A Variable-Focus X-ray Compound Lens*

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Abstract

Design and fabrication of an x-ray lens assembly for focusing x-ray beams is described. The assembly consists of a number of precisely stacked and aligned aluminum parts. These parts are cut from a long extruded section having sixteen parabolic cavities along its length. The thickness of the wall between adjacent cavities is 0.2 mm. By cutting the assembled parts diagonally as shown below, a variable-focus lens system can be made. Moving the lens horizontally allows the incident beam to pass through fewer or more cavities, collimating or focusing the emerging beam at a desired distance downstream.
The variable focus aluminum lens has been used at the Advanced Photon Source to collimate a monochromatic, 81-keV undulator beam to increase downstream crystal monochromator throughput. Results indicate collimation consistent with theoretical expectations.

Keywords: x-ray, optics, lens, compound lens, variable focus, extrusion

1. Introduction

Focusing or collimating diverging x-ray beams produced by synchrotron sources or other x-ray sources is important for a range of applications. Mirrors, crystals, zone plates, and capillaries have been suggested and used to focus x-rays. Focusing x-rays by refraction, proposed a few decades ago and presumed ineffective, has recently been implemented through the use of a compound x-ray lens system (CXL). [1]

For a lens system consisting of N concave lenses of radius of curvature R, the focal length is simply given by (see Fig. 1):

$$F = \frac{R}{2N\delta} ,$$

where δ is the real index of refraction decrement. The index of refraction is given by $n = 1 - \delta + i\beta$. From the relationship above, it can be deduced that to collimate 10-keV photons using a beryllium (δ=3.4E-6) CXL positioned at 30 m from the source, one needs five 1-mm-radius cavities. To focus the same 2 m downstream, it should have an additional 74 lenses.

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The main drawback of the CXL is its substantial absorption of x-rays. Thus, the use of this type of a lens is justifiable if the gain obtained by focusing more than offsets the loss due to absorption. The lens materials suitable for focusing x-rays in the 5-100 keV range are the low-atomic-number elements, such as Li, Be, B, C, Al, Si, etc., and their compounds. For low-to-moderate-energy x-rays (5-20 keV), Li and Be are most suitable because of their low absorption. For higher energies, Al and other elements or compounds can be used.

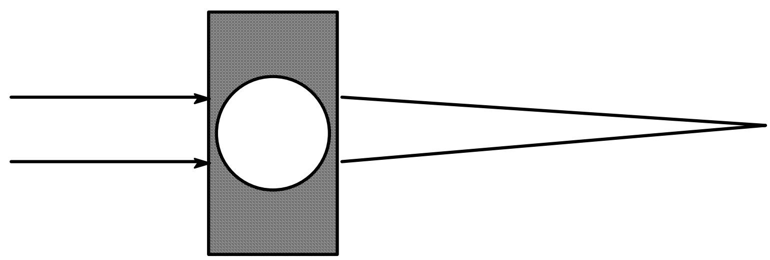


Fig. 1: Focusing x-rays can be accomplished by using concave lenses. In this figure, a substrate consisting of two one-sided concave lenses configured by drilling a hole is shown. The focal length for such a lens is typically in the 10s-100s meter range, which is why a large number of aligned lenses are used to obtain short useful focal lengths (under a meter).

The other challenge in the development of CXLs is in fabrication. A suitable lens system is one that is relatively easy and economical to manufacture, provides thin walls between adjacent cavities (to reduced absorption), is robust, requires no or little alignment of individual lenses, and has relatively smooth walls.

A variety of schemes to fabricate CXLs have been suggested. These range from routine machining processes, such as milling or drilling, to more specialized processes, such as electrical-discharge machining (EDM), molding, stamping, etching, casting, electroplating, etc.

If one-dimensional focusing is sought, then a substrate with a number of aligned cylindrical holes drilled into it may be used. If two-dimensional focusing is desired, then spherical cavities may be configured. To reduce optical aberrations, the holes and cavities should have parabolic and paraboloidal shapers, respectively.

The earliest CXLs were aluminum lenses developed at the European Synchrotron Radiation Facility (ESRF) by drilling a set of aligned holes into an aluminum block with a thin wall between adjacent holes [1]. This was used for one-dimensional focusing. The Advanced Photon Source (APS) developed the first two-dimensional focusing lens in Be by configuring one hundred 1-mm-radius hemispheres into a beryllium blocks [2]. Cutting the block into two and matching and aligning the hemispheres made a lens assembly consisting of fifty spherical cavities.

In this paper, a CXL system for high-energy x-rays developed by extrusion of aluminum is described. This is a one-dimensional focusing device, but, in theory, two sets of such systems can be set normal to each other to focus in both directions (at the expense of doubling absorption). Because of its high absorption of low-energy photons, an aluminum lens is deemed suitable for energies above 30 keV and preferably above 60 keV.

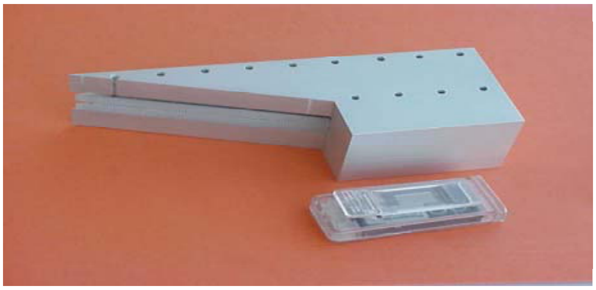
2. Extrusion

The extrusion technique used here is more appropriately known as hot microextrusion. In hot extrusion of hollow or tubular profiles, a die is used that has openings corresponding to the negative of the part to be made. A hollow extrusion die is one in which the mandrel, which forms the inner surfaces of the profile, is an integral part of the die assembly and is supported in place by a bridge. Allowance for thermal shrinkage and other effects are made in the die design. By pushing heated soft aluminum into the die, soft aluminum flows around the bridge supporting the mandrel and into the openings in the die. The open sections metallurgically join prior to exiting the die assembly to make the desired part. After cooling, the long, extruded section or lens is coiled or cut into the desired length for shipping.

The first generation of the lenses produced and reported here has a cross section of 2 mm × 20 mm, with 16 parabolic cavities. The on-axis radius of curvature is 1 mm, and the thickness of the wall between adjacent cavities is about 0.2 mm.

To make a lens assembly, a sufficient number of the extruded parts are cut into shorter lengths (via EDM) and laid side-by-side to make the assembly with any desired number of cavities (see Fig. 2). The pieces are sandwiched between two flat plates to align and maintain alignment. This section is then inserted into the opening of a U-shaped aluminum holder and held there by a number of set screws.

The assembly is then diagonally cut, and, as shown in Fig. 2, a variable focus device is produced: by moving the assembly horizontally, the incident beam passes through fewer or more cavities, focusing the incident beam vertically at different focal spots. As seen, one section of the assembly has a fixed number of lenses, in this case 70, as it was deemed unnecessary to have continuous variation of the number of lenses down to zero.



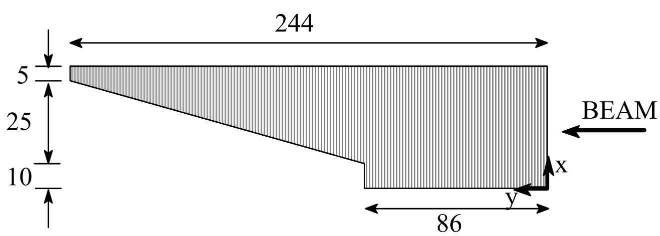


Fig. 2: Top picture is a prototype, aluminum-extruded, variable-focus x-ray lens assembly. The assembly consists of a U-shaped aluminum block in which the two flat plates sandwiching the extruded pieces are laid side by side between them and inserted and held in position by several set screws. The assembly is then cut by EDM to provide the sloped section seen, giving the assembly its variable focus ability. The drawing in the bottom shows the top view of the lens assembly tested and its dimensions in mm. During the test, the lens assembly is moved horizontally in the x-direction to allow the beam to transverse fewer or more cavities.

3. Advantages and Limitations of Extruded X-ray Lenses

Extruded lenses have several inherent advantages and limitations. One of the main advantages is the ability to produce noncircular (e.g., parabolic) cavities in long parts. Any other alternative technique is much more costly and, for very long parts, impractical. The second advantage is that the process is very economical as a large number of lenses can be made by the amount of material produced by a minimum extrusion run. A 100 kg aluminum billet or ingot will produce over one km of parts sufficient for over 100 lens assemblies.

The dimensional precision of the extruded lenses is reasonably good, within a few microns, and very complex 2-dimensional profiles can be fabricated. As we have found, complex parts with very thin walls (0.2 mm in the present case) can be made. In fact, we have developed second-generation lenses with only 0.1 mm wall thickness, but these have not been tested. The surface roughness of the extruded parts is on the order of 0.4 µm (15 micro-inch) R_a.

The extrusion process has its limitations too. Three-dimensional structures cannot be produced. This perhaps explains why we could not find any record of optics developed by extrusion. In addition, one is limited to highly formable material that can be extruded through hollow dies.

4. Evaluation of the Extruded Lenses

A prototype variable-focus aluminum lens was evaluated at the APS 1-ID beamline. It was used to collimate a monochromatic 81 keV undulator beam. The beamline layout is shown in Fig. 3. The beam from undulator A (A) is monochromatized by a double-crystal monochromator (C) and passes through the lens assembly at E located 35 m from the source (A). The beam is vertically scanned at two locations to determine its size: at slit (F) immediately downstream of the lens and another at slit (I), 24 m downstream from slit (F). Vertical collimation is achieved when these two are identical. This was accomplished by first aligning the lens assembly such that the monochromatic x-ray beam, 0.6 mm high, passed symmetrically along the optical plane of the lens and through the diagonally uncut section of the assembly, traversing 70 lenses. The FWHM of the beam at the two slit locations (F and I in Fig. 3) was measured as the lens assembly was moved horizontally allowing the beam to traverse more lenses. The results are shown in Fig. 4.

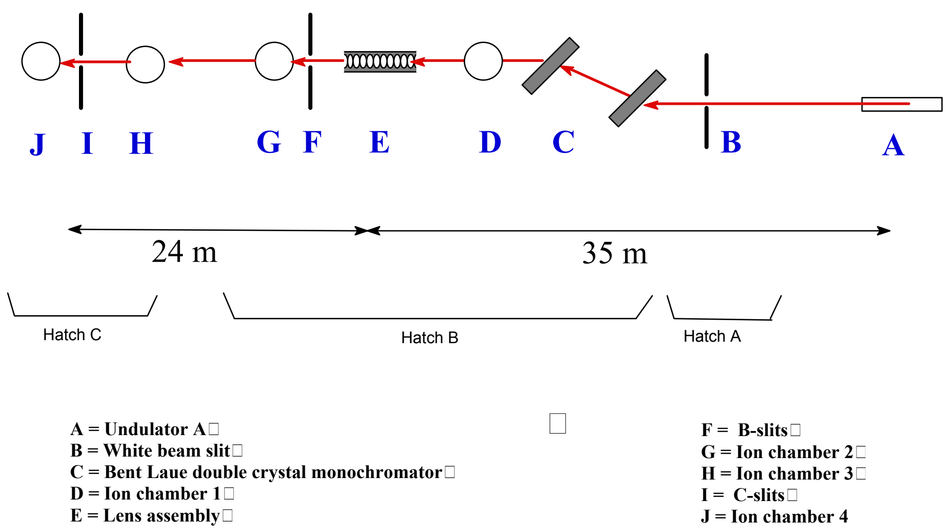


Fig. 3: Side view (not to scale) of the layout of the beamline used for testing the prototype compound x-ray lens. The beam traverses from right to left passing through the double-crystal monochromator C that is set to reflect 81 keV photons. The bent Laue double-crystal monochromator used here does not affect the beam size or divergence [3].

As shown in Fig. 4, collimation occurs at about x=32 mm corresponding to about 157 lenses. With that many lenses, the beam size immediately (30 mm) downstream of the lens is the same as that 24 m from the lens. The observed reduction in the beam size immediately downstream of the lens is purely due to the absorption: because of the curved shape of the lenses, the beam goes through a varying thickness of aluminum, and it is attenuated least at the center and most on the periphery. The flat parts of the curves in right side of the same figure correspond to the part of the lens assembly that is not sloped and has a fixed number (70) of lenses.

The real part of the index of refraction for aluminum at 81 keV is δ=8.23 E-8. As such, the number of lenses needed to collimate the beam from the source at 35 m is:

$$N = \frac{R}{2F\delta} = \frac{1x10^{-3}(m)}{2[35(m)][8.23x10^{-8}]} = 174\cdot$$

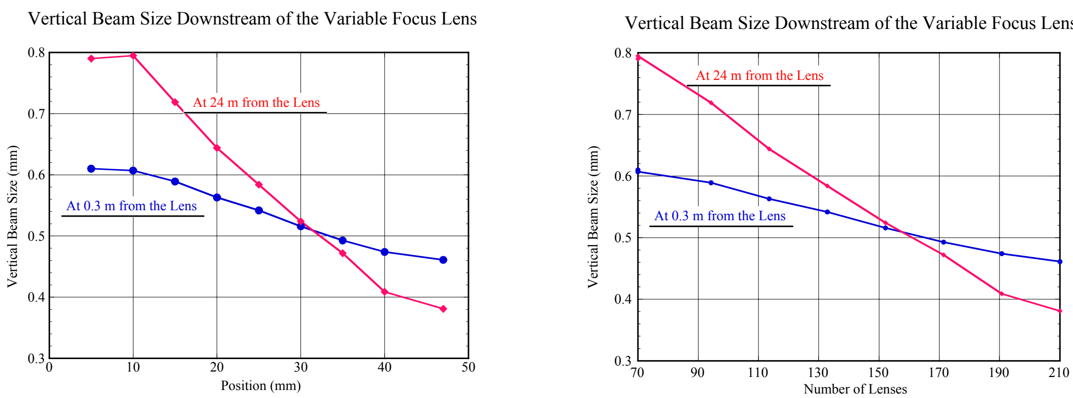


Fig. 4: Vertical FWHM of the x-ray beam at 0.3 m and 24 m downstream of the lens assembly as a function of the position (left) or the corresponding number of lenses through which the beam passes. Collimation is achieved when the beam has the same size at both locations. This occurs in this case at x=32 mm corresponding to 157 lenses. The changes in the slope of the curves at the two ends are the result of the way the lens assembly is cut (see Fig. 2).

This value is within 10% of the measured value and is well within the error bar for this type of experiment because of uncertainty in lens radius, number of lenses traversed, index of refraction of the metal (due to impurities), etc.

5. Use of the Lens Assembly for Beam Collimation

One of the reasons for developing this lens assembly was to collimate the beam, thereby increasing the x-ray throughput of subsequently placed narrow-angular-acceptance optics [4]. In one case, a pair of flat Si(111) crystals in a dispersive arrangement is positioned immediately downstream of the lens assembly (not shown in Fig. 4). The purpose is to further monochromatize the 81 keV beam off the bent Laue pre-monochromator from an energy resolution of 120 eV to 7 eV, as required for some applications. The Darwin width (i.e., the narrow angular acceptance range about the Bragg angle within which diffraction occurs) of the second set of monochromator crystals is a few microradians, about 10 times smaller than the divergence exiting the Laue monochromator. This means that, uncollimated, much of the radiation will not propagate through the high-resolution system. Collimating the beam can increase the throughput if the absorption in the lens is relatively small. Calculations show that, with 157 lenses and an average lens thickness of 0.22 mm, only about 12% of the x-ray beam is transmitted (=exp (-μz) ~ exp (-0.054 × 157 × 0.22) = 15%. Yet with this huge 85% absorption, the throughput of the analyzer crystals only modestly deteriorated, by only between 10 to 20%, meaning that, were it not for this absorption, the collimating lens could increase the system throughput by more than a factor of 6. Reducing the average wall thickness to 0.1 mm, as in the second generation of lenses, will increase transmission to 43% and more than double the system throughput, making the use of this lens well worthwhile.

6. Conclusions

The fabrication of an extruded aluminum compound x-ray lens assembly with a parabolic profile is described. The lens system design has a continuous variable-focus feature giving it on-line operational versatility. The assembly can be cooled and, as such, can be used on monochromatic, as well as white, beam beamlines. Collimation was demonstrated on an undulator beamline at the APS, and the results are in good agreement with theory. Thus production of x-ray lenses by aluminum extrusion is possible, and the extrusion process used has sufficient precision to render parts that have acceptable profile, figure and finish. The process is very economical. The next-generation x-ray lenses, having a wall thickness of 0.1 mm, have been fabricated and will be tested shortly for collimation and focusing. Plans are underway to produce lenses with even smaller wall thickness.

7. References

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