Design and Optimization of the Optics for the EDGE Wide-Field Spectrometer

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ABSTRACT

We have been performing design and optimization of the optics for the Wide Field Spectrometer (WFS), one of the core instruments of the EDGE mission whose science targets are the studies of formation and evolution of large scale structures in the universe. WFS mirrors are based on a conical approximation of the Wolter-I design fabrication technique already applied for ASCA and SUZAKU satellites. In order to give both a large effective area and grasp with small TES detector, we use a very short focal length with 1.2 m and 4 reflections system for the outer diameter. The effective area and grasp, including the detector efficiency and the filter transmission, are 1163 cm^2 and 405 cm^2deg^2 at 0.6 keV, respectively.

Keywords: X-ray telescope, soft X-ray, wide field spectrometer, EDGE mission

1. INTRODUCTION

One of the fundamental issues in astrophysics is to understand the formation of large scale structures from the early universe up to present time. Most of our knowledge originates from observations of relatively dense gas accumulated in stars, AGNs and clusters of galaxies. Key information of the history of the baryons is encoded in the properties of the diffuse gas in the universe: the history of gravitational collapse and heating at the accretion shocks, the history of metal enrichment, and the history of kinetic energy injection from galactic winds and AGN jets, interaction with magnetic fields which are amplified from intergalactic seed fields the gravitational shocks.[1] As cosmic structure take shape, gravitational collapse of Dark Matter halos create the seeds where star formation occurs, galaxies form, therefore merging into groups and clusters through a hierarchical build up process.

The EDGE (Explorer of Diffuse Emission and Gamma-ray burst Explosion)[2] will be able to study the formation and evolution of structures on various scales from the early universe. EDGE will measure the three tracers, warm hot intergalactic medium (WHIM), cluster of galaxies and gamma-ray bursts. The science requirements of EDGE targets are shown in Table 1. EDGE will observe the very weak emission lines or absorption features using its unique four instruments schematically illustrated in Figure 1. A Wide Field spectrometer (WFS) with high spectral resolution, a Wide Field Imager (WFI) with high angular resolution, a Wide Field Monitor (WFM) which monitors a significant part of the sky and triggers the fast repointing and a GRB detector (GRBd) which extended the energy range of 25-2500 keV.

In order to meet the science requirement, WFS needs the capability to observe weak emission and absorption features. This can be achieved with an effective area larger than 1000 cm^2 at 0.5 keV. In this paper, we present our studies on the design and optimization of the wide field telescope of the WFS. We improved the reflectivity of X-ray mirror, the mirror structure and telescope design. We made baseline design of the telescope and evaluated its performance using ray tracing numerical simulation. The expected performance of the optics for the WFS is also described.

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Optics for EUV, X-Ray, and Gamma-Ray Astronomy III, edited by Stephen L. O'Dell, Giovanni Pareschi
Proc. of SPIE Vol. 6688, 668809, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.733713

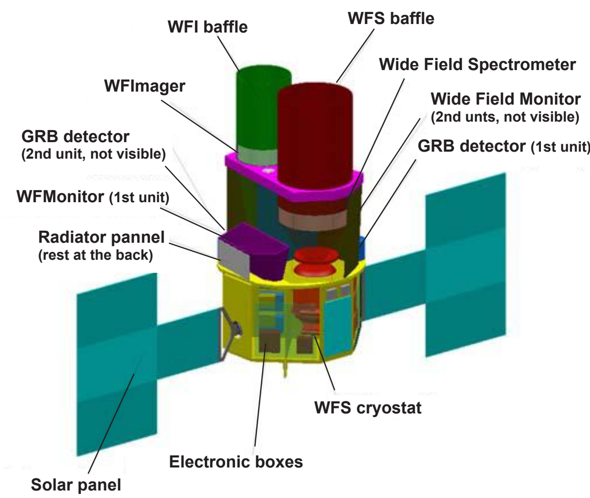

Figure 1. Design of the EDGE satellite

Table 1. Overview of the science requirements

Science	Effective Area [cm^2]	Energy Range [keV]	Angular Resolution	Field of view [$degree^2$]	Spectral Resolution [eV]
Missing baryons					
absorption	1000@0.5keV	0.2 - 1.0	n/a	n/a	3@0.5keV
emission	1000@0.5eV	0.2 - 1.0	4'	0.7×0.7	3@0.5keV
Cluster physics	500@1.0keV	0.3 - 4.0	15"	1.5^{ϕ}	80@1.0keV
Cluster formation and evolution	500@1.0keV	0.3 - 4.0	15"	1.5^{ϕ}	80@1.0keV
Metal enrichment	1000@0.5keV	0.2 - 2.0	n/a	n/a	3@0.5keV
Dark ages	1000@0.5keV	0.2 - 2.0	n/a	n/a	3@0.5keV
80 burst with fluency $> 10^{-6}$ erg/cm^{-2}/s over the $8 - 150$ keV per year					

2. WIDE FIELD SPECTROMETER

The Wide Field Spectrometer (WFS), the high resolution X-ray imaging spectrometer will enable the accurate measurement of weak absorption and emission feature. The WFS is a major part of EDGE enabling key measurements related to GRBs, the WHIM and cluster. In order to achieve the science requirement, WFS needs a large effective area and high energy resolution. WFS consist of a wide field telescope and a Transition Edge Sensor (TES)[3,4] as the focal plane detector. The instrument designs and their parameters are shown in table 2 and figure 2. The telescope has a very short focal length with 1.2 m using 2 and 4 fold reflections system and a wide Field of View (FOV) with $0.7° \times 0.7°$ for a TES 32×30 array of 0.5×0.5 mm^2 pixels. A cryogen-free cooler will be cooled to 50 mK. The baselines of the angular and energy resolution are better than 4 arcmin and 3 eV at half power diameter, respectively. The detection efficiency at low energy is limited by four entrance filters (50 nm parylene + 20 nm Al on a Si support grid). The mirror temperature is controlled using a long thermal baffle and heaters.

3. OPTICAL DESIGNS AND OPTIMIZATION

The WFS requires large effective area and grasp in the soft X-ray region. However, the grasp is strongly constrained by the small detector size. It is then necessary to use a short focal length to observe wide field angles. The WFS mirror design and fabrication methods are based on a conical optics, a technique that has been already successfully applied for the Japanese satellites ASCA and SUZAKU.

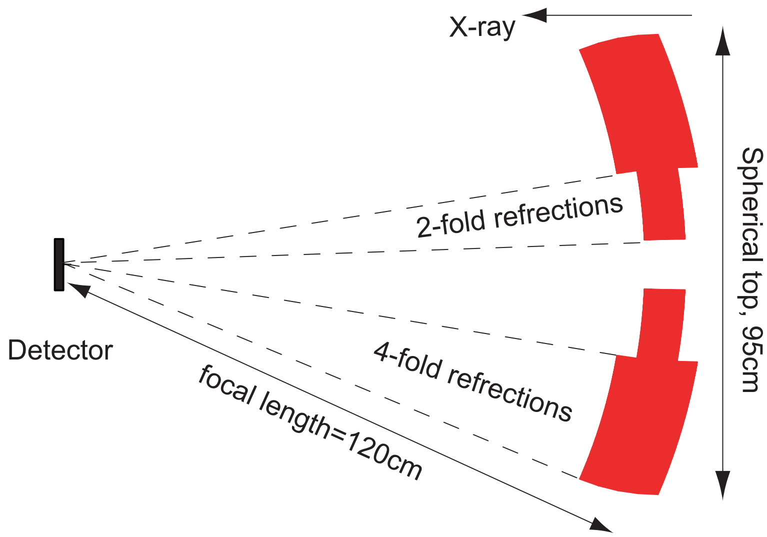

Figure 2. Schematic design of the mirror system and the overview of the WFS. The telescope adopts a spherical top.

Table 2. Mirror and Detector design of the Spectrometer

Parameter	Design	Comment
Telescope		
Focal length	1.2 m	
Mirror inner diameter	10 cm	
Mirror outer diameter	95 cm	
Change of reflectors	20 cm	Change from 2 to 4-fold reflectors.
Mirror length	4 cm	
Foil thickness	0.2 mm 0.3 mm 0.4 mm	Radius $r < 30$ cm 30 cm $< r < 40$ cm 40 cm $< r$
Coating of the mirrors	C + Pt Ni	Radius < 30cm Radius > 30cm
Weight	94 kg	Including housing, sieve slit and mirrors.
TES Detector		
Pixels	32×30	
Pixel size	0.5 mm	
Angular pixel size	1.4 arcmin	Focal length is 1.2 m.
Energy resolution	3 eV	

Our design is based on a mixed system with 2 reflections optics for the inner diameter shells and with 4 reflections optics at the outer diameter shells because the incident angle of 4 reflections system became a half in comparison with 2 reflections increasing the grasp considerably.[5] Our simulation shows that a transition between 2 and 4 reflection radius R_{24} is 20 cm. This radius corresponds to an inclination angle of 2.4 degree at 2 reflections where the reflectivity at 1.5 keV of the proposed coating, C + Pt and Ni starts to decrease. Figure 3 show the reflectivity versus incident angle for 0.5 keV and 1.5 keV X-rays for the Ni and C + Pt mirror. The optimized design then gives 129 shells with 2 reflection and 170 shells with 4 reflections.

From figure 3 we note also that, the C + Pt coating has high reflectivity for small incident angles at 1.5 keV; on the other hand, the Ni has higher reflectivity up to large incident angle compare to C + Pt at 0.5 keV.

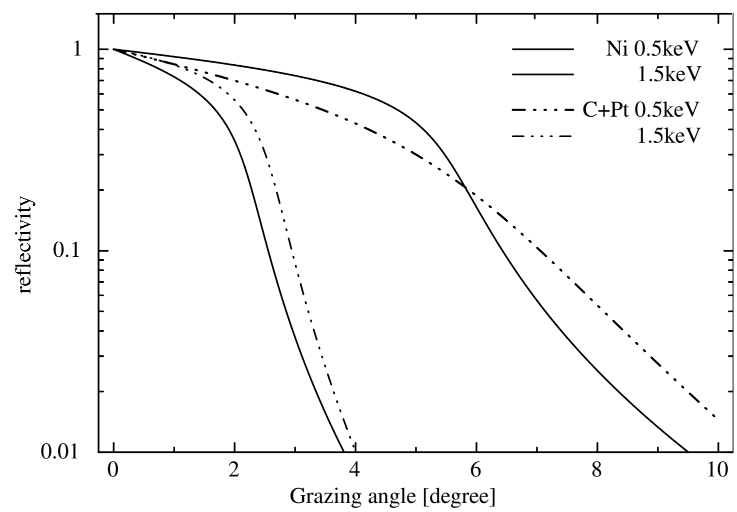

Figure 3. Calculated reflectivity vs. incidence angle for 0.5 and 1.5 keV X-rays.

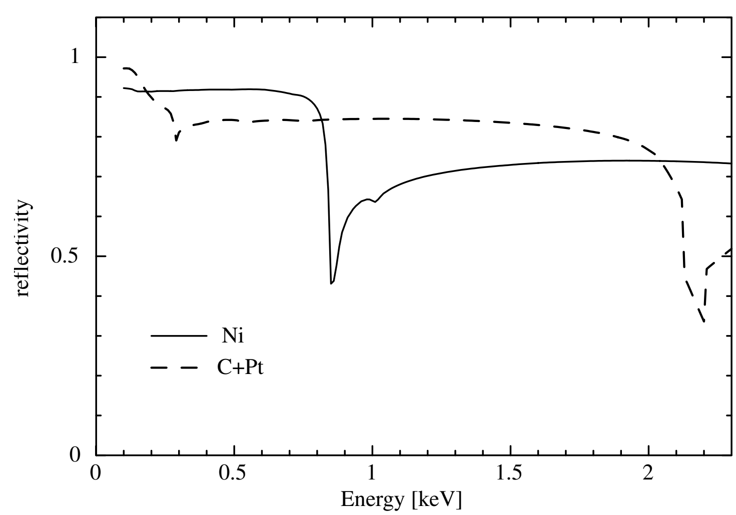

Figure 4. Calculated reflectivity of composit mirror at grazing angle of 1.0 degree. The reflectivity curves are Ni (solid line) and C + Pt (dashed line) in figure.

Moreover figure 4 shows the energy dependence of reflectivity at critical angle of 1.0 degree for the Ni, and C + Pt mirrors. Whereas Ni would be favorable below 0.8 keV, C + Pt mirror will improve the response above 0.8 keV and will give a smoother response as function of energy. We then studied the improvements of the optics performance using the two proposed coating depending on the shell inclination. The optimization of the mirror reflectivity gives a coating change radius Rcoat of 30 cm, derived at an average incident angle of 1.8 degree, for the 4 reflections system.

If the telescope using conical optics has the good angular resolution, it is necessary to have the short length mirrors. On the other side, the angular resolution is rapidly deteriorated by a mirror positioning error that in the case of the WFS can be quite severe due to the huge number of mirrors required. We adopted the same mirror length L = 4 cm at the 2 and 4 reflections system. The entrance aperture has a spherical shape which defines the same focal length at different radii and decreases the stray from the backside reflection on the mirrors. The total mass for the mirrors made of aluminum is about 44 kg excluding the housing of telescope.

4. EXPECTED PERFORMANCE

We calculated the expected performance of the telescope for soft X-ray region using ray-trace program which is the simulation program according for the housing structure, mirror reflectivity, mirror substructure thickness, mirror surface micro roughness and positioning error of each mirror. Figure 5 and figure 6 show simulated X-ray images and off-axis angle dependence of angular resolution at 0.5 keV. The angular resolution is 3.7 arcmin at HPD with positioning error of shells of $\pm 8\mu$m which already achieved on the SUZAKU mission. Figure 7 shows the calculated effective area (upper panel) and the grasp (lower panel) of telescope. In this design, the effective area is about 1650 cm^2 at 0.6 keV. The vignetting curve at 0.6 keV, 1.0 keV, 1.5 keV and 2.0 keV by detector size 15$\times$15 mm^2 are shown in figure 8. From this figure, the field of view is found to be 56 arcmin FWHM at 0.6 keV and the grasp is 605 cm^2 deg^2 at 0.6 keV. The total effective area and grasp, including the detection efficiency and the transmission of optical blocking filter, are 1163 cm^2 and 405 cm^2 deg^2 at 0.6 keV, respectively.

Table 3. Instrument requirement and performance

Parameter	Requirement	Performance
Resolution @0.5 keV [eV]	3	3
Field of View [degree^2]	0.7$\times$0.7	0.7$\times$0.7
Energy range [keV]	0.2 - 2.2	0.1 - 2.2
Effective area @ 0.6 keV [cm^2][1]	1000	1163
Effective area @ 1.5 keV [cm^2][1]	100	499
Grasp @ 0.6 keV [cm^2 deg^2][1]	Derived	405
Angular resolution (HPD) [arcmin]	4	3.7

[1)] The effective area and grasp includes mirror, detector efficiency and filter transmission.

5. FURTHER OPTIMIZATION OF MIRROR DESIGN

We have been trying to fabricate the multi-stage solid mirror using super polished mandrel with Wolter-I optics.[6] The mirror optics is fabricated as the paraboloid-hyperboloid and the paraboloid-hyperboloid-hyperboloid-hyperboloid for 2 and 4 reflections system, respectively. If we can make Wolter-I mirrors using this mandrel, we can expect a better angular resolution compared with conical optics and we can greatly reduce the number of element mirrors in comparison with single stage quadrant mirrors previously used for ASCA and SUZAKU. This is quite important especially for 4 stage mirror system.

A ray trace simulation of the telescope with Wolter-I optics was performed. Angular resolution is shown in figure 9, a function of off-axis angle. The angular resolution is below 1.3 arcmin. The effective area and grasp does not show significant change in the all energy range of WFS. So we do further investigation of the multi-stage solid mirror using super-polished Ni mandrel for replica mirror fabrication.

6. CONCLUSION

We studied the design and optimization of the telescope of the WFS on EDGE. WFS mirror is based on a conical optics. Comparison with other mission, EDGE can observe the very weak emission lines and absorption features using the wide field telescope. In order to have large field of view, we use a very short focal length with 1.2 m and 4 reflections system for the outer diameter. We calculated effective area of X-ray telescope for various X-ray energies using ray trace program. Based on their results, we decided the design parameters of the telescope, and found that the effective area, grasp and angular resolution in all energy range (0.1-2.2 keV) of WFS. The simulated performances of the telescope are better than science requirement, shown in table 3. We also study the performance of the telescope using Wolter-I optics and which gives good angular resolution compared with conical optics, as a preparation of future development of Wolter-I mirror.

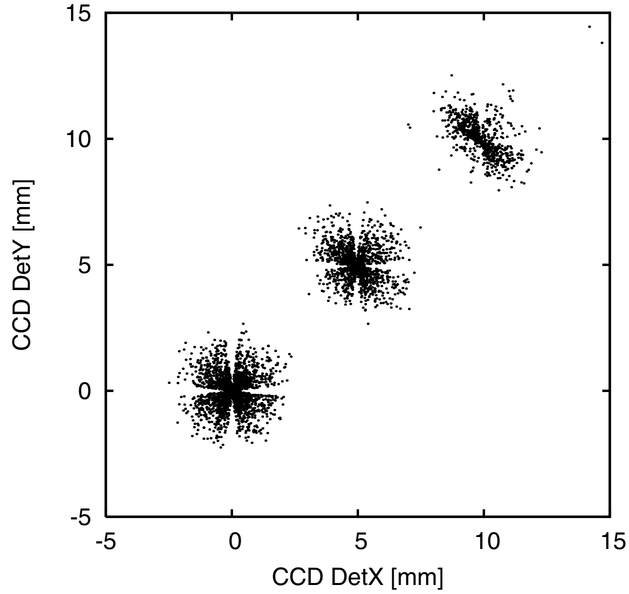

Figure 5. The simulation of the mirror response for an on- and off (20 and 40 arcmin) point source. The housing of telescope assumes the same design as SUZAKU satellite.

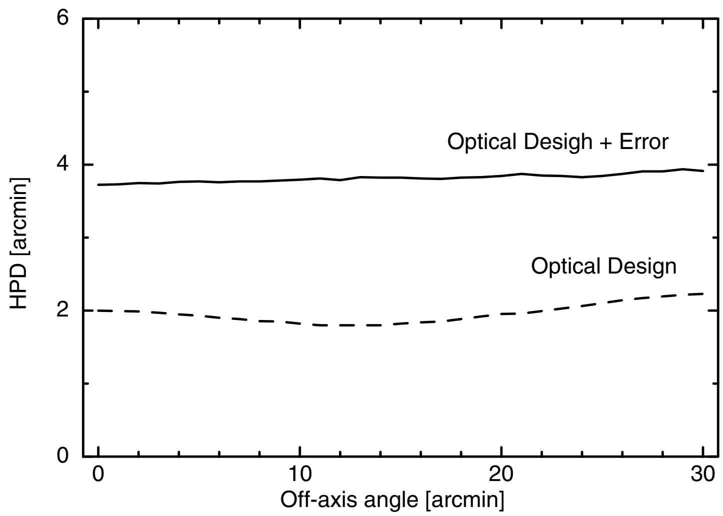

Figure 6. The calculated position resolution of the off-axis angle for the telescope. The dashed line presents the ideal design. The solid line is a prediction including the mirror positioning error $\pm 8\mu$m.

ACKNOWLEDGMENTS

The EDGE mission has been proposed to the Cosmic Vision Program of ESA. A large science groups from many countries, Italy, Japan, Netherlands, Denmark, Germany, France, Switzerland, UK and USA has contributed to EDGE project. We would like to thank the project leader J. W. den Herder, the PI Luigi Piro, and the members of WFS team.

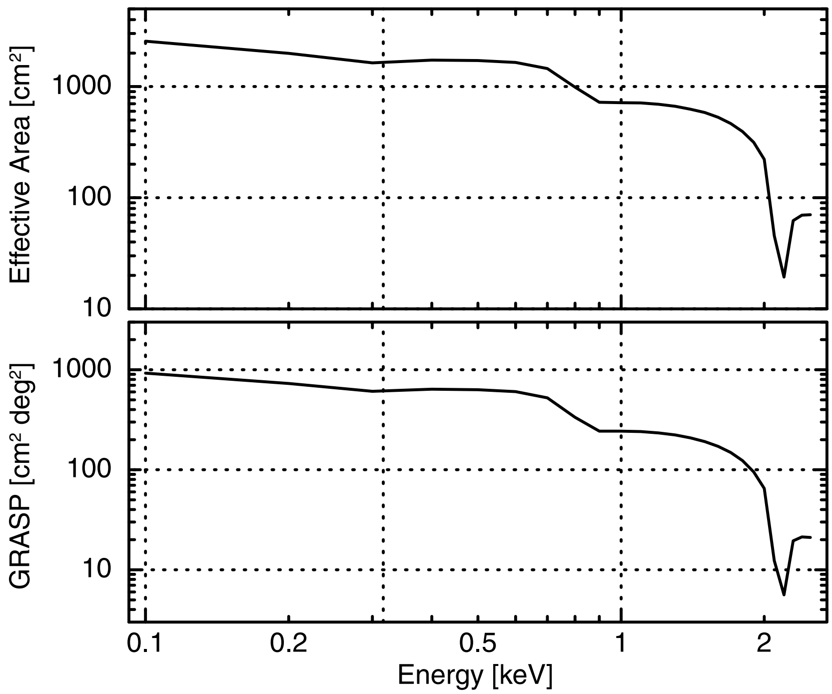

Figure 7. The calculated effective area [cm^2] of the telescope in the upper panel. In the lower panel is the grasp [cm^2 degree^2] with detector 15×15mm^2.

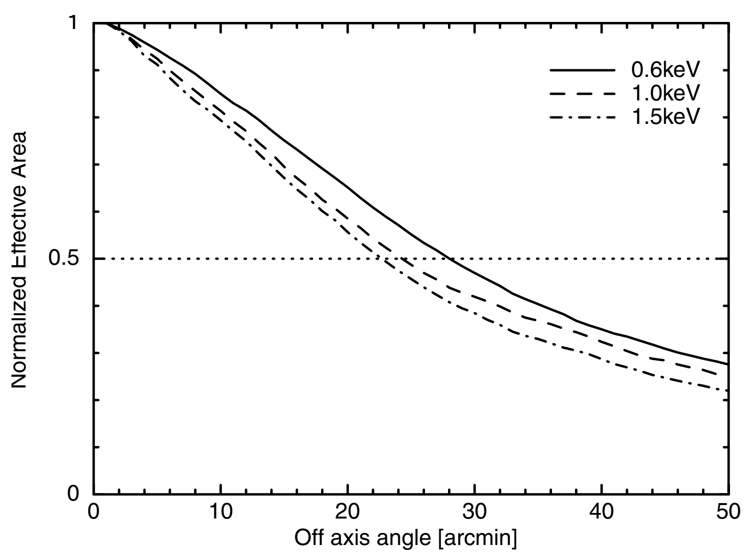

Figure 8. The vignetting curve with off-axis angle at 0.6, 1.0 and 1.5 keV.

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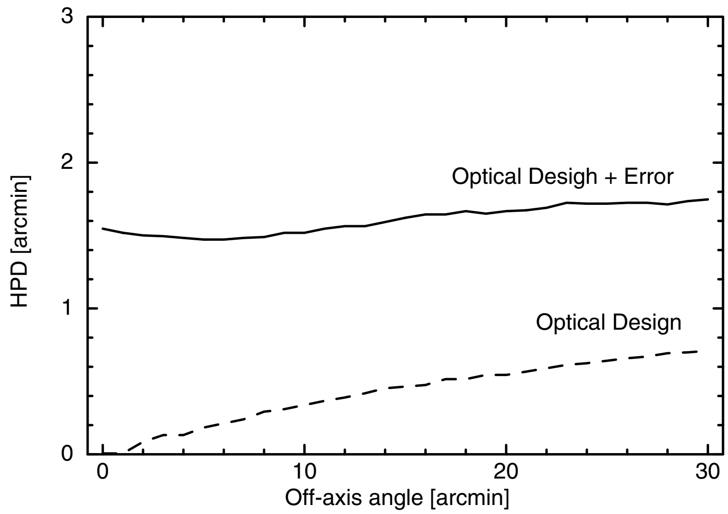

Figure 9. The calculated angular resolution of the off-axis angle with positioning error for the telescope using Wolter-I optics. The dashed line presents the ideal design.

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