X-ray optics with ultra high angular resolution

Schemes for future diffraction-limited x-ray telescopes are investigated. Based on transmission-based diffractive lenses, an angular resolution of about 10^{-3} arcsec will be achieved. For sake of efficiency, phase shifting Fresnel lenses are most likely preferred over simple zone plates. Using higher diffraction orders, Fresnel lenses may provide high focal intensities over several keV. Their chromatic error may be eliminated within a limited energy range by means of an additional refractive component, also enhancing the total focused power.

Thin transmissive X-ray lenses have the potential to overcome the era of low-resolution but high-mass Wolter telescopes, as they allow diffraction-limited imaging even in presence of relatively large manufacturing tolerances. For example, at an energy of 1 keV, an aperture diameter $Ø_A \cong 25$ cm would comply with 10^{-3} arcsec, generally to be considered as a „frontier" with respect to scientific requirements. Unfortunately, high angular resolution comes along with long focal distance F. Sensible detector pixel sizes in the µm range lead to $F \sim 1$ km, far too much for single spacecraft design. Focal lengths would even be elongated for large-scale objectives with diameters of several meters necessary due to sufficient effective area. In this case, segmentation to small panels is inevitable as well as good support structure. The latter diminishes transmission – however, depending on chosen lens profile (fig. 1), residual effective areas of a few m² up to some 10 m² are attainable.

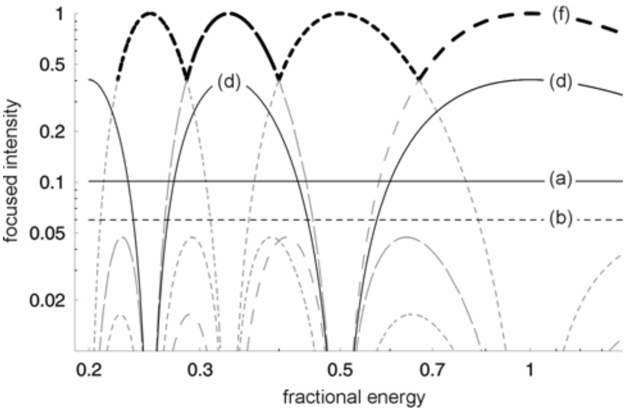

Figure 1. Focusing efficiencies of various diffractive lenses as a function of the fractional energy E/E_0. Amplitude modulated profiles like binary zone plates (a) exhibit energy-independent but modest intensity in the focal plane. „Photon Sieves" (b), made of large numbers of tiny holes, perform even worse, but with the advantage of higher flexibility. Phase zone plates (d) show oscillating efficiencies up to 40% only at certain energies in 1st order. Neglecting absorption, up to 100% may be nevertheless theoretically achieved with Fresnel lenses at distinct energies $E = m^{-1} E_0$, when used in higher orders (f). In-between, efficiency decreases to ≥ 40%.

Unfortunately, diffractive lenses suffer from severe dispersion $F \propto E$, which requires fine spectral selection in focal plane in order to maintain angular resolution but at cost of low efficiency. Chromatic correction can be done in first order with the help of a refractive device of proper shape, leading to a so called „hybride" lens. Despite severe absorption by thick refractive lens profiles, the enhanced bandwidth usually results in a net gain with respect to the sole diffractive analogue. This gain depends both on material properties at selected energy and the diffractive lens' zone number N as well. For low-Z solid-state materials like Be and Li, focused power may be enhanced by roughly a factor of 10 - 20 at 4 keV. Fig. 2 gives design limitations for such achromatic lenses partially based on this fact.

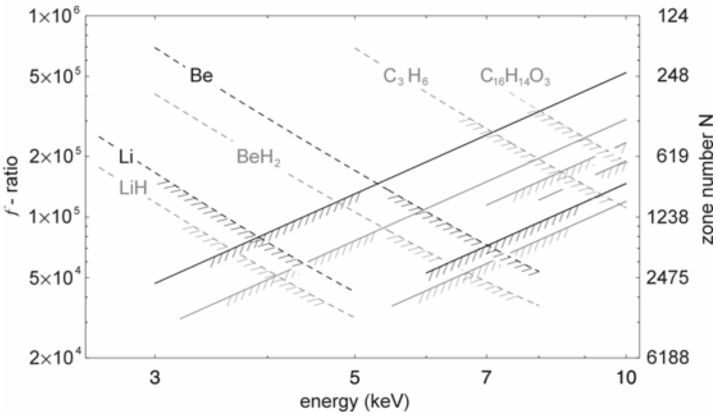

Figure 2. Approximate lower bounds on *f*-ratios and related zone numbers N for solid-state hybride achromatic lenses. Dashed lines refer to a minimum gain of 4 compared to the corresponding single diffractive component. Solid borderlines originate from restrictions on lens curvature radii and forbid usage for more or less hard X-rays. Obviously, sensible application of plastics like polycarbonate ($C_{16}H_{14}O_6$) is limited to high energies. In contrast, Li, Be and their hydrides better perform for soft and medium X-rays.

References:

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