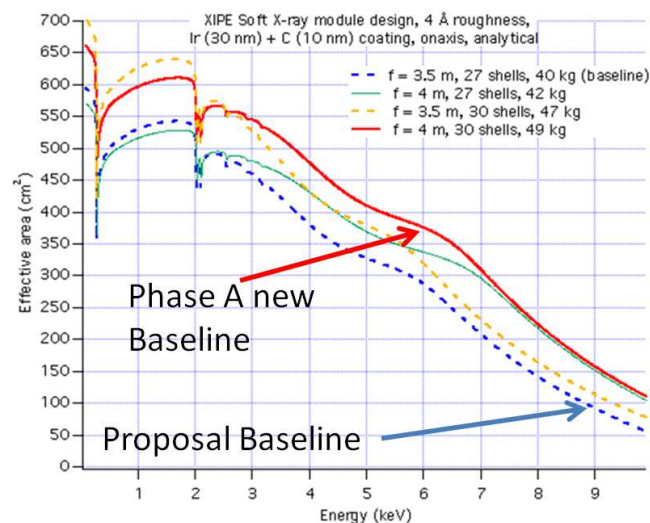|	
Geometrical profile	Wolter I
Focal length	4 m
Mirror length	60 cm
Max/Min shell diam.	407-180 mm
no. of spiders	2
no. of spoke of spiders	20
Spider and case materials	Steel
Wall materials	Electroformed NiCo
Coating	Ir (30 nm)+ C(10 nm) bilayer
Weight (1 MM)	68 kg
Power	50 W

Figure 2. The effective area of one mirror module. The blue curve is the effective area adopted in the proposal. The red curve is the one now adopted in phase A. This new baseline has a focal length of 4 m and 30 shells.

6.2 The Detector Unit and the Back End Electronics

The Focal plane comprises three DUs coupled to their BEEU. Each DU includes the GPD and the calibration system (see figure 3) in their housing. The GPD is filled with a mixture of He-DME (20 % - 80 %) at 1-bar with 1 cm of drift length. A Peltier cell keeps the temperature of the GPD within the requirement of stability of 1°C. The FW on top of it, is equipped with a set of calibration sources, diaphragms and filters for a total of 8 positions selectable via telecommand during observation. One of this source is a polarized one exploiting Bragg diffraction at 45° either at 2.6 keV and at 4.5 keV. The other calibration sources allow for calibrating the gain and as a check of absence of spurious polarization. A closed position allows for gathering the internal background.

The BEEU must be close to the GPD by less than 20 cm. A laboratory BEEU is routinely used for on-ground calibration purposes and some of its components, such as the FPGA and the ADC, will be changed, for the flight design, to space qualified ones.

Here below in a synthetic way we describe the functionality of the BEEU:

- Manage the ASIC power supply and readout.

- Provide the High Voltage to the GEM.

- Interface the Peltier Driver for the detector temperature control.

- Analogue to Digital convert the data from the ASIC.

- Analogue to Digital convert the housekeeping data.

- Zero-suppress the empty pixels for each event.

- Time tag the event with 1 MHz clock and the PPS signal.

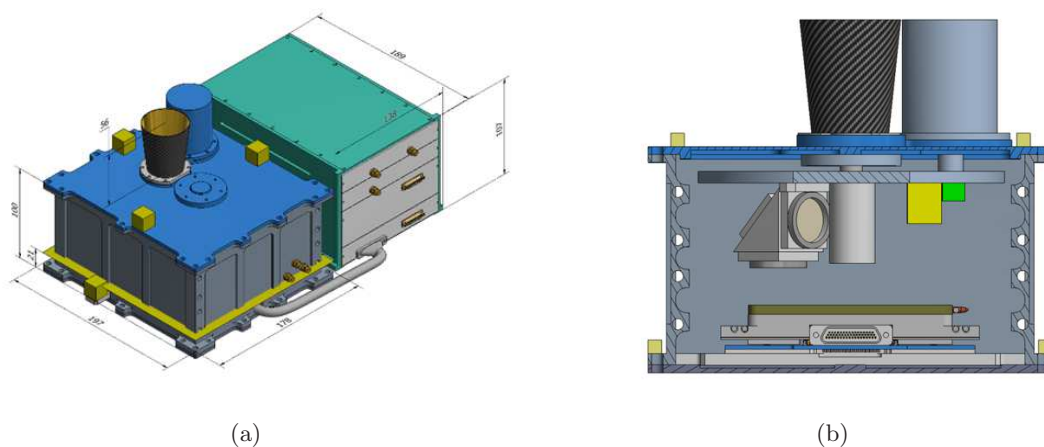- Format the data and send it to the Instrument Control Unit.

| (a) | (b) |

Figure 3. (**a**). The Detector Unit which comprises the Gas Pixel detector and the Filter Wheel. On its side the Back End Electronics Unit(**b**). The exploded view of the Detector Unit with on top the Filter Wheel equipped with a set of calibration sources including the polarized X-ray source and on the bottom the Gas Pixel Detector.

6.3 The Focal Plane Assembly Support Structure

The detector units and BEEU are arranged in a 120° symmetry supported by an instrument platform at a distance with respect to the Service Module (SVM) and connected to it by means of a Structural Tube (ST). The Focal Plane Assembly Structure (FSS, baseline configuration see figure 4) consists of two different stacked panels. Each panel consists of Carbon Fiber skins and a cardboard honeycomb. This solution accommodates the DU and the BEEU that have different thermal requirements. Indeed the GPD has an operative working temperature of 5-25 °C and a stability requirement of 1 °C while the BEEU has a wider operative/non operative temperature range and a much less stringent stability requirement. This configuration solves this issue because the DU and the BEEU are thermally decoupled. Two titanium rings keep this structure tight, and allow for interfacing the FSS with the star tracker and the ST.

While writing this proceeding, a trade-off study has being performed. One aspect of this trade-off is the compliance with the following requirement: (1) capability of alignment of the GPD, with respect to the optics, (2) capability of replacing one DU if needed and (3) capability to replace/insert the calibration sources prior integration in the fairing. These requirements are suggesting a different solution, similar to the one adopted to eRosita, with respect to the baseline described above. This solution foresee of connecting the DU from the external side of the FSS with suitable cuts and reinforcement on it.
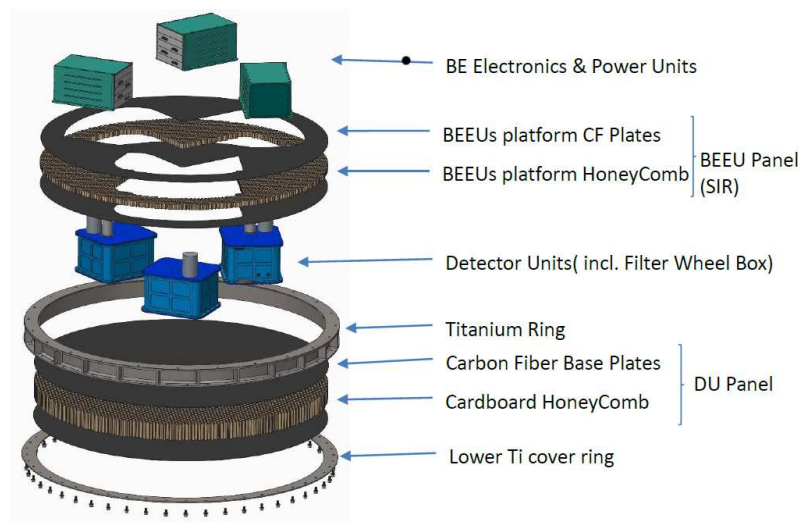
Figure 4. The Focal Plane Assembly Structure. This design represents the XIPE baseline while a trade-off study is underway.
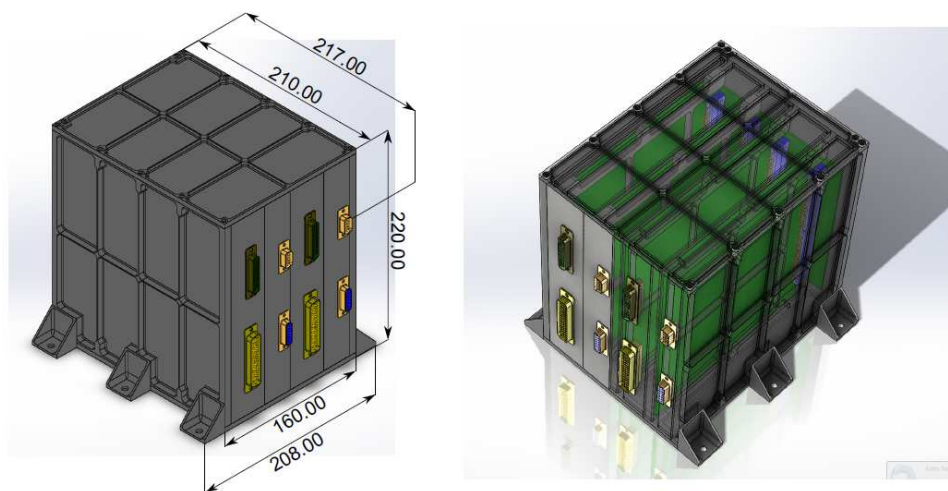
Figure 5. The Instrument Control Units. Double Eurocard standard are foreseen.

6.4 Instrument Control Unit

The ICU is a data processing box which also controls the three BEEUs. It consists of a Micro-processor & Memory board, a power distribution boards, a Filter Wheel driver board and a Peltier driver Board (see fig. 5).

The ICU is in charge of:

- managing the individual SpaceWire interfaces to the three BEEUs.

- Manage the Pulse-per-Second (PPS) signal and the 1 MHz clock for the on-board time and synchronization of the BEEU.

- Retrieve science data and housekeeping (HK) data from the BEEUs.

- Store data into the Mass Memory (32 GB) before sending them to on-board data handling for downlink.

- Generate the Quick Look Analysis (QLA) data from the science data.

- Take care of TM/TC Spacewire interface to the spacecraft, of the execution and of the distribution of commands.

- Manage the payload operative modes.

- Perform instrument health monitoring.

- drive the Peltier cooler and the FW.

Moreover the ICU will:

- Receive the non-regulated primary power from the Service Module.

- Generate and distribute the regulated low voltages to the BEEs.

- Manage the high voltage of the GPD basing on the rate of an on-board radiation monitor during passages through the SAA or for a solar flare

- Operate the filter wheels (FWs).

- Operate the Peltier coolers

- Generate HK data about voltage, current, temperature and operational parameters.

QLA data are data processed on-board consisting of spectra, light-curves, images and modulation curves delivered to the science data center (SDC) well in advance with respect to the complete scientific and ancillary data. The aim of these data is to monitor the behavior of the source on orbital base.

The design of the ICU is based on the use of double-eurocard boards. The ICU is located inside the Service Module. Currently some ongoing trade-off studies will establish if some of the functionality now allocated into the ICU (and in particular the driver for the FW, that of the Peltier and the DC/DC converters) will be, instead, located in the BEEU. This is due to the current long distance of the ICU from the DU (about 4 m).

7. XIPE IN THE VEGA FAIRING

We designed XIPE to be installed into the fairing of the Vega launcher with a trade off between volume and mass, therefore performances, and cost. At the time of the proposal we exploited the heritage of POLARIX which telescopes had the same focal length. The Concurrent Design Facility (CDF) of ESA confirmed that indeed Vega is capable to accommodate XIPE. Here we show (see figure 6) the accommodation at the time of the proposal. While writing, the companies which are studying XIPE during the phase A confirmed the accommodation in the Vega launcher (or in the larger Vega C currently under developing) of MMs with even a larger focal length.

8. SCIENTIFIC PERFORMANCES

We present here, see table 4, the scientific performances of XIPE based on laboratory measurement on a prototype filled with He-DME mixture at 1-bar. The MDP is (see figure 7) evaluated taking into account the configuration of the proposal with 3.5 m of focal length and 27 shells. This MDP is actually very conservative due to the increased sensitivity allowed by the 4 m, 30 shell configuration. At the present time the sensitivity is (energy averaged), 10 % better (20 % less needed observing time and 50 % less at higher energies). In the same plot we also showed some representative X-ray sources which are target for X-ray polarimetry.

We show, in table 5, the number of sources for which is possible to perform sensitive X-ray polarimetry with XIPE. At this regard we assumed a mission lifetime of three years and different threshold (depending on the source class) on the MDP. We used current available X-ray catalogues for deriving the source flux and, therefore, the MDP. We, then, derived the total number of sources with a MDP better then the threshold and the number of source within three years of operation.
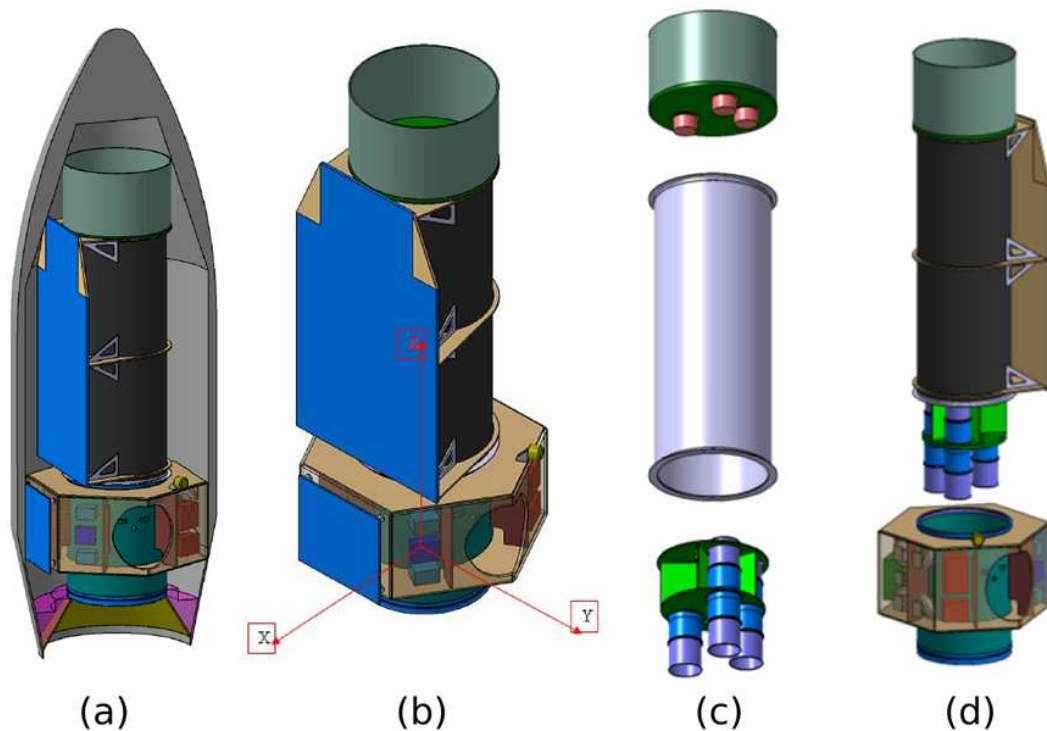
Figure 6. **a**. XIPE into the Vega fairing (from the proposal) **b**. Mirror Modules inside the service module. A Structural Tube connects the Service Module to the Focal Plane Assembly Support Structure **c**. Three Detector Units and three Back End Electronics Units are disposed with 120° symmetry onto the focal plane structure. **c,d**. These figures show how the design allows for a parallel development of the Service Module, the Mirror Modules and the Focal Plane Instrument and the plug&play philosophy.

Table 4. The characteristics of XIPE.

Polarization sensitivity	1.2 % MDP for $2\text{x}10^{-10}$ erg/s/cm2 (10 mCrab) in 300 ks
Spurious polarization	< 0.5 % (goal: < 0.1 %)
Angular resolution	< 26 arcsec
Field of view.	15x15 arcmin^2
Spectral resolution	16 % @ 5.9 keV.
Timing	Resolution 8 μs
	Dead Time 180 μs
Stability	> 3 yr
Wall materials	Electroformed NiCo
Energy range	2-8 keV
Background	10^{-5} c/s or 20 nCrab

9. THE CONSORTIUM

The consortium comprises (see figure 8) many countries across Europe. They have responsibility either in providing payload items but also for work activities related to its development. The responsibility of providing the DU is italian (INFN-Pi) while UK is responsible for the Filter Wheel (UCL/MSSL) and, also, of supervising the thermal-mechanical aspects at system level for the consortium. The High Voltage and Low Voltage Power
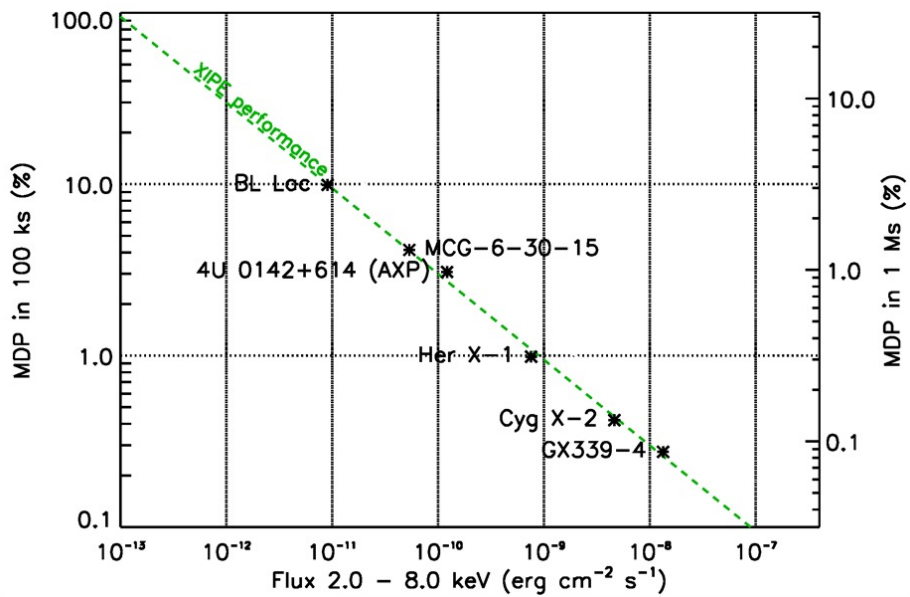
Figure 7. The Minimum Detectable polarization of XIPE taking into account a configuration of 3.5 m focal length and 27 shells.

Table 5. This table shows how many sources are available to XIPE for performing sensitive polarimetry either during three years of operation and in total. The number of the putative sources are in the range of hundreds and, for each class, a fair number of these can be studied and so not only the brightest ones.

Target Class	T_{tot} (days)	T_{obs} (Ms)	MDP (%)	Number in 3 years	Number available
AGN	219	0.3	< 5	73	127
XRBs (low+high mass)	91	0.1	<3	91	160
SNRe	80	1.0	< 15 % (10 regions)	8	8
PWNe	30	0.5	<10 % (more than 5 regions)	6	6
Magnetars	50.	0.5	< 10 % (more than 5 bins)	10	10
Molecular clouds	30	1-2	< 10 %	2 complexes (5 clouds)	2 complexes (5 clouds)
Total	**500**			**193**	**316**

Supplies are procured by Poland (SRC/PAS). Germany (IAAT) will provide the ICU, the Electrical Ground Support Equipment (EGSE) and the end-to-end calibration facility (MPE, Panter). Spain (UoV and INTA) is responsible for the FSS and the environmental test. Sweden (KTH) takes care of the evaluation of the background. ESA will procure the X-ray optics, using the valuable expertise of OAB/INAF and it is responsible for the ground segment. Italy (ASI) provides, also, the back-up for Kourou (ESA) of the Ground Station. The Science Data Center is responsibility of Switzerland (UoG). The responsibility of the whole payload is italian (IAPS/INAF).
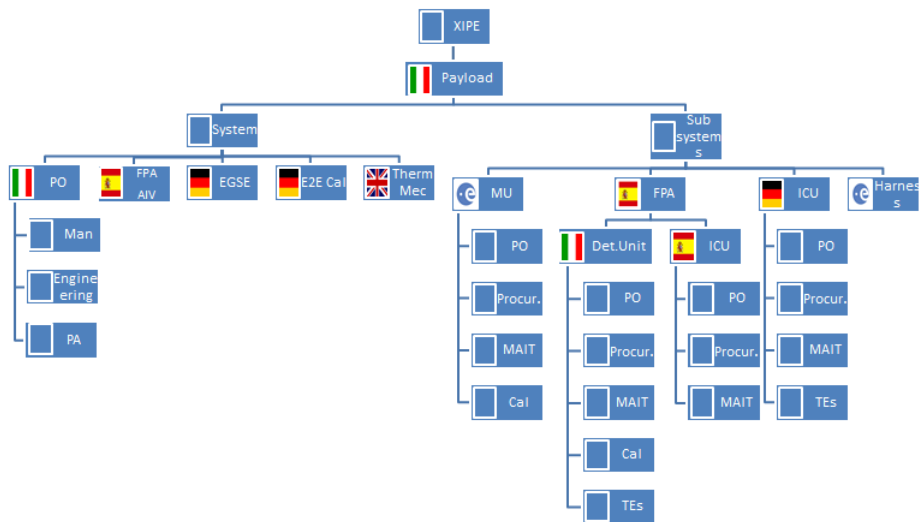
(a)
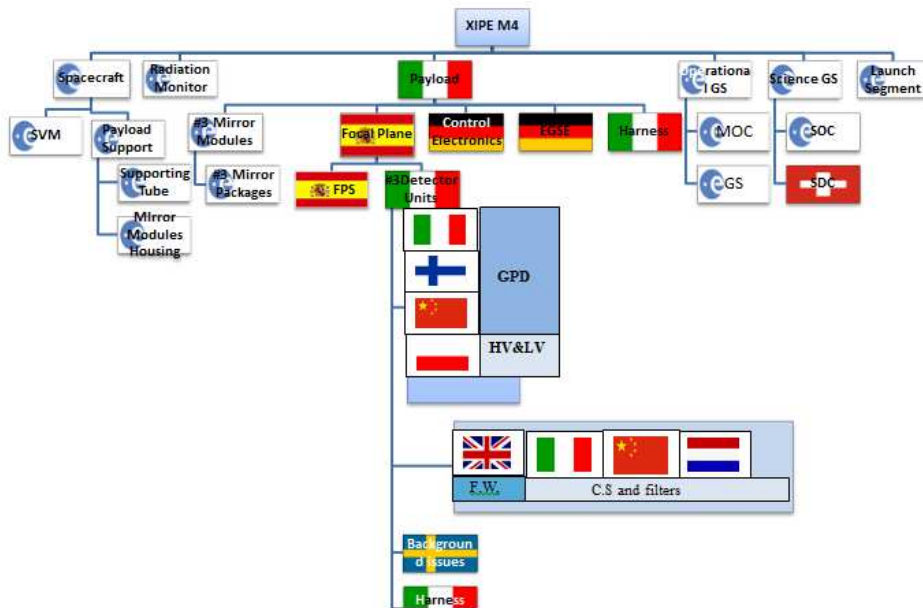
(b)

Figure 8. (**a**). The Work Breakdown Structure with main national responsibilities(**b**). The product tree with main and contributory nations.

ACKNOWLEDGMENTS

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