

Large aperture x-ray refractive lens from lithium.

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Abstract.

Lithium's low x-ray absorption should give refractive x-ray optics their highest possible performance. We made low-cost lithium lenses that are easy to align and match the ~ 1 mm beam size. This paper summarizes lithium lens performance to date, and what might be done in the future.

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INTRODUCTION.

Refractive x-ray optics for synchrotrons[1] became an interesting alternative to mirrors and zone plates optics after the first demonstration of the Compound Refractive Lens (CRL)[2]. Compared to those for visible light, x-ray refractive lenses are weak because the index of refraction $n = 1 - \delta + i\beta$ for x-rays differs so little from unity. A recent article[3] summarizes the accomplishments of a most active group in this field. Their lenses are parabolas because these lack spherical aberration, and the lens curvature decouples from the aperture:[4] N lenslets with a radius of curvature R_0 in series have a focus at $f = R_0/2N\delta$.

Without optical equivalent is Cederstrom's multi-prism.[5] The multi-prism cleverly adds the small deflection of x-rays in each prism to approximate a parabolic lens. The path length of the x-rays is linear with the distance to a prism's top, hence summing the linear paths gives a parabola when the prisms span the x-ray beam under an angle. The parabola's effective radius depends on the multi-prism angle to the x-ray beam path, giving the multi-prisms a simple way to change its focal length. And, prisms are easier to make than parabolas.

The performance of a refractive x-ray lens is a function of δ/β , i.e. the ratio of the index of refraction decrement over the absorption coefficient. Because lithium produces the largest phase shifts per unit absorption length of all solids, we[6, 7, 8, 9] and others[10, 11] use lithium in the best available lens designs.[4, 5]

Micro-focusing optics have short x-ray path lengths, so that x-ray attenuation is less important in micro-focusing than when the purpose is the opposite, to gather most of the x-ray beam into a smaller spot that matches a particular experiment, or the aperture of another x-ray optic. The right lens to gather the x-rays has an aperture that is comparable to the beam, say 1 mm, while the focus should be $\simeq 0.1$ mm or so. A one-dimensional multi-prism that squeezes a rectangular x-ray beam into a square also useful. For these purposes lithium's long x-ray attenuation length ℓ ($\ell \simeq 60$ mm at 10 keV) is ideal.

For lithium x-ray lenses the main issues are fabrication and corrosion. Corrosion is under control: our lithium lens prototypes perform just as well now as they did a few years ago. But, lithium fabrication methods must become better to achieve the theoretical performance predicted for x-ray optics from lithium. Lithium is easy to shape by embossing or molding. However, standard metal dies can cause problems because lithium tends to stick to metals. A good die material for lithium is polypropylene, which can be used even without lubrication provided that the sliding angle between die and lithium is limited. For the parabola our limit is 60° , which gives a 1 mm aperture lens a radius of curvature $R_0 \simeq 0.263$ mm. For the multi-prism a convenient die is a polycarbonate Fresnel beam splitter that comes with 0.5 mm high rectangular prisms and a sliding angle of 45° angle. The multi-prism needs only a single pressing, while the parabolic lenslets are pressed individually.

The lens packaging in Figure 1 lets x-rays in and out through 10 mm diameter and 0.126 mm thick beryllium windows in the center of two 70 mm ConFlat flanges connected by a glass tube. The package is high-vacuum quality, but not under vacuum: it contains a slight overpressure of helium. A lithium getter visible through the glass gives additional protection: when the getter remains shiny, the lithium in the lens should be clean too.

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FIGURE 1. Lithium lens packaging.

PARABOLIC CRL FROM LITHIUM.

Figure 1 contains a 76-lenslet CRL. The two parabolas in each lenslet are together just under 1 mm thick, but because of the $d \simeq 50$ to $100 \mu\text{m}$ dead layer between the parabolas and the slight spacing between the lenslets, the total lens is about 100 mm long. The dead layers in a lithium lens absorb a negligible amount of the hard x-rays (at 10 keV about 10%).

Figure 2 is a result from this parabolic lithium lens at 10 keV, and Figure 3 below has similar data for a two-dimensional multi-prism lens. The measurement setup is straightforward.[12] Briefly, monochromatic[13] x-rays from the Advanced Photon Source's (APS's) beam line 7-ID pass through various beryllium and kapton windows, and a rectangular aperture in front of the lens. A YAG:Ce scintillating screen converts the x-rays into visible light that is observed by a CCD at $5\times$ magnification.[14] The setup is ideal to quickly focus the beam, and adequate to evaluate the quality of the x-ray optic. The CCD is linear, in observation time and in x-ray intensity up to 75 % of the maximum pixel value (4095). In some measurements the x-ray intensity exceeded the linear range, leaving some caveats in the x-ray transmission and gain that must be resolved by independent measurements in the future.

Given that lithium's $\delta \simeq 0.95 \times 10^{-6}$ at 10 keV, the 76-lenslets CRL has a nominal focal length $\simeq 1.82$ m. An x-ray source $d_s = 49.4$ m before the lens then puts the image $d_i = 1.89$ m behind the lens. However, the smallest x-ray spot is found at 1.52 m from the lens, about 0.3 m closer than it should be even when correcting for the lens length (0.1 m).

The left part of Figure 2 is the unfocused beam apertured to a $500 \mu\text{m}$ square before the lens, seen by the diagnostics 1.52 m behind the lens as a $515 \mu\text{m}$ square. Fresnel fringes are visible only along the top and bottom edges because the source penumbra from the slit is much smaller in the vertical than horizontal direction due to the ratio of the source sizes. Thanks to continuous improvements in the beam line, the horizontal striations are smaller here than in previous measurements[8] and Figure 3.

The right part of Figure 2 is the best x-ray focus, after attenuation with 0.038 mm aluminum to bring the intensity into the CCD's range. The aluminum reduces the fundamental x-rays at energy $E_1 \simeq 10$ keV about 250-fold, while the beam's harmonics at $E_3 = 3E_1 \simeq 30$ keV decrease by only 0.8 or so and become visible. This is convenient for focusing: a cylindrically symmetric lens has its focus on the beam axis, so that the best orientation of the lens is when the bright focus is in the center of the harmonic beam.

The index of refraction decrement $\delta \propto 1/(E)^2$ for photon energy E , hence the third harmonic deflects $1/9^{\text{th}}$ less than the fundamental. In the focal plane for the 10 keV x-rays, the harmonic x-rays at 30 keV give a factor $1 - (1/3)^2 = 8/9$ smaller beam than the original as is indeed seen on the right side of Figure 2. However, the square is slightly distorted, due to a $\simeq 0.1$ mm misalignment of the individual lenslets[9] that gives the edge of the lens a small deviation from the ideal parabolic profile. Improvements[11] to the molding and mounting hardware are needed to minimize misalignment.

At 10 keV the lens has an x-ray transmission of $T \simeq 0.5$, and a 50-fold intensity gain G that is an order of magnitude lower than the theoretical $G \simeq TM^2 \simeq 500$. The difference is mostly due to the larger image. An ideal image is a demagnified x-ray source, with a demagnification factor $M = d_s/d_i \simeq 32.5$. The source's FWHM is $478 \mu\text{m}$ horizontal and $33 \mu\text{m}$ vertical, hence the ideal image is a $\simeq 15 \mu\text{m}$ long needle of $\simeq 1 \mu\text{m}$ height. The resolution of the diagnostics[14] is $\simeq 5 \mu\text{m}$, and the expected image is therefore $15.5 \mu\text{m}$ wide by $5 \mu\text{m}$ high.

Horizontally the FWHM is $36 \mu\text{m}$, about $20 \mu\text{m}$ more than expected. Vertically the FWHM is $26 \mu\text{m}$, also $20 \mu\text{m}$ too large. The focal region is consistent with a demagnified image widened by isotropic scattering over a $\simeq 13 \mu\text{radian}$ angle. Some motion of the beam in the vertical direction, as could sometimes be seen with a faster CCD (with lower

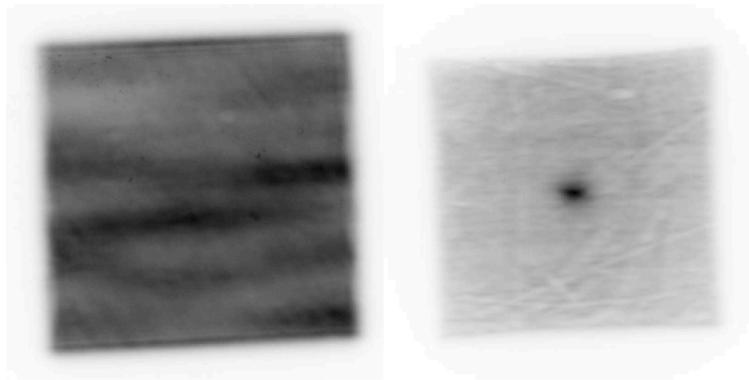


FIGURE 2. Original x-ray beam without (left) and with the lens and an x-ray filter 1.52 m downstream (right).

dynamic range) may explain some of this broadening. The actual versus theoretical performance of the lenses must be a fabrication issue that we have yet to identify.

TWO DIMENSIONAL FOCUSING WITH MULTI-PRISMS.

Figure 2 for a parabolic lens is similar to Figure 3, the two-dimensional focus obtained by placing two multi-prisms under 90° in a single housing. The left side of Figure 3 is the 0.5 mm by 0.5 mm square incoming beam, the right side is the image at the focus. In this image the focus is in the upper right corner of the original beam. The x-ray transmission of the two lenses is comparable, but here the gain is $G \simeq 18$. Another difference with Figure 2 is the spot's asymmetry.

The lithium multi-prism lens has similar problems as discussed for a multi-prism monochromator,[15] notably the imperfect shape of the prism's peaks and their counterpart, the valleys. Imperfections along the prism's peaks show up as an irregular focal line, narrower in some places than in others. Mounting two multi-prisms in a single housing allows the two-dimensional lens to align with only a single manipulator, but the fixed position of the multi-prisms with respect to each other rules out optimizing the focus. Cederstrom's original lens doubles the aperture of the lens in Figure 3, with two opposing multi-prisms in each dimension. The two additional multi-prisms, four in total, should give the lens a $4\times$ larger (1 mm by 1 mm) aperture and up to a fourfold gain, from $G \simeq 18$ to perhaps 72 but more likely lower. The gain from such a multi-prism would be comparable to the 50-fold gain of the parabolic lens, but over a larger spot.

CONCLUSION.

Future work should improve lithium manufacture, with as purpose to make lithium x-ray optics approach its theoretical performance. Lithium's corrosion is not a primary issue: the lens in Figure 3, which was made inside a glove box from extruded strips that lack an oxide layer, behaves little better than an earlier lens that may have had an oxide layer.

Probing the lens with a $20 \mu\text{m}$ square beam[9] indicates that the lens is quite good in some places, but not so good in others. X-rays scatter everywhere across the lens, but scattering by itself gives no clue to its origin: possible causes are surface imperfections and non-uniformities in the bulk lithium material. Getting distortion and scattering under control is essential for better lenses.

One issue is fundamental: what is the x-ray optical quality of lithium metal after extrusion and molding? Plastic deformation creates dislocations, which may cause x-ray scattering from nominally uniform material. Good lenses use optical-quality glass that is amorphous, uniform, and stress-free, quite unlike the polycrystalline lithium metal that is forced into the shape desired for x-ray lenses.

Research on lithium's metallurgy[16, 17] emphasizes lithium's unique status as a model for bcc metals. Lithium metal is polycrystalline, fully annealed since lithium's melting point ($T_m \simeq 453 \text{ K}$) is so low that annealing occurs at room temperature (at about $2/3 \times T_m$ for bcc metals). It is not obvious that lithium mistreated by extrusion and molding

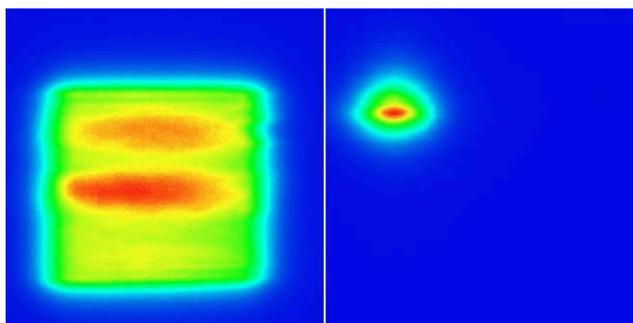


FIGURE 3. Focusing by two multi-prisms under 90° with each other in a single housing.

can have the requisite x-ray optics-quality: this can be verified from the x-ray phase behind two nominally uniform cylinders of lithium with different lengths.

Despite the need for further research to make still better x-ray optics from lithium, the $T \simeq 0.5$ x-ray transmission and 50-fold gain already available from lithium lenses is unquestionably useful for many experiments on the beam line. In particular, lithium lenses are much easier to handle than what was feared earlier: proper packaging guarantees that the lithium lenses behave the same now as when they were made a few years ago.

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REFERENCES

1. S. Suehiro, H. Miyaji, and H. Hayashi, *Nature* **352**, 385 (1991).
2. A. Snigirev, V. Kohn, A. Snigireva, and B. Lengeler, *Nature* **384**, 49 (1996).
3. B. Lengeler, C. G. Schroer, M. Kuhlmann, B. Benner, T. G. Günzler, O. Kurapova, F. Zontone, A. Snigirev, and I. Snigireva, *J. Phys. D: Appl. Phys.* **38**, A218–A222 (2005).
4. B. Lengeler, C. Schroer, J. Tuemmler, B. Benner, M. Richwin, A. Snigirev, I. Snigireva, and M. Drakopoulos, *J. Synchrotron Rad.* **6**, 1153 (1999).
5. B. Cederstrom, R. Cahn, M. Danielsson, M. Lundqvist, and D. Nygren, *Nature* **404**, 951 (2000).
6. E. M. Dufresne, D. A. Arms, S. B. Dierker, R. Clarke, N. R. Pereira, and D. Foster, *Appl. Phys. Lett.* **79**, 4085 (2001).
7. D. A. Arms, E. M. Dufresne, S. B. Dierker, R. Clarke, N. R. Pereira, and D. Foster, *Rev. Sci. Instrum.* **73**, 1492 (2002).
8. N. R. Pereira, E. M. Dufresne, D. A. Arms, and R. Clarke, *Rev. Sci. Instrum.* **75**, 37 (2004).
9. N. R. Pereira, E. M. Dufresne, D. A. Arms, and R. Clarke, *Proc. SPIE* **5539**, 174–184 (2004).
10. J. T. Cremer, H. R. Beguiristain, M. A. Piestrup, and C. K. Gary, *Rev. Sci. Instrum.* **74**, 2262 (2003).
11. C. Young, *Focusing Optics for X-ray Applications*, Master's thesis, Illinois Institute of Technology (2005).
12. E. M. Dufresne, N. R. Pereira, and D. Arms, *Proc. 2003 SRI Conference and AIP Conference Proceedings* **705** (2004).
13. E. M. Dufresne, D. Arms, S. Dierker, R. Clarke, Y. Yacoby, J. Pitney, B. MacHarrie, , and R. Pindak, *Rev. Sci. Instrum.* **73**, 1511 (2002).
14. E. M. Dufresne, N. R. Pereira, D. Arms, and P. Ilinsky, *Proc. 2003 SRI Conference and AIP Conference Proceedings* **705** (2003).
15. W. Jark, *X-Ray Spectrom.* **33**, 455–461 (2004).
16. M. Krystian, and W. Pichl, *Phys. Rev. B* **62**, 13956 (2000).
17. M. Krystian, and W. Pichl, *Materials Characterization* **46**, 1 (2001).