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Kirkpatrick Baez X–ray optics for astrophysics: Recent status

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Abstract. X-ray optics in Kirkpatrick Baez arrangement represent promising alternative to Wolter optics in common use. We present briefly recent status of design, developments, and tests of this kind of X–ray optics including Kirkpatrick Baez module developed and tested within the EU AHEAD project.

Key words: X–ray optics – X-ray telescopes – X–ray astrophysics

1. Introduction

X-ray optics in Kirkpatrick Baez (KB) arrangement illustrated in Fig. 1 represent promising alternative to Wolter optics in common use (Hudec, 2011). We present a review of the recent status of design, simulations, development, assembly and tests of X–ray optics including the KB module developed and tested within the EU AHEAD project. Various KB test modules were simulated, designed, assembled and tested at several X–ray test facilities. Selected results are briefly presented and discussed below.

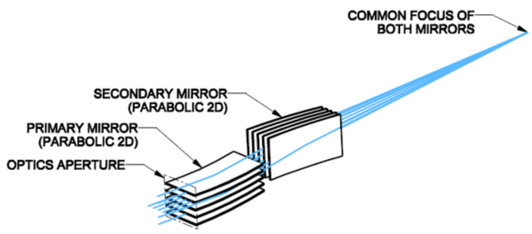


Figure 1. The principle of KB X–ray multifoil optical system.

2. Alternative Design for Astronomical X-ray Telescopes: Kirkpatrick-Baez X-Ray Optics.

The KB X–ray optics was the first X-ray imaging system proposed (Kirkpatrick & Baez, 1948). Kirkpatrick-Baez were not only proposing the geometry but they built and demonstrated a microscope using two crossed spheres. The KB X–ray optics is frequently used in laboratory and synchrotron as imaging system with high angular resolution. In space, it was used only on rockets at the early stages of X–ray astronomy (Gorenstein et al., 1971a,b,c) so far. Various modifications of the KB design exist (parabolic vs. elliptical, various number of reflections, 2 to 4).

Kirkpatrick-Baez is a double reflection X-ray optics and hence consists of two mirror sets one is aligned vertically and the second is aligned horizontally (Fig. 1). The quality of the focal spot image depends on the quality of substrates (shape, micro-roughness, etc.). Thin float glass foils and/or silicon wafers were used in the KB modules developed and tested. These substrates were mostly of standard quality, hence additional improvements can be expected if superior quality substrates will be used.

In the KB system, both mirrors are curved parabolically – the first mirror focuses in vertical plane and the second mirror focuses in horizontal plane in left picture of Fig. 2. Single focal point is formed in the crossection of the two focal planes as is shown in right picture of Fig. 2. Nested systems in order to increase the collection area are possible.

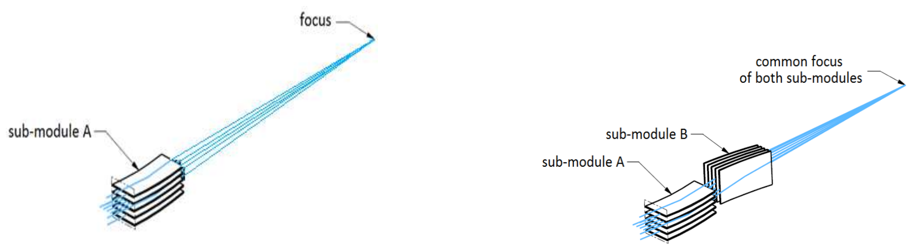


Figure 2. 1D (left) and 2D (right) X-ray optics of Kirk-Patrick Baez type both sub-modules (A and B) have common focus .

The technology of manufacture of KB modules is not necessarily based on precise and expensive mandrels (the KB reflecting substrates are almost flat plates, with curvatures of order of km), hence cost–effective manufacture (recent requirements of space agencies) of a high angular resolution ($\sim$ 5 arcsec) X–ray optics is feasible at affordable cost (Pina et al., 2011).

Historically, KB telescope applications were based on thin sheets of float glass because the quality of substrates for silicon wafers was inadequate for X–ray optics. The recent availability of substrates with considerably improved parameters and flatness now makes silicon wafers a more promising choice, especially for segmented telescopes (Hudec et al., 2006, 2008a,b; Willingale & Spaan, 2009). Novel methods also exist for further improving the quality of thin float glass (e.g., by thermally shaping the sheets on flat mandrels). Next–generation materials and substrates for glass foils and silicon wafers must also be thin and light (Hudec et al., 2009). Shaping them to small radii, as called for in Wolter designs, is not an easy task. KB arrangements consequently represent a less-laborious and hence less-expensive alternative.

3. Simulations

For every KB test module developed and assembled, ray–tracing simulations were performed in order to simulate the ideal imaging performance. Few selected results are given in Tab. 1 and in Fig. 3 and 4.

Table 1. Maximum intensity and FWHM dependence on used X–ray source

Energy (eV)	Maximum Intensity (counts)	FWHM (arcsec)
100 % reflection	5 329	3.8
280 (C)	4 893	3.7
1 500 (Al)	4 865	3.7
4 500 (Ti)	4 235	3.7
8 000 (Cu)	4 432	3.7
11 200 (Se)	4 394	3.7
17 500 (Mo)	2 036	3.4
25 300	1 075	3.1
30 000	575	2.9

4. X–ray tests at Boulder and Pennstate

Several KB modules were prepared for X–ray tests at the US test facilities. Typical KB module consisted of 144 commercially available 525 μm thick Si wafers with Au surface coating. For focus to focus tests, the mirrors arranged into planar-ellipsoidal shape with axial symmetry, with the 1st mirror at a distance of approx. 16 mm from optical axis. Typical mirror size was 100×100 mm with 3 sets of 24 (18+6) reflecting substrates in each module. Spacing between substrates was 1.5 to 2.5 mm with wedge smaller than 10 microns.

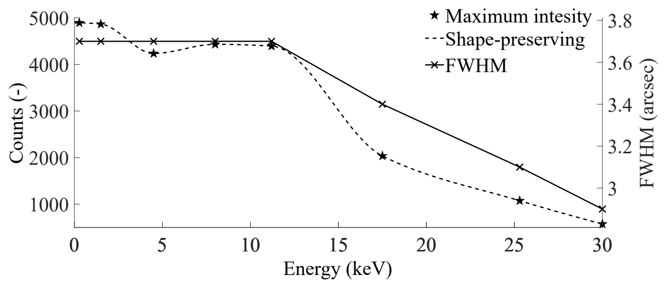


Figure 3. KB modules – ray tracing simulations, dependence on energy. Input parameters (mirror material properties, arrangement of mirrors in modules, experiment geometry, etc.) are the same as in the experiment. Point source was considered.

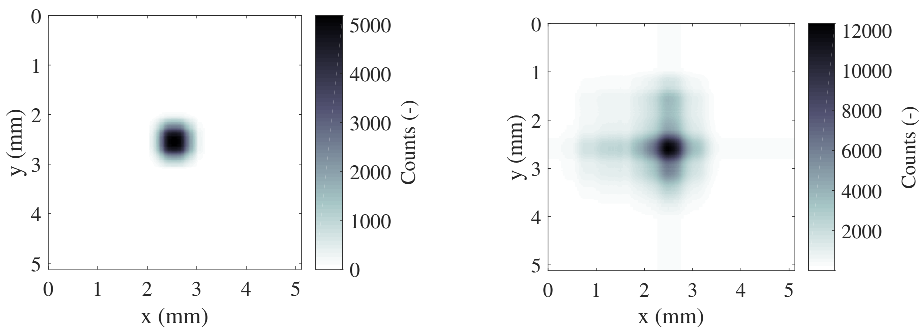


Figure 4. KB modules – ray tracing simulations. Input parameters (mirror material properties, arrangement of mirrors in modules, experiment geometry, etc.) are the same as in the experiment, for energy 453 eV (Ti L alpha). Left: Theoretical focus: FWHM = 0.58 mm 3.7 arcsec, right: Theoretical focus with 0.2 mm source diameter and 2 microns manufacturing errors: FWHM = 0.59 mm.

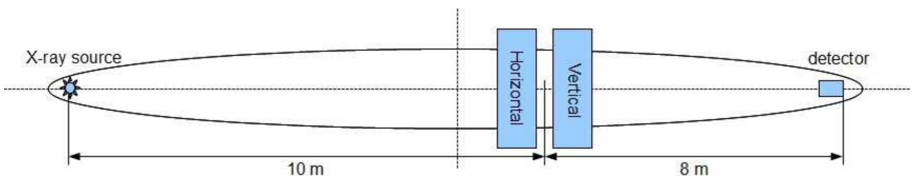


Figure 5. Experimental setup of the Boulder X–ray test experiment.

Modules were designed for vacuum chamber tests at CASA University of Colorado at Boulder, with small modifications for Pennsate tests.

KB modules were tested in vacuum chamber at CASA UC (Fig. 5), taking into account the experimental arrangement of the test facility (focus to focus) the KB test modules were of elliptical geometry, with source to optics distance: 10 m, optics to detector distance: 8 m, module position adjustment in visible light (Xe lamp), and a MCP detector as X–ray focal plane detector, with diameter of 1 inch (Figs. 6, 7). The examples of KB modules tested are in Fig. 8. For Pennstate tests, Timepix detector (Jakubek et al., 2014) was used to record the images (Fig. 9).

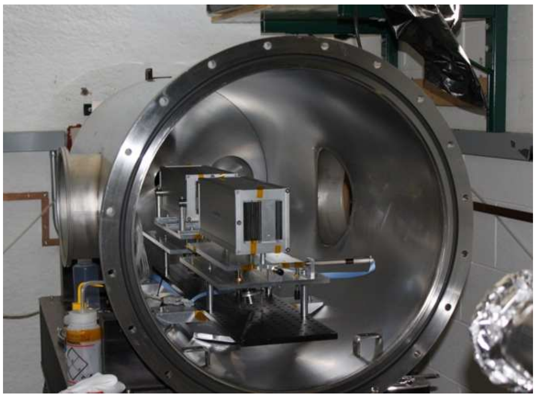


Figure 6. KB test modules – Boulder tests experimental arrangement.

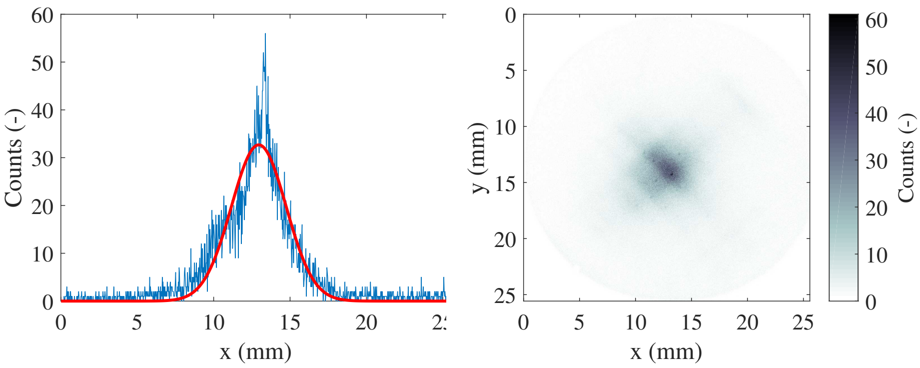


Figure 7. KB modules Boulder X-ray test results. MCP detector, diameter 1” Energy of X-rays: 453 eV, FWHM = 2.75 mm, Angular resolution: 10.2 arcsec (after ellips. correction).

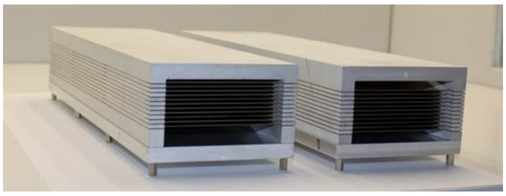
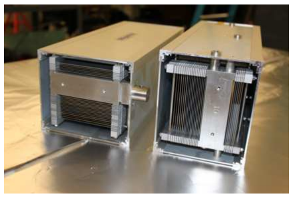
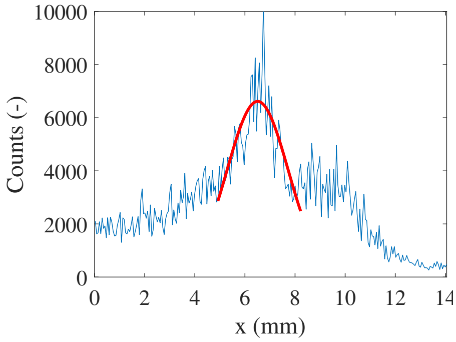



Figure 8. KB modules tested at Boulder (left) and Pennstate (right) X-ray test facilities.



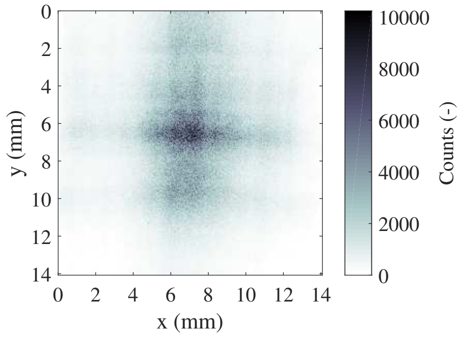


Figure 9. KB modules – Pennstate X–ray test results. Timepix detector (IEAP CTU in Prague), size 14 mm, 500 nm Al filter, Energy of X-rays: 4.5 keV, FWHM = 2.97 mm, Angular resolution FWHM: 8.7 arcsec (after ellips. correction).

5. X–ray tests at PANTER

The full illumination X–ray tests of the first KB module (see Fig. 10 and Tab. 2) designed and assembled within the AHEAD project (Piro et al., 2015) were performed at the Max Planck Institute for extraterrestrial Physics at PANTER facility in Neuried, Germany in 2017, with preliminary results shown in Fig. 11. More details on these tests (including other types of X–ray optics) are given in another paper in this volume (Pina et al., 2018).

Table 2. Parameters of KB X-ray optics module for PANTER X ray tests. These parameters are for one 1D KB sub-module. Full 2D KB system is represented by 2 analogous modules.

Properties	Value
Number of foils in one sub–module	17
Dimension of foils	$50 \times 100 \times 0.625\,\mathrm{mm}^3$
Spacing	4.5 mm
Reflective surface	Au
Dimension of sub–module	$105 \times 105 \times 50\,\mathrm{mm}^3$
Aperture	$80 \times 80\,\mathrm{mm}^2$
Focus z_α/z_β	6 500 mm
Source distance	123 m
Detector resolution	256×256 pixels
Pixel size	75 μm

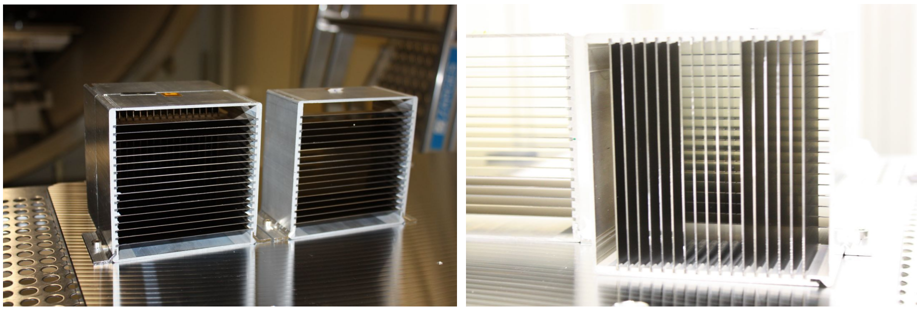


Figure 10. AHEAD KB X–ray optics.

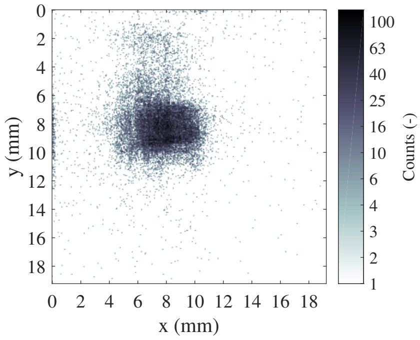


Figure 11. AHEAD KB 2D X–ray optics – the best 2D focus at 1.49 keV (33 arcsec FWHM).

6. Conclusions

Various Kirkpatrick Baez X–ray optics modules were assembled and tested, based either on glass foils or high–quality silicon wafers, all of them in multi–foil arrangement, i.e. as stacked modules with typically 72 nested parabolic or elliptic X–ray reflecting substrates 10×10 cm each. These modules were tested at several X–ray test facilities, with very promising results, with around 10 arcsec FWHM for the full stack.

The KB X–ray optics represent promising alternative to widely used Wolter mirrors, mainly because of less expensive manufacture (no need for expensive mandrels, use of commercially available parts such as silicon wafers etc.).

In summary, the availability of high-quality novel materials such as superior silicon wafers and/or glass foils will enable the design and construction of KB X-ray optical systems with very high angular resolution at reasonable cost for various applications both in space, astronomy, as well as in the laboratory. In the near future, we plan to continue the development of advanced astronomical KB X–ray test optics with assembling and testing both in visible light and in X–rays, stacked KB modules with longer focal length and improved performance, based on superior quality substrates, e.g. Si wafers with further improved flatness and surface quality.

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