Fabrication and Performance of a Lithium X-Ray Lens

Kristina Young[ac], Ali Khounsary[ac], Andrew N. Jansen[b], Eric M. Dufresne[a], and Philip Nash[c]

[a]*Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439*
[b]*Chemical Engineering Division, Argonne National Laboratory, Argonne, IL 60439*
[c]*Department of Mechanical, Materials, and Aerospace Engineering, Illinois Institute of Technology, Chicago, IL 60616*

Abstract. Compound refractive lenses (CRLs) are arrays of concave lenses whose simple design and ease in implementation and alignment make them an attractive optic to focus x-rays. Factors considered in designing CRLs include lens material, fabrication, and assembly. Lithium is a desirable material because it provides the largest index of refraction decrement per unit absorption length of any solid elements. Lithium is a difficult material to handle and fabricate because it is rather malleable and more importantly, it reacts with moisture, and to a lesser extent, with oxygen and nitrogen in air. It also tends to adhere to molds and dies.

We report on the fabrication and performance of a parabolic lithium lens consisting of 32 lenslets. Lenslets are fabricated in a precision press using an indenter with a parabolic profile and a 100 µm tip radius. The indenter is made of stainless steel and is figured using a computer numerically controlled (CNC) machine. The lens is designed to have a 1.7 m focal length at 10 keV energy. In an experiment conducted at the Advanced Photon Source (APS), a 0.5 mm x 0.5 mm monochromatic undulator beam strikes the lens. A focal length of 1.71, a focal spot size of 24 µm x 34 µm, and a peak intensity gain of over 18 are obtained.

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INTRODUCTION

Compound refractive x-ray lenses have been successfully demonstrated as capable imaging devices that can be employed on synchrotron beamlines in a variety of applications such as x-ray microscopy [1], fluorescence tomography [2], and tomographic absorption spectroscopy [3]. Such applications require high quality lenses that provide short focal lengths and high transmission of the incident x-ray beam. They are also well suited as collimators, providing increased throughput through monochromators with small acceptance angles. Lenses from a variety of materials have been fabricated including aluminum [4], beryllium [5-6], Kapton [7], and lithium [8-10,12]. All lithium lenses constructed to date perform below theoretical expectations, probably due to poor figure and finish characteristics of the lens surfaces. However, lithium has the potential to be competitive with improved fabrication technology.

Lithium is the lightest metal having an atomic number of three and allows a high transmission of x-rays through a given solid thickness. It is the material of choice for x-ray lenses in the moderate (2-15 keV) x-ray energy range because of its high transmission, and its high refractive index decrement. This means that lens-for-lens, a lithium lens has the highest ratio of focusing over absorption than other elemental materials in this range. Lithium hydride has the potential to surpass lithium with regard to absorption but is extremely reactive, brittle, and is typically available as a powder. Figure 1 relays the ratio of the index of refraction decrement over the absorption coefficient for various materials [11]. The short focal lengths afforded by lithium CRLs however, allow their use not only on synchrotron x-ray beams but also potentially on laboratory-based x-ray systems in widespread use worldwide.

The major obstacle to fabricating suitable lithium lenses is that lithium reacts strongly and rapidly with moisture and to a lesser extent with oxygen and nitrogen. Thus, it is necessary to conduct lithium work in a dry environment and preferably in an inert atmosphere (e.g. argon or helium). This has impeded the use of lithium as x-ray lenses. Nonetheless, a number of lithium CRLs has been fabricated [8-10,12].

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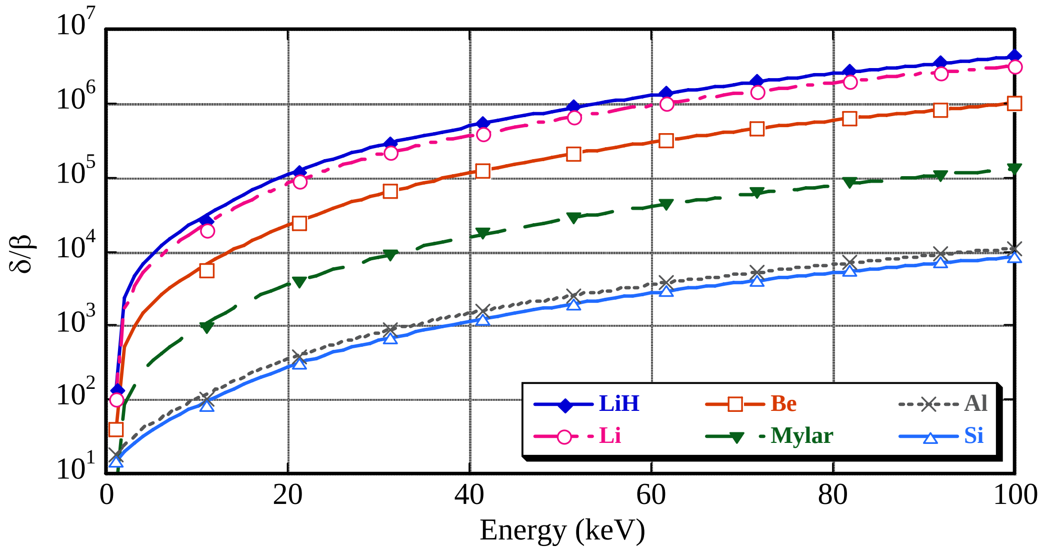

FIGURE 1. Plot of the ratio of the index of refraction decrement over absorption index for several materials.

The first successfully tested lithium CRL [12] utilized a multi-prism (alligator jaw) geometry that was first proposed by Cederstrom [13-14]. This geometry consists of two strips each having a given number of triangular teeth that act as jaws and may open and close to adjust the focal length. At 10 keV, this lithium lens achieved a gain of 3 compared to a theoretical expectation of 4.5, and yielded a focused beam profile with a full-width at half-maximum (FWHM) of 0.18 mm. The gain of a lens compares the peak intensity of an x-ray beam without the lens to the peak intensity in the focus. The shortfall in gain was attributed to the poor surface figure and finish of the die tooling used to press the saw tooth profile into the lithium strips. Lithium CRLs containing an array lenslets with parabolic profiles were then fabricated with radii of curvature at the tip equal to 1 mm [9]. At 8 keV a measured gain of 18.9 was obtained with a theoretical expectation of 47.7, and yielded a FWHM of 43.7 µm. Again the lower value of measured gain was attributed to figure and finish of the pressed lithium lenslets. The latest reported [10] lithium CRLs with parabolic lenslet profiles had radii of curvature at the tip equal to 0.263 mm and obtained a measured gain of 20 to 40 compared to a theoretical gain of 259 and yielded a FWHM of 33 and 17 µm in the horizontal and vertical directions respectively. A consistent theme with the lithium CRLs fabricated to date is that the figure and finish of the lenslets are not adequate to allow the lenses to perform to the theoretical expectations. In addition, no metrology on the lithium lenses has been performed to date. Refinement of the fabrication techniques of lithium CRLs and characterization of the lens surfaces is a necessary step to improve the performance of lithium CRLs.

LITHIUM LENS DESIGN

The design of a lithium compound refractive lens has to account for four major considerations; fabrication techniques that best accommodate lithium's properties, including the figure and finish of the lenslet profiles, the alignment of the lenslets, and the containment of the lens unit as a whole to prevent the degradation of the lithium.

TABLE 1. Lithium lenses and performance published to-date.

Year	Group	E (keV)	R (mm)	F (m)	Ideal Gain	Measured Gain
2005	APS	8	0.1	1.7	770	18.9
2004	Ecopulse	10	0.263	2.13	259	40
2003	Adelphi	8	0.95	0.9	48.8	18.9
2001	Ecopulse	10	saw tooth	8.5	4.5	3

Lithium's reactivity and malleability dictate the techniques that can be employed to fabricate lenslets with a given profile. Conventional machining is not feasible because lithium is too soft and the friction between the lithium and the machining tool would increase the temperature of the lithium causing it to become more reactive. Casting and extrusion also involves heating lithium. A list of results of lithium lenses tested to date is shown below in Table 1. In addition, lithium tends to adhere to dies and tooling, requiring lubricants that would not leave any films or residue that would react with lithium or simply cause added absorption of x-rays. Techniques that have and may be proven feasible include pressing and punching, however, punching is less favorable because it produces lenses that are capable of one-dimensional focusing only.

In this light, pressing is the simplest and most cost effective means of producing high quality lenslets given lithium's properties. By employing pressing, it is possible to impress the lithium with a very accurate spherical or parabolic indenter with good surface roughness characteristics and imprint the figure and finish of the indenter onto the lithium.

Prototype parabolic indenters with tip radii of 0.1 mm have been fabricated using 316 stainless steel with a CNC lathe unit at the Illinois Institute of Technology (See Fig. 2a). These parabolic indenters are mounted on a high precision die set within a small manual-pressing fixture. The rms surface roughness of the parabolic indenters was measured to be approximately 1.6 µm (64 µin), requiring further polishing to improve their surface finish. Mechanical polishing was attempted although the accuracy of the final shape of the machined piece was suspect. Electropolishing was then viewed as the means for achieving the best surface finish on the parabolic tips and was successful using a perchloric ethynol alcohol solution [15]. Using this solution, the finish of the indenters was improved from 1.6 µm (64 µin) to approximately 0.8 µm (32 µin) rms. Better results can be achieved using vendors specialized in electropolishing. Many of the solutions, conditions, and techniques employed in electropolishing materials are patented and trade secrets, making it difficult to achieve optimal results in the first attempt.

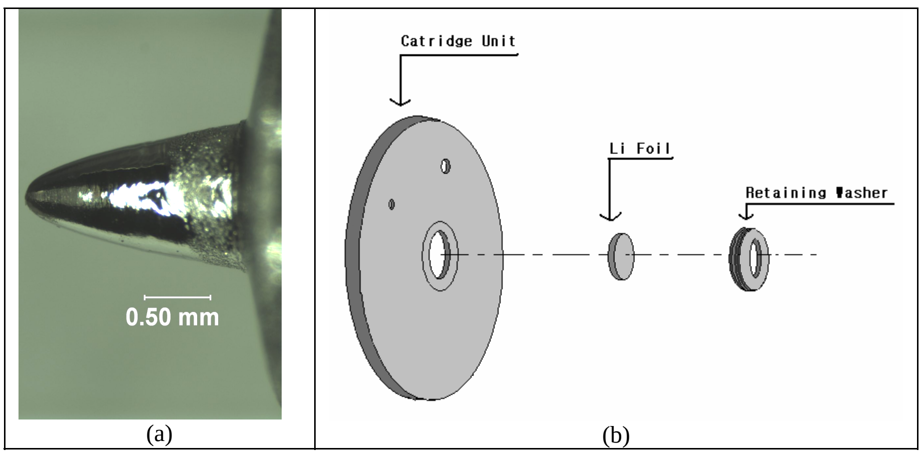

FIGURE 2. Parabolic stainless indenter (a) and the cartridge unit assembly (b) that holds the lithium foil for pressing.

The lithium lens assembly consists of 32 parabolic lenslets with a 100-µm radius of curvature at the tip and a 0.51 mm aperture. Lenslets were fabricated with a 316 stainless steel parabolic tips. This lens design corresponds to a focal length of 1.7 m for 10 keV photons. Individual lenslets are fabricated by cutting lithium foil into small disks, then placing each disk into a cartridge securing it by a retaining threaded washer, and finally loading the cartridge into the pressing fixture to impress the parabolic profiles onto the lithium disk. The cartridge units (See Fig. 2b) serve as protective containers for the lenslets holding the lithium in place during pressing. They further allow for easy assembly and alignment: the cartridges are placed, one by one, onto a pair of long precision pins held in an end cap, The other end is capped when the assembly is completed making the assembly to act as a single rigid body. The entire array is then secured in place within an airtight housing, which has 127 µm (5 mils) beryllium windows on both ends to allow the x-ray beam to traverse through the lens array.

LITHIUM LENS TESTING

The lens assembly is evaluated by measuring the location and size of the focal spot, its transmission, and the gain. The lens was built for use on beamline 7ID at the Advanced Photon Source (APS). The beamline 7ID layout is shown below in Fig. 3. The x-ray beam from APS undulator A has a source size of 270 µm *rms* horizontally and 8.8 µm *rms* vertically. The L5 white beam slit has a 0.5 x 0.5 mm aperture intended to limit the size of the beam. A double crystal Si (111) cryogenically cooled monochromator diffracts a 10 keV x-ray beam, with an energy bandwidth of 1.4 eV. Another slit is placed just before the lithium lens to act as an aperture. Neither slits limit the source size, as viewed by the lens, however.

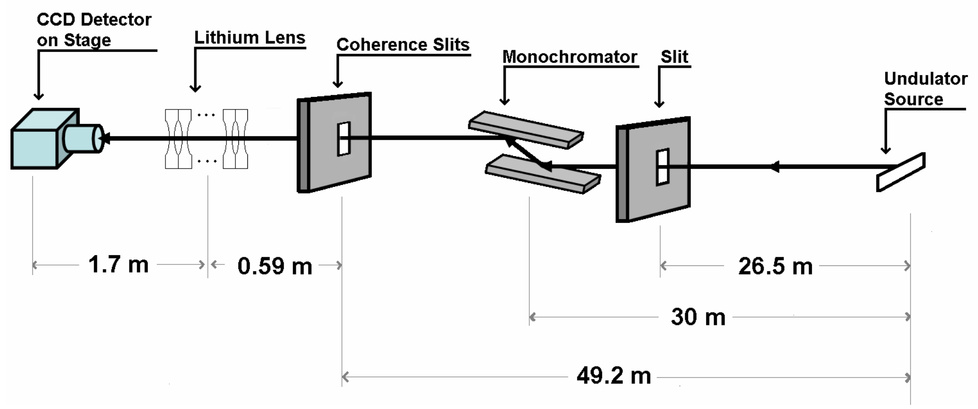

FIGURE 3. Schematic of the APS 7ID layout (not to scale).

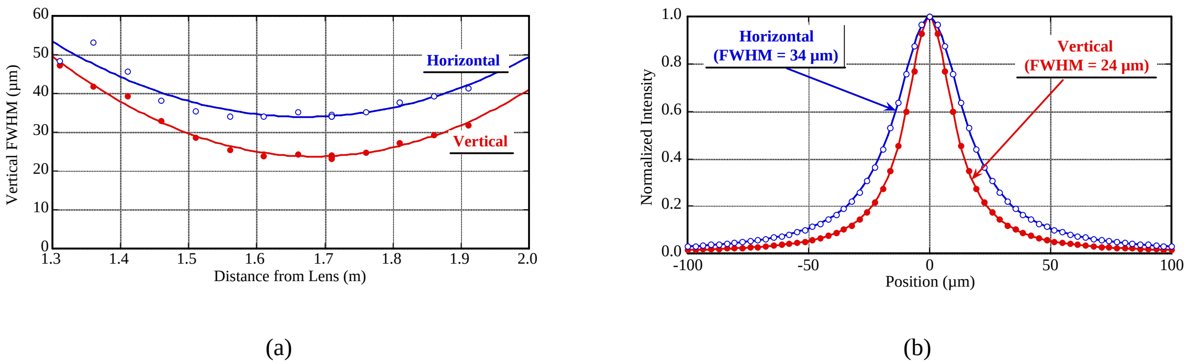

FIGURE 4. Location of focus is identified (a) and its size (b) in the vertical and horizontal directions measured.

The detector on the optical axis consisted of a cerium-doped YAG crystal used as a scintillator and a 12-bit charge coupled (CCD) camera (Photometrics CoolSNAP HQ) equipped with a 2x lens objective [16]. The CCD detector has a 1392 x 1040 pixel imaging array with 6.45 x 6.45 µm pixels. The 2X objective lens increases the camera resolution to 3.23 x 3.23 µm per pixel. The smallest focal spot size was obtained at a focal length of 1.71 m, just 10 mm from the theoretical focal length of 1.7 m (Fig. 4a) by moving the CCD along a slide. The vertical and horizontal full-width at half-maximum (FWHM) was 23.7 and 34.3 µm respectively (Fig. 4b). Theoretical calculations expected a horizontal and vertical FWHM of 0.7 and 22 µm respectively. The image profile conforms best to a Lorentzian fit with the presence of shoulders due to imperfections in the finish of the lens profiles.

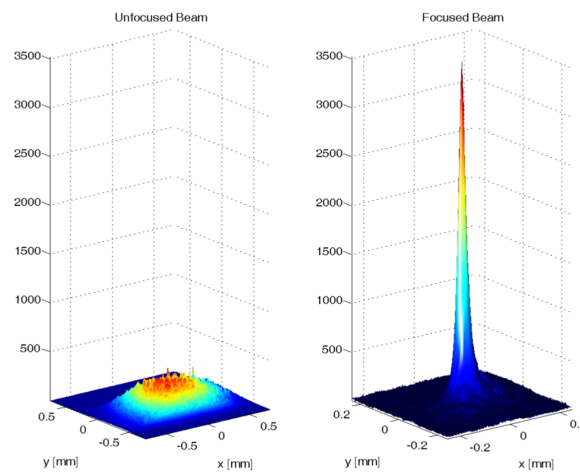

FIGURE 5. Unfocused (left) and focused beam (right) profiles.

Figure 5 compares the size and structure of an unfocused beam with that of a focused beam at the focal spot. The increase in peak intensity between the unfocused and focused beams (gain) was measured to be 18.4. This should be compared with the theoretical value (diffraction limit is ignored for simplicity):

$$G \approx M^2 T \quad (1)$$

Here G represents the gain of the lens, M is the demagnification factor, and T is the lens transmission, ranging from about 98% at the center of the lens to about 85% at the periphery, averaging to about 91% overall. The expected gain from Eq. (1) is about 770. The discrepancy in gain is primarily due to imperfections in the lens surface roughness and profile, which detract form the peak intensity of the beam.

SUMMARY AND CONCLUSIONS

Fabrication of a lithium x-ray assembly using a precision press and robust alignment procedure has been carried out. The results reported here represent the performance of the first generation lithium lens at APS. A FWHM focal size of 24 µm x 34 µm was achieved with a peak gain of 18. Lithium thus remains a viable material for compound refractive lenses and we expect to improve the fabrication process to make better lenses. It is anticipated that imperfections in the lens surface and profile - the primary causes of focus degradation - can be reduced to obtain higher gains / smaller focus. Comparing the expected and measured focal size in the vertical and horizontal directions, it can be concluded that the imperfections in the assembly of 32 lenslets broaden the focal size by about 22-25 µm. Overall, the performance of this lens is comparable with those reported in the literature (Table 1).

Much of the effort in this project was spent on the design of a precision press, the cartridge assembly, and the fabrication and characterization of the indenters. The quality of the first generation indenters was limited by the machine tools used to make the parabolic profile. Improvements will be made using 316 stainless steel indenters and high precision figuring tools followed possibly with eletropolishing if needed. Design for such indenters is currently underway. The results presented here demonstrate the feasibility of lithium lenses with small radii. The next generations of lithium lenses at the APS are expected to approach the performance of compound refractive lenses constructed from aluminum and beryllium.

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