Modeling of a compound imaging system with a curved monochromator and polycapillary optics

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ABSTRACT

Monochromatic x-ray beams improve image contrast but suffer from low intensity if produced with a flat monochromator crystal. A doubly-curved crystal makes more efficient use of the source. However, the beam shape is not conducive to imaging. A combination of a bent crystal followed by a polycapillary optic can be used to monochromatize and focus x rays to a small spot to perform monochromatic x-ray imaging with good resolution. Ray-tracing simulations have been developed which account for defects in both optics types. A comparison was made to measurements of focal spot sizes, angular divergence, and image quality parameters including resolution and contrast. Simulations support the experimental results that geometric blur is significantly reduced, and resolution enhanced, for magnification imaging with this optic combination.

Keywords: doubly curved crystals, polycapillary optics, x-ray imaging.

1. INTRODUCTION

1.1 Experimental Design

A conventional x-ray tube produces a beam that contains a broad spectrum of radiation, including soft x rays that increase the patient dose and hard x rays that give high scattering and poor contrast. Using a monochromatic x-ray beam can enhance contrast in imaging. Monochromatic beams can be produced from a conventional source by diffraction off a monochromator crystal. However, only a small fraction of the incident beam within a narrow range of angles and energies can diffracted from the crystal. This will result in low power density. Further, a flat crystal monochromator results in a beam with low divergence in the plane of incidence, and hence no magnification of the sample.

These shortcomings may be overcome by using a toroidally curved crystal, as shown in Figure 1(a), which can collect and focus x rays from a large solid angle and produce a focused monochromatic beam. Because the optic collects efficiently from a point source, it provides enough intensity for imaging. The divergent beam provides magnification. However, the crescent-shaped output beam, as shown in Figure 1(b), is unsuitable for imaging due to its internal structure.

Figure 1. (a) A toroidally bent, doubly curved crystal collects radiation at the Bragg angle from the source S and focuses it. (b) Output of the bent crystal.
The combination of a polycapillary optic and a doubly curved crystal, as shown in Figure 2, can be used to create a beam suitable for monochromatic x-ray imaging. Polycapillary x-ray optics are made of hundreds of thousands of thin-walled capillary tubes fused into a single bundle. The incident x-ray photons are guided along these micro channels by total external reflection.

1.2 Geometrical Blur from a Point Source

An important consequence of the size of the source or virtual source spot is local divergence, which creates geometric blur in imaging, as shown in Figure 3. The blur $\Delta y$ on a detector a distance $L$ from a point in the sample is

$$\Delta y = 2L \tan \left( \frac{\xi}{2} \right) = W_s \frac{L}{z} \approx L \xi . \quad (1)$$

This limits the image resolution of a point object in the sample to the blur $\Delta y$.

In order to verify the resolution testing for the simulation, at first a simple Gaussian point source was simulated, using the geometry of Figure 4(a). The result for a 4 lp/mm grating (250 μm period), normalized by the no grating photon count in each vertical bin, is shown in Figure 4(b). The contrast is taken as

$$C = \frac{I_{\text{peak}} - I_{\text{min}}}{I_{\text{max}}} , \quad (2)$$
where $I_{\text{max}}$ is 1 due to the normalization and the peak and minimum values are taken as averages over three oscillations of the grid period. The theoretical contrast is

$$C = \exp\left[-\left(\frac{2\pi}{G} \Delta y\right)^2\right], \quad (3)$$

where $G$ is the grid period and $\Delta y$ is the blur. The simulation is in good agreement with the theory, as shown in Figure 5.

Figure 5. Simulated and theoretical resolution for a point source.

2. DOUBLY CURVED CRYSTAL ALONE

2.1 Experimental Measurements

The experimental set up, shown in Figure 2, consists of a conventional molybdenum Oxford Ultra bright microfocus x-ray source with a source size of approximately 100 µm. The doubly curved crystal (DCC) used in the experiment was X-ray Optical System serial number A723, a thin Si 220 crystal designed for use with the $K_{\alpha}$ emission of Mo at 17.5 keV, which has a Bragg angle of 10.6°. The DCC, which was 11.5 mm wide and 45 mm high, was symmetric, with the input and output focal lengths measured to be $191 \pm 3$ mm and $192 \pm 2$ mm respectively. It was comprised of three Si crystals approximating the Johann geometry, with output shown in Figure 1(b).
The output focal spot size of the DCC, shown in Figure 6(a), with profiles shown in Figures 6(b) and 6(c), was measured to be 258 µm x 347 µm, with uncertainties of 50 µm due to the pixel size of the camera used to image the spot.

2.2 Simulation

The simulation is based on simple ray tracing, similar to that used in Shadow. The finite source is modeled by moving an ideal source over a grid of points within a finite radius of the source center. Photons are emitted from the grid point in triplets, two at the Kα₁ energy, and one at the Kα₂ energy. To obtain the best fit, the required crystal bandwidth for optic A723 was 0.050 ± 0.005 °, a factor of three higher than the theoretical crystal bandwidth. A possible explanation is a manufacturing defect which has created incorrect angular displacement between the three crystal segments shown in Figure 1(b). This is supported by powder diffraction data taken with this optic, which showed significant resolution degradation if multiple optic segments were illuminated. The simulated focal spot is shown in Figure 7.

The width is quite narrow across the center, but the overall size of the simulated spot that is consistent with the measured size when taking into account the “x” shaped halo surrounding it. A simulated image from a 4 lp/mm grating placed 24 cm beyond the focal spot, with a detector distance of 70 cm, is shown in Figure 8(a). Surprisingly, the contrast is quite high, which is unexpected for the large spot size. An explanation for this may be in the unusual correlation between ray position and velocity, as shown in Figure 8(b).
The unexpectedly low geometric blur makes these optics interesting for magnification imaging, but the high degree of internal structure in the beam makes them difficult to use. An actual image of the resolution phantom of Figure 9(a) is shown in Figure 9(b). At larger distances the image becomes difficult to resolve.

### 3. POLYCAPILLARY OPTIC

In order to improve the beam shape, a polycapillary optic was added to the set up, as shown in Figure 2.

#### 3.1 Measurements

The focusing polycapillary used in the experiment, XOS 3204, was placed after the DCC so the output focal spot of the DCC would serve as its input. It has input and output focal distances of $f_{in} = 52$ mm and $f_{out} = 50$ mm, input and output radii of $R_{in} = 1.05$ mm and $R_{out} = 0.9$ mm, and is encased in an L=80 mm long metal casing. The channel diameter of the capillaries is 6.2 µm. The spot size of the polycapillary expected to be

$$d_{spot} \approx \sqrt{c^2 + (1.3 \cdot f \cdot \theta_c)^2} \approx 110 \mu m,$$

where $c$ is the channel diameter, $f$ is the focal length, and the critical angle of grazing incidence is

$$\theta_c \approx 30 \text{ keV mrad/E} \approx 1.7 \text{ mrad}$$

for Mo Kα1. The actual spot of the polycapillary when placed after the DCC was measured to be 120 µm x 122 µm, with uncertainties of 22 µm, the pixel size of the camera used to image the spot. An image of this spot is shown in Figure 10.
3.2 Simulation

The simulation for the polycapillary optic is a simple ray tracing Monte Carlo code written in Visual Basic for ease of modification. It models a focusing optic in two parts: a collimating lens attached to focusing lens as shown in Figure 11. The simulation requires two parameters which may not be specified by the manufacturer. The first is the total the maximum radius of the glass, which is also the radius at the artificial division, \( R_{\text{mid}} \). The second is the distance, \( d \), from the front face to this artificial division.

Making simple assumptions about the optic shape and continuity, the length, \( d \), of the collimating lens portion is

\[
d = \frac{f_{\text{in}} \left(3 R_{\text{out}} f_{\text{out}} + 2 R_{\text{out}} L - 3 R_{\text{in}} f_{\text{out}}\right)}{2 \left(R_{\text{in}} f_{\text{out}} + R_{\text{out}} f_{\text{in}}\right)},
\]

where the parameters were defined in the previous section. The output radius of the collimating part is

\[
R_{\text{mid}} = \frac{R_{\text{in}} R_{\text{out}} \left(2L + 3 f_{\text{in}} + 3 f_{\text{out}}\right)}{3 \left(R_{\text{in}} f_{\text{out}} + R_{\text{out}} f_{\text{in}}\right)}.
\]

4. Resolution of the Combined System

The combination of the two optics yields a much smoother virtual source, as the crescent is smoothed out into an oval, shown in Figure 12.

A resolution phantom was placed 240 mm from the polycapillary focal point and images were taken at various distances from the phantom. The resulting contrast is shown in Figure 13. Unlike either the case of Figure 5, or the theoretical calculation, the contrast is high at large distances. The contrast actually increases with distance, presumably because Compton scatter from the glass phantom decreases the contrast when the object is close to the...
detector. However, a preliminary measurement of the contrast with the bars placed horizontally agrees more closely with the theoretical expectations, as shown in Figure 14.

5. DISCUSSION AND CONCLUSIONS

The local divergence is the range of positions on the source that are seen at a point on the optic. For a point source, this is the full diameter of the source at every point on the object, as shown in Figure 15.

For the curved crystal, the distribution at the center of the detector is quite narrow, as shown in Figure 16. This may contribute to some apparent lack of geometrical blur and enhanced image resolution.

Figure 13. Contrast of the image of the resolution phantom as a function of distance between the sample and the detector. The black squares are the measured data. The red dashed line is the computed effect of the increasing magnification on the resolution due to the finite pixel size. The blue dotted line shows the expected effect of the increasing geometrical blur. The product of these two effects is shown as the solid purple line.

Figure 14. Measured horizontal contrast does not increase with distance.

Figure 15. Simulated source locations for rays hitting at various detector positions, for a 200 mm diameter Gaussian point source.
Figure 16. (a) Horizontal position on the source from which the ray originated vs horizontal location on the detector, for the doubly curved crystal simulated optic. (b) Vertical source origin point as a function of the vertical position on the detector for the doubly curved crystal optic

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7. REFERENCES


