Technical Note

Effects of the radiation environment on the XIPE instrumentation

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Applicable documents		
Reference	Reference name	Title
[AD1]	P. Soffitta et al., XIPE Proposal to ESA M4	XIPE The X-ray Imaging Polarimetry Explorer
[AD2]	XIPE_SciRD_v0.3	XIPE Science Requirements document
[AD3]	D. Spiga, XIPE-OAB-TN-001 (2014)	Mirror module design for XIPE
[AD4]	ECSS-E-ST-10-04C	Space engineering - Space environment

Reference documents		
Reference	Reference name	Title
[RD1]	R. Bellazzini et al. (2010), in "X-ray polarimetry: A New Window in Astrophysics", Cambridge University Press, 2010, pag. 269-274.	A polarimeter for IXO
[RD2]	M. Kruglanski et al., 38th COSPAR Scientific Assembly, 38, 4176 (2010)	Space Environment Information System (SPENVIS)
[RD3]	P. Soffitta et al., Procs. of the SPIE, 8443, article id. 84431F (2012)	The background of the gas pixel detector and its impact on imaging X-ray polarimetry
[RD4]	S. Diebold et al., Experimental Astronomy, in press (2015)	Soft Proton Scattering Efficiency Measurements on X-Ray Mirror Shells
[RD5]	J. F. Ziegler, www.srim.org	SRIM - The Stopping and Range of Ions in Matter

List of Acronyms	
amu	atomic mass unit
AOCS	Attitude and Orbit Control System
BEE	Back-End Electronics
CE	Control Electronics
DME	Dimethyl Ether
FoV	Field of view
GPD	Gas Pixel Detector
HIMAC	Heavy Ions Medical Accelerator in Chiba
HV	High Voltage
ISS	Instrument Supporting Structure
LEO	Low Earth Orbit
MIP	Minimum Ionising Particle
SAA	South Atlantic Anomaly
WCA	Worst Case Assumption

Contents

1 Aim of the document

The instrumentation for satellites is sensitive to the radiation damage, produced by charged particles in orbit. In addition, the interaction of such particles may increase the background of the detectors.

We recall here that the Gas Pixel Detector (GPD), the sensor aboard XIPE to measure the polarisation of X-ray Astrophysical sources, already survived an irradiation with a beam of Fe ions at the Heavy Ions Medical Accelerator in Chiba (HIMAC), Japan [AD1]. The beam had an energy of 500 MeV/amu and a total fluence of 1.7×10^4 Fe ions, corresponding to ~42 years in orbit. During the irradiation the GPD was powered on, at the nominal voltage levels. The authors did not register any damage or performance loss in the detector ([AD1] and [RD1]).

In this document we estimate the flux of charged particles at the orbit of the XIPE satellite, we calculate the radiation damage on the XIPE instrumentation, we give a rough estimate of the increase in the instrument background produced by the particle interactions, we compare the value with the science requirements, and we describe the possible mitigation strategies.

We indicate the worst case assumptions adopted throughout the document as **WCA #** followed by a number.

2 The radiation environment at the XIPE orbit

The baseline orbit of the XIPE satellite is an Equatorial Low Earth Orbit (LEO) with the altitude below 600 km and the inclination lower than 6° [AD1]. We estimated using the SPENVIS web-based code [RD2] the flux of protons at an orbit with altitude of 600 km and inclination of 6°, as shown in Figure 1. As clearly shown in the figure, the proton flux is concentrated in the South Atlantic Anomaly (SAA). The spectrum of these protons is shown in Figure 2.

An additional component to the protons trapped in the SAA is represented by Galactic protons, which are evenly distributed along the orbit and not concentrated in the SAA. We show in Figure 3 the spectrum of the Galactic protons and, for comparison, we show in Figure 4 the spectrum of the Galactic He ions (α particles), the second most abundant species after protons. All other ion species are more than a factor of 30 less abundant than He ions (see for example Table 1 in Sect. 5.2).

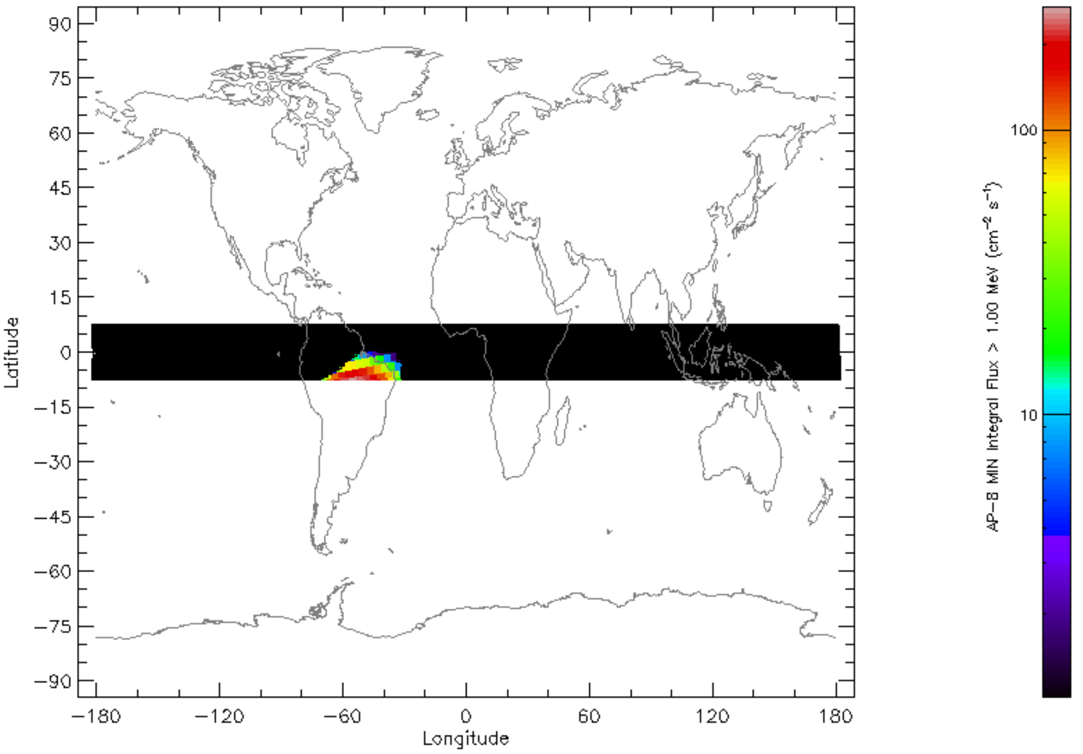

Figure 1: Map of the trapped proton flux at a XIPE orbit with 600 km altitude and 6° inclination. The flux is omnidirectional (4π sr) and is clearly concentrated in the SAA.

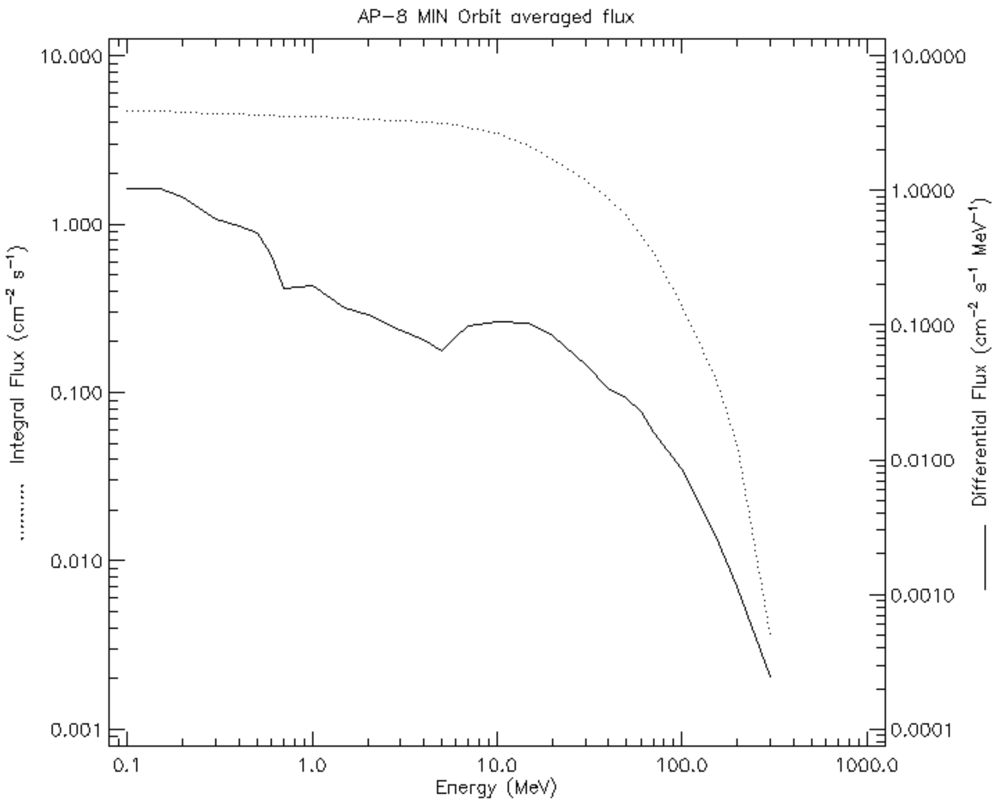

Figure 2: Spectrum of the trapped protons along the XIPE orbit (600 km altitude and 6° inclination). The flux is omnidirectional (4π sr).

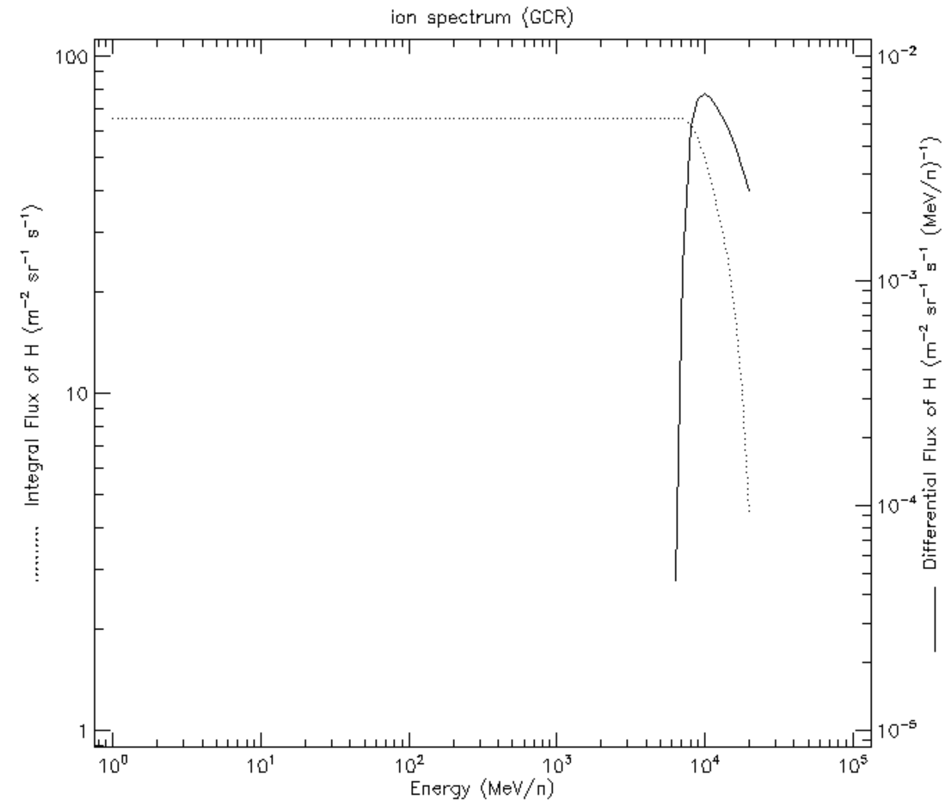

Figure 3: Spectrum of the Galactic protons at the XIPE orbit (600 km altitude and 6° inclination).

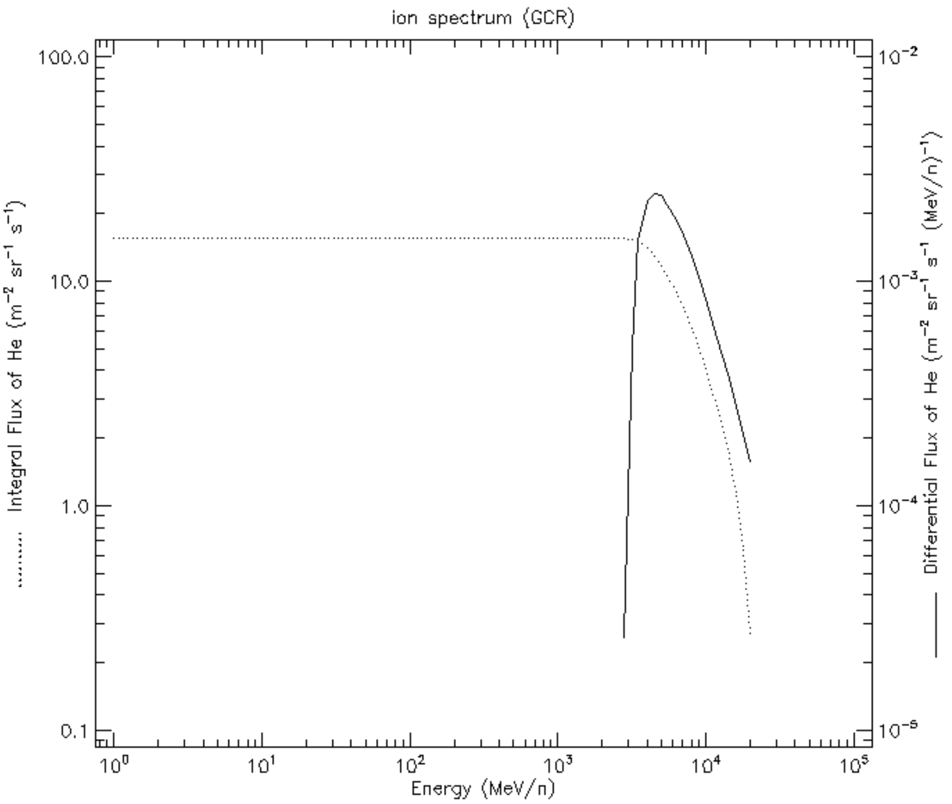

Figure 4: Spectrum of the Galactic He ions, the second most abundant species after protons, at the XIPE orbit (600 km altitude and 6° inclination).

3 The XIPE instrumentation

A sketch of the different subsystem which compose the XIPE satellite is shown in Figure 5 (from [AD1]). The GPD is in the "Detection Set " indicated in the figure.

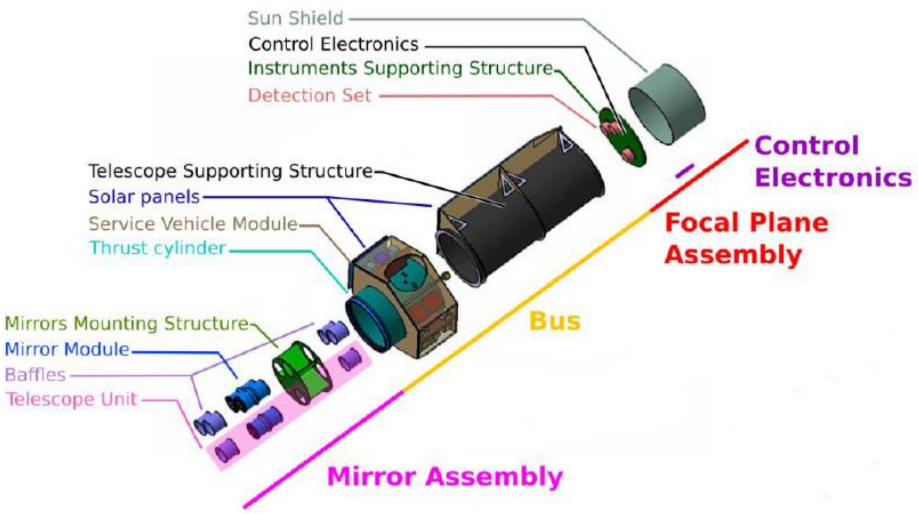

Figure 5: Sketch of the different subsystem composing the XIPE satellite. The GPD is inside the box named "Detection Set" in the figure.

We show a close-up view of the detection set in Figure 6 (from [AD1]). The sensitive element within the GPD is the gas cell, of 1.5 cm × 1.5 cm surface and 1 cm thickness, filled with a mixture composed of 20 % molar fraction of He and 80 % molar fraction of C_2H_6O (Dimethyl Ether, DME). The fractions 20 % and 80 % represent the fraction of molecules of He and DME over the total number.

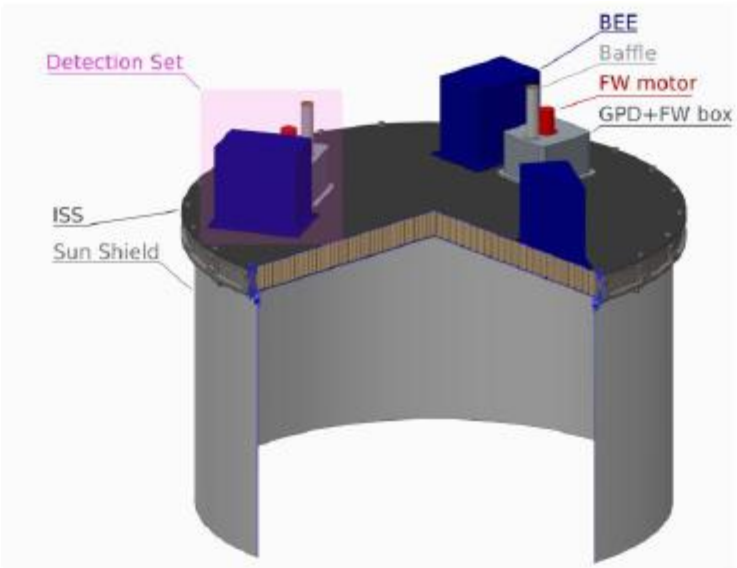

Figure 6: Accommodation of the XIPE Detection Set on the Instruments Supporting Structure (ISS in the figure).

The GPD is built with a frame of Macor (machineable glass-ceramic of 2.52 g/cm^3 density) ~1 cm thick, with an Alumina (Al_2O_3 with density of 3.95 g/cm3) plate of ~1 mm thickness at the bottom and a Ti layer ~5 mm thick on top, where the Be window is placed, as shown in Figure 7. The GPD is enclosed in an Al box of 3 mm (TBV) thickness at the sides and 5 mm at the bottom (see Figure 7).

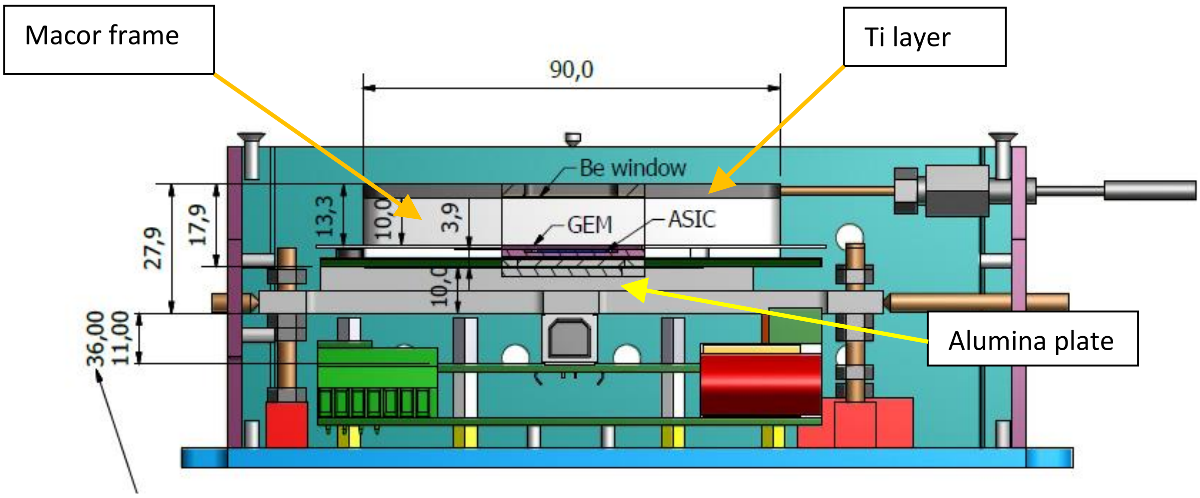

Figure 7: Assembly of the GPD for IXO. Highlighted are the locations of the Macor, Ti layer and Alumina plate.

The gas cell is shielded from particles impinging from the top by ~5 mm Ti (2.25 g/cm^2). The total surface density is 2.25 g/cm^2, equivalent to 8.3 mm of Al. This equivalent thickness can stop protons below ~40 MeV. The surface of the Ti frame is 9 cm × 9 cm, the surface of the Be window is 1.5 cm × 1.5 cm. Consequently, 97 % of the surface is covered by the Ti frame.

At the sides the shielding is represented by ~1 cm of Macor frame (2.52 g/cm^2) and 3 mm Al box. The total surface density is 3.33 g/cm^2, equivalent to 12.3 mm of Al. This equivalent thickness can stop protons below ~50 MeV.

Below the GPD, the ISS is composed of a honeycomb of Al and carbon fiber of 50 mm thickness. Assuming for the honeycomb a typical density of 6 pounds per cubic feet (TBV), corresponding to 0.1 g/cm^3, the surface density of the ISS is 0.5 g/cm^2, equivalent to 1.9 mm Al. In addition, the GPD has a bottom plate of 1 mm Alumina (0.40 g/cm^2) and an additional layer of Al, 5 mm thick. The total surface density is thus 2.24 g/cm^2, equivalent to 8.3 mm of Al. This equivalent thickness can stop protons below ~40 MeV.

4 Rejection techniques planned for the GPD

The background produced by the interaction of charged particles in orbit is a well-known issue in the design of detectors for X-rays. A list of the background rejection techniques envisaged for the GPD, from [RD3], is:

- **Amplitude selection**. Thanks to the spectroscopic capability of the GPD, we can select events in energy within a lower threshold, set by the sensitivity to polarization, and a higher threshold set by the efficiency of detector and the optics. In particular, protons of energy below ~100 MeV are expected to deliver more than ~10 keV in the GPD (see Figure 8). The amplitude selection method can be introduced “in hardware” in the GPD Back-End Electronics (BEE) or in the XIPE Control Electronics (CE);
- **Window frame maximum size**. Long tracks typical of background are rejected by means of a user selected maximum window. This selection is sensitive to tracks parallel to the detection plane. This method can be introduced in hardware as a parameter of the ASIC;

- **Comparison at a given energy of the detected number of pixel of background tracks with that expected by X-ray tracks of the same energy**. Minimum ionizing particles (MIPs) would provide a larger number of pixels;
- **Contiguity of the track**. The MIPs are expected to deposit about 1.5 MeV g^{-1} cm^2, an energy density lower for more than a factor of ten with respect to photoelectron tracks. Background tracks are therefore expected to be more frequently discontinuous with respect to photoelectron tracks with similar deposited energy and an analysis and a cut on the cluster multiplicity can discriminate between the two;
- **Difference in skewness**. Being dE / dx the differential energy loss, more rapidly evolving in the development of the photoelectron tracks with respect to background tracks at their minimum, it could be possible to discriminate X-rays from background by selecting events on the base of their skewness being the photoelectron tracks more skewed.

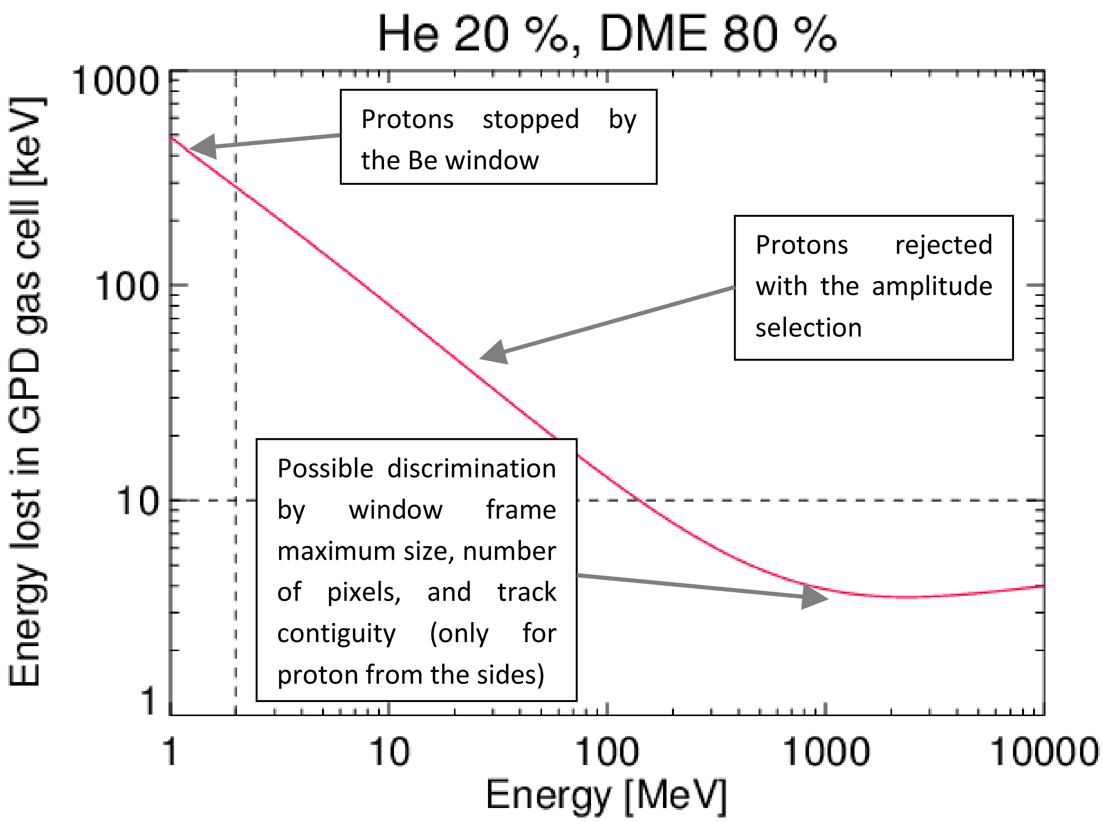

Figure 8: Energy lost in the GPD gas mixture by protons of different energy at normal incidence. In the plot, a thickness of 1 cm is assumed for the gas cell. The vertical dashed line indicates the minimum energy of protons not stopped by the Be window. The horizontal dashed line indicates a possible value of the higher upper threshold for the amplitude selection, 10 keV.

Some of these techniques (e.g. the amplitude selection and the window frame maximum size) can be included in the XIPE hardware to reduce the telemetry load due to background events. Other methods can be applied offline on the data. By means of the methods listed above, we plan to suppress the background produced by protons interacting in the GPD from the sides.

5 Additional background from charged particles

We assume that using the rejection techniques described in Sect. 4 (in particular the window frame maximum size, the number of pixels in the track, the contiguity and skewness of the track), we can suppress all the background produced by protons interacting in the GPDs from the sides. On the contrary, the background produced by charged particles interacting in the GPDs from the pointing direction, reflected by the telescopes shells or crossing the telescopes, cannot be suppressed with these techniques. In this section we estimate the background increase produced by the non-rejected particles.

We recall here that the requirement on the XIPE background specified in the Science Requirement document [AD2] is **8×10^{-4} cts/cm^2/s/keV**.

5.1 Additional background from protons

5.1.1 Protons focussed by the X-ray telescopes

Grazing incidence telescopes for X-rays can reflect protons (see e.g. [RD4]). The authors of [RD4] estimated using the SRIM software [RD5] the reflection efficiency for protons of 250 keV, 500 keV and 1 MeV energy, incident at angles between 0.33° and 1.20° on the X-ray telescope of the *eROSITA* mission.

The Be window (50 μm thickness) of the GPD can stop low energy protons, below ~2 MeV. In addition, protons above ~2 MeV and below ~100 MeV lose an energy more than ~10 keV in the GPD (see Figure 8) and can be discriminated by using the amplitude selection method specified in Sect. 4. Since the energy lost by protons above ~100 MeV will be within the XIPE energy band, we estimate the reflection efficiency of protons at these energies.

We use the SRIM software [RD5] to estimate the reflection efficiency of protons of 100 MeV energy on the XIPE telescope. Since the proton reflection efficiency decreases if the angle of incidence θ_{inc} on the mirror shell increases, we assume as a worst case (**WCA #1**) the minimum incidence angle specified in the design document of the XIPE telescopes [AD3], 0.006438 rad corresponding to 0.3689°. Using SRIM, we simulate the interaction of 10000 protons with θ_{inc} = 0.3689° on a single shell of Ni (assumed as 300 μm thickness), coated with 100 Å of C on 300 Å of Ir [AD3].

From the geometry of the telescope, only the protons reflected two times in the narrow range of angles between θ_{inc} – 7.5 arcmin and θ_{inc} + 7.5 arcmin can reach the GPD. From the SRIM simulation, the efficiency of a single reflection in the angle range specified above is 12.0 % (see Figure 9). The efficiency of two reflections is thus 1.4 %.

We plan to verify the SRIM results with an independent simulation with GEANT. We will introduce the GEANT results in a future updated version of this technical note.

The spectrum of Galactic protons is centred around an energy of the order of 10 GeV (see Figure 3), consequently these protons will not be focussed by the X-ray telescopes.

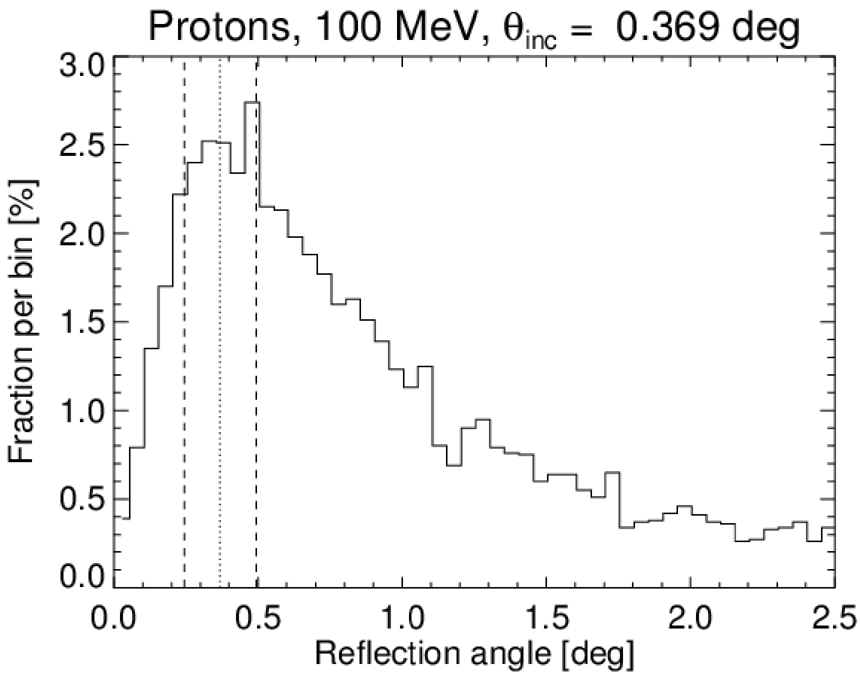

Figure 9: Distribution of the reflection angles for protons of 100 MeV energy incident at θ_{inc} = 0.369° on the shells of the XIPE telescope. The vertical dotted line indicates θ_{inc}, the vertical dashed lines indicate the interval [θ_{inc} – 7.5 arcmin, θ_{inc} + 7.5 arcmin], in which the protons can reach the GPD after two reflections.

In order to estimate the increase of background due to the reflection of protons we assume

- an integral flux of protons of is 2.6 × 10^{-2} p/cm^2/s/sr at energy > 100 MeV and at the XIPE orbit. The integral flux is estimated with the AP8-MIN model, considered as a worst case (**WCA #2**) in the [AD4];
- the field of view is an annulus with 15 arcmin aperture, corresponding to 1.8 × 10^{-4} sr;
- all the protons incident on the geometric area of the telescope of 600 cm^2 [AD3] are focussed on the GPD of 2.25 cm^2 [AD1] geometric area (**WCA #3**);
- the estimated reflection efficiency is 1.4 %;
- the reflected protons are not rejected on the basis of the techniques specified in Sect. 4 (**WCA #4**);
- in the estimation we apply a margin of a factor of 10 on the proton flux (**WCA #5**).

With all these assumptions, we obtain a total background of **8.8 × 10^{-5} cts/cm^2/s/keV**, about one order of magnitude smaller than the requirement of **8 × 10^{-4} cts/cm^2/s/keV** specified in the [AD2].

It is worth stressing here that this additional background is produced only by protons in the SAA. We plan to reduce the GPD High Voltage (HV) during the passage through the SAA, consequently this background will be significantly reduced.

5.1.2 Protons crossing the X-ray telescopes

Protons arriving from the pointing direction and transmitted through the telescope shells can reach the GPD. XIPE includes three telescopes, each one coupled to a single GPD. Each telescope is composed of 27 concentrical electroformed Ni shells of Wolter I type, with a total length of 60 cm (30 cm with parabola shape and 30 cm with hyperbole shape) [AD3]. Each Ni shell has a thickness ranging between 200 μm and 330 μm. The resulting mass of a telescope is 31 kg [AD3].

In order to estimate the stopping power of a telescope, we compute the equivalent density from the ratio mass / volume. By approximating the shape with a cylinder of 60 cm length, minimum diameter of 18 cm and maximum diameter of 38 cm [AD3], the resulting volume is 18850 cm^3. The "spider" and the telescope mounting structure stop all the protons impinging in the volume internal to the shell with the minimum diameter. The resulting density of the telescope in this approximation is 1.64 g/cm^3.

With this cylindrical approximation and the focal length of 3.5 m, the solid angle "seen" by the GPD at the telescope focus and in which charged particles can reach the gas cell is $9.1 * 10^{-3}$ sr.

Assuming normal incidence on the telescope with the equivalent density of 1.64 g/cm^3, protons of energy below ~400 MeV have a range in Ni smaller than ~60 cm and are stopped by the telescope shells. Only protons above ~400 MeV can cross the telescope and reach the GPD. The residual energy after passing through the telescope shells and the Be windows in above ~100 MeV, the energy lost in the gas cell is below ~10 keV and consequently these protons cannot be filtered with the amplitude selection method (see Figure 8).

We assume for this computation that all the protons with energy above ~400 MeV which cross the telescope can reach the GPD (**WCA #6**) and are not rejected on the basis of the methods in Sect. 4 (**WCA #4**).

Since in the AP8-MIN model of protons trapped in the SAA the integral flux is formally zero at 400 MeV, we assume the flux at 300 MeV (**WCA #7**): 3.6×10^{-3} $p/cm^2/s$, coming from a solid angle of 4π sr. Given the large uncertainty of the fluxes contained in the proton models, we assume a margin of a factor of 10 in our estimation (**WCA #5**). With this margin, on the solid angle of $9.1 * 10^{-3}$ sr subtended by the telescopes the flux is 2.6×10^{-5} $p/cm^2/s$ per GPD. For the 3 GPDs and on the energy band from 2 to 8 keV, **the additional background rate produced by protons in the SAA is 1.3×10^{-5} cts/cm²/s/keV**. This value is compared to the requirement of **8×10^{-4} cts/cm²/s/keV** in [AD2].

In SPENVIS the integral flux of Galactic protons at 400 MeV is 6.6×10^{-3} $p/cm^2/s/sr$, estimated using the ISO 15390 model. This is an average value on the whole duration of the orbit and these protons are not trapped in the SAA. Applying the same margin of 10 (**WCA #5**), the additional background is **10^{-4} cts/cm²/s/keV** per GPD, corresponding to a total value of **3×10^{-4} cts/cm²/s/keV** (to be compared with the requirement of **8×10^{-4} cts/cm²/s/keV** in [AD2]).

5.2 Additional background from ions

Most of the heavy ions (e.g. Fe), especially at low energy, have a range of hundreds of μm in Al and will be stopped by the detector boxes. Consequently, most of the ions impinging on XIPE from the sides will be stopped by the satellite structure, the GDP box or the Macor frame. The residual ions can be rejected using the methods described in Sect. 4. Here we study the background produced by ions reaching the GPDs from the pointing direction and not discriminated following the techniques in Sect. 4.

Similarly to Galactic protons, Galactic minimum ionising He ions (i.e. at an energy of ~10 GeV/amu) are not focussed by the X-ray telescopes.

Only the integral flux of He ions (α particles) transmitted through the telescope shells can give a contribution to the background. All other species have a flux more than ~30 smaller than He, as shown in Table 1, and can be neglected. A He ion which enters the telescope with an energy of 1.5 GeV/amu has a residual energy of ~300 MeV/amu when reaching the gas cell (after crossing the Be window). This ion loses

~63 keV in a thickness of 1 cm of the gas mixture (He 20 % and DME 80 %) and can be discriminated using the amplitude selection method. Similarly, the energy lost in the gas cell by minimum ionising He ions (i.e. at an energy of ~10 GeV/amu) is ~13 keV. **All the background produced by Galactic ions from the pointing direction can be discriminated by using an amplitude selection with an energy higher threshold of ~10 keV**.

Table 1: Minimum energy and integral flux of ion species which can reach the GPD crossing the telescope.

Ion species	Atomic number	Mass number	Minimum energy to reach the gas cell [GeV/amu]	Integral flux at minimum energy [ions/m^2/s/sr]
He (α particles)	2	4	1.5	15.5
Li	3	7	3.0	$7.2 * 10^{-2}$
Be	4	9	5.0	$3.4 * 10^{-2}$
B	5	11	7.0	$1.2 * 10^{-1}$
C	6	12	9.0	$4.4 *10^{-1}$

6 Radiation damage

We show in Figure 10 the Total Ionising Dose (TID) estimated with SPENVIS for the XIPE orbit (600 km altitude and 6° inclination) and the nominal mission duration of three years, starting on 1 Jan 2025. Most of the TID is produced by trapped protons.

Assuming for the instrumentation a typical shielding equivalent to 5 mm (TBV) of Al, the expected TID is smaller than 1 krad in 3 years.

As described in Sect. 3, the shielding of the gas cell inside the GPD is higher, equivalent to at least 8.3 mm Al.

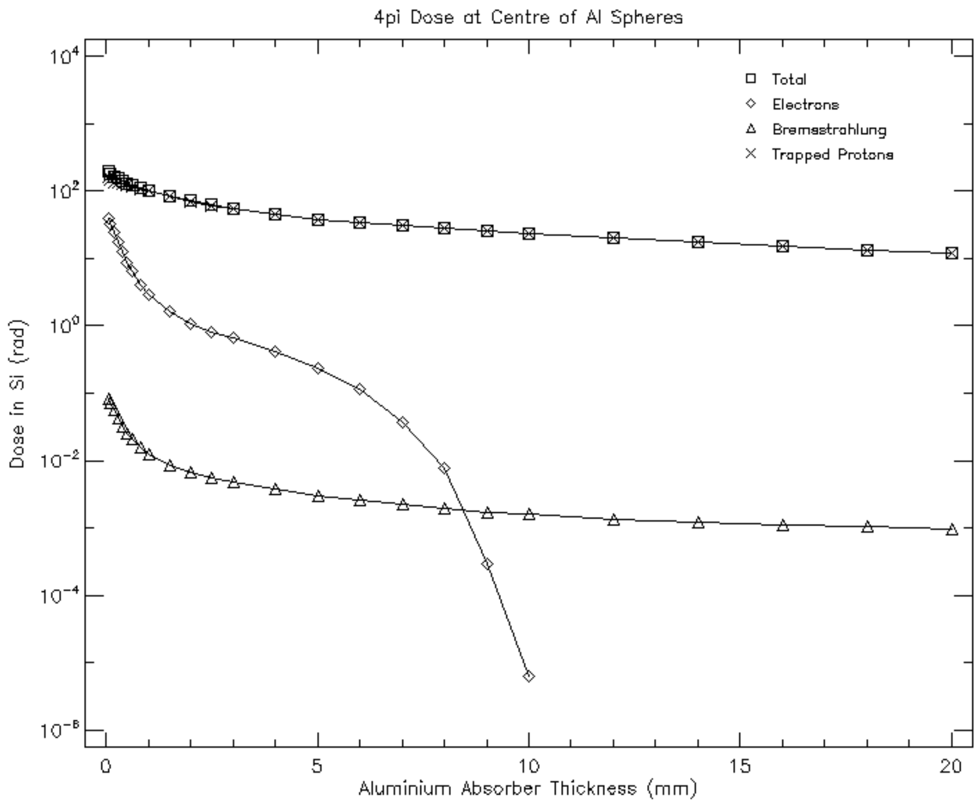

Figure 10: Total Ionising Dose (TID) estimated with SPENVIS for the nominal XIPE orbit (600 km altitude and 6° inclination) and the nominal mission duration of three years, starting on 1 Jan 2025.

7 Summary and conclusions

By means of the rejection methods already planned for the GPD and listed in Sect. 4, we are able to suppress the background produced by protons and ions interacting on the sides of the GPDs.

The protons reaching the gas cell by crossing the X-ray telescopes and the Be windows will give an additional background of **3×10^{-4} cts/cm^2/s/keV** (Galactic protons) and **1.3×10^{-5} cts/cm^2/s/keV** (trapped protons). **These numbers are derived using simple rough estimations and by applying a margin of a factor of 10 on the proton flux**. Ions crossing the telescopes and the GPD Be windows can be easily discriminated by setting an energy upper threshold of ~10 keV and will not contribute to the background.

Protons of 100 MeV energy are focussed by the X-ray telescopes with an efficiency of 1.4 % and contribute an additional background of **8.8×10^{-5} cts/cm^2/s/keV**. **It is worth stressing again that this additional background is produced only by protons in the SAA. We plan to reduce the GPD High Voltage during the passage through the SAA, consequently this background will decrease. We will verify using GEANT the proton reflection efficiency computed with SRIM.** Galactic protons have an average energy of ~10 GeV and are not focussed.

The background values are compared to the requirement of **8×10^{-4} cts/cm^2/s/keV** in [AD2]. The additional background from Galactic protons is higher than from trapped protons because the flux of high energy protons (able to pass through the telescope shells) is higher for Galactic protons (see Figure 2 and Figure 3).

The TID expected for XIPE is smaller than 1 krad in three years and is mostly produced by trapped protons.