Performance of Be Refractive Lens X-ray Optics

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Introduction

A description of the design of the beryllium (Be) refractive lens and calculations for its expected performance were published in the July 1997 SPIE proceedings [1]. The Be lens (aligned hollow spheres in a solid block of Be) differs markedly from early lenses [2] and from the most recent lenses [3]. Two synchrotron experiments were performed with the Be refractive lens. The first experiment was performed on APS beamline 1-ID at an x-ray energy of 10 keV. A preliminary report on the performance of the Be lens in the first experiment was presented at the 2000 SRI conference in Berlin. The second experiment was performed on APS beamline 2-BM at x-ray energies from 8 to 12 keV. A modified version of the original Be lens was used in the second experiment, and results were improved.

Methods and Materials

The Be compound refractive lens is a series of 50 aligned hollow spheres in a 20 × 30 × 55-mm block of Be (Fig. 1). The aligned series of hollow spheres in the solid block was constructed by first splitting the Be substrate in half, then forming a series of matching half spheres in each substrate, and finally assembling the two halves to make the series of hollow spheres. The spheres are 1 mm in diameter. The thinnest part of the web between the spheres is 0.10 mm. The perfect shape for the surface of the hollow cavities would be parabolic. The spherical shape approximates this surface when it is near the axis of the lens. In this case, the focal length of the lens is given to a first approximation by the following equation:

$$\text{Focal Length} = R/2N\delta, \qquad (1)$$

where R is the radius of the hollow spheres, N is the number of spheres, and δ is the refraction coefficient. For Be in an energy range of 6 to 60 keV, δ is approximately equal to $3.41 \times 10^{-4}/E^2$ (keV). The next equation:

$$\text{Focal Length (cm)} = 1.466\, E^2 \text{ (keV)}, \qquad (2)$$

gives the focal length of the Be lens, where R = 0.5 mm and N = 50. The refractive lens behaves very much like a simple convex lens using visible light. To the first approximation, the Be refractive lens follows the simple lens law illustrated by the next equation:

$$1/\text{Focal Length} = 1/L1 + 1/L2, \qquad (3)$$

where L1 is the distance from the source to the lens and L2 is the distance from the lens to the focal spot. In this simple approximation, the diameter of the focal spot, d_2, is given by the following:

d2 = d1 ¥ L2/L1, (4)

where d_1 is the diameter of the source. The transmission of the lens, defined as the ratio of the number of photons exiting the lens that will contribute to the focused beam, divided by the number incident on the lens, is given by the following equation:

$$\text{Transmission} = \frac{2\exp(-\mu N t)}{(\mu 2NR_0)^2 \times (\sin\theta)^2} \times \{(\mu 2NR_0 - 1) - (\mu 2NR_0\cos\theta - 1)\exp[-\mu 2NR_0(1 - \cos\theta)]\}, \qquad (5)$$

where μ is the coefficient of mass absorption, R_0 is the radius of the lens, N is the number of hollow spheres, and $\sin\theta = R/R_0$, where R is the radius of the incident x-ray beam on the lens. The focusing properties of the Be lens were measured in the energy region of 8 to 12 keV by using x-ray beams from the APS. Two experiments were performed with this Be lens. The experimental setup, which was similar in both experiments, is shown in Fig. 2. A monochromatic x-ray beam from an undulator, monochromatized with a two-crystal monochromator, is collimated by a double-slit assembly, passes through the Be lens, and is focused on a detector imaging system.

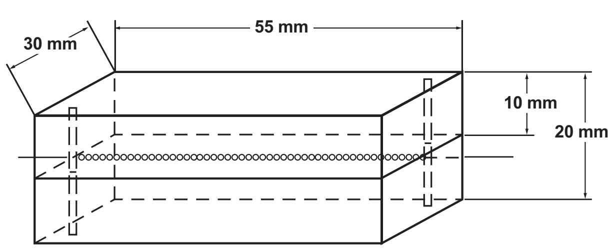

FIG. 1. Be refractive lens for focusing x-rays in the energy range of 6-60 keV.

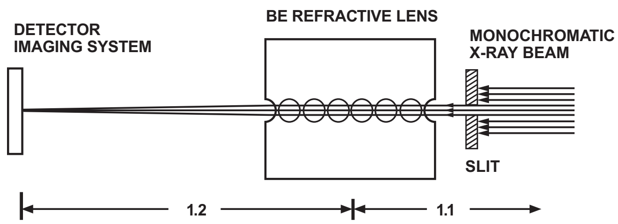

FIG. 2. Experimental setup used in both experiments.

Results

The first experiment was performed on APS beamline 1-ID. In this experiment, the position of the lens was fixed at 60 m from the source. The energy of the monochromatic beam was fixed at 10 keV. The x-ray beam was collimated by a double-slit system that reduced the beam profile to 0.50 × 0.50 mm. A 2-D image of the focal spot was obtained by scanning the beam with a detector mounted behind a 10-μm pinhole. Images were taken for distances between the lens and the detector, L2, between 1500 and 1300 mm. The smallest focal spot was found at L2 = 1356 mm, with a focal spot (full width at half-maximum [FWHM]) of 35 _m in the horizontal direction and 45 _m in the vertical direction. When the measured value for L2 = 1358 mm, defined as the position of the smallest image, is combined with L1 = 60 m, in Eq. (3), one obtains a focal length of 1328 mm. This is in considerable disagreement with the theoretical prediction of 1466 mm from Eq. (2). The reason for this difference is explained by the differences in the way a spherical lens focuses and a parabolic lens focuses. The slope of the surface of the lens element determines the change in the angle of the x-ray as it passes through the lens. This angle plus the radius of the incident x-ray determine the distance at which the x-ray incident at this radius will focus, L2. For a parabolic surface, the combination of slope and radius gives the same value of L2 for all radii. For the spherical lens, each radius focuses at a different L2 value. The following equation:

$$\text{Focal Length Ratio (spherical/parabolic)} = 1/2 \tan(\arcsin R/R_0), \quad (6)$$

gives the ratio of the focal length of an x-ray incident at a radius of R on a spherical lens with a radius of R_ to the focal length of an x-ray focused by a parabolic lens whose curvature on axis matches the curvature, and thus the focal length, of the spherical lens on axis. Thus x-rays incident at the larger radii focus closer to the lens than the rays incident close to the axis of the lens. Using these values in Eq. (6) gives shifts of 14.9 cm and 17.9 cm. The x-ray beam is attenuated quite strongly at a radius of 0.35 mm, so the effective radius to use in the calculation of the shift is the minimum diameter of the beam close to the 0.250-mm radius value. This correction gives a focal length for the 10-keV x-rays close to the axis of the lens of 147.7 ±2 cm, in agreement with the value of 146.6 cm predicted by Eq. (2). The estimate for the diameter of the focal spot based on this approach is 17.6 _m. As big as the estimate for the minimum diameter of the focal spot is, it is still smaller than the measured value at 10 keV. Thus, this additional increase over the expected value for a perfect lens with parabolically shaped surfaces is, in part, due to the difference between a spherically shaped lens and the ideal parabolic shape and partly due to the imperfection in the spherical shape of the cavities. The second experiment was performed on APS beamline 2-BM. A slightly modified version of the

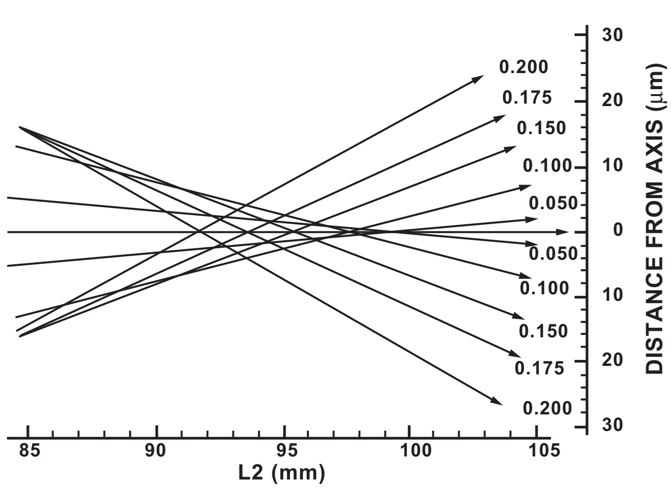

FIG. 3. Schematic drawing showing how the x-rays from different radii in a perfect spherical lens would focus on the axis of the Be lens.

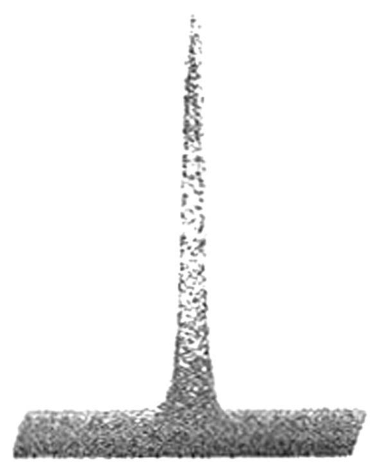

FIG. 4. 2-D image of the focal spot of the 9.1-keV focus at L2 = 116 cm.

original Be lens was used in this experiment. The modification consisted of polishing the spherical surfaces. This resulted in a more spherical shape for the hollow cavities, resulting in improved performance of the lens. The experimental setup was quite similar to that of the first experiment (Fig. 2), except that the L2 distance was fixed at 116 cm and the energy was varied between 8 and 12 keV. The detector was a charged-coupled device (CCD) viewing a scintillate. Images of the x-ray beam were taken at energies between 8 and 12 keV at 0.1-keV intervals. The best focus was obtained at an energy of 9.1 keV. The x-ray beam profile was 0.30×0.30 mm. By applying Eq. (3), with L1 = 31.6 m and L2 = 116 cm, one obtains an equivalent focal length of 111.9 cm. This value needs to be corrected for the focusing properties of the spherical lens, as discussed above. This correction gives a value of 120.2 cm for the focal length of x-rays close to the axis of the lens. This value is close to the value of 121.4 cm predicted by Eq. (3). A 2-D image of the focal spot is shown in Fig. 4. The FWHM of the peak is 30 _m in the vertical direction (direction perpendicular to the surface of the half substrate) and 25 _m in the horizontal direction. The flux enhancement, the increase in photons per mm^2, can be estimated by the following equation:

$$\text{Flux Enhancement } (\gamma/\text{mm}^2) = (d_1/d_2)^2 \times \text{Transmission}, \quad (7)$$

where d_1 and d_2 are the radii of the incident beam and the focal spot. The incident beam is square (0.300×0.300 mm), so d_1 is the diameter of a circle of equivalent area and it is 0.339 mm, and d_2 is the average FWHM diameter, 0.0275 mm. The estimate of the flux enhancement for the 10-keV beam is 72:1. The experimental value taken from a comparison of the flux in the incident beam with the flux in the focused beam gives an enhancement of 60:1.

The most likely applications of this type of lens would be to increase the photon density (γ /mm^2) in experiments that require a small but not very fine beam of the quality produced by a zone plate. The enhancement of flux density of 60:1 could be quite useful. It could also be used to focus a high-energy beam in the ne/xt hutch some 30 m away. To focus a beam from a source 30 m in front of the lens, at a point 30 m after the lens, would require a focal length of 15 m, corresponding to an x-ray energy of 33.6 keV. The lens could also be used to generate a parallel beam of high-energy x-rays. For a source 30 m from the lens, this would require a focal length of 30 m, corresponding to an energy of 47.6 keV. Two lenses in series could focus a 47.6 keV x-ray beam, 30 m after the lens, and make a parallel beam of 67.3 keV.

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