Applications of x-ray magnifier and demagnifier to angle-resolved x-ray computed tomography

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Abstract. We have introduced an x-ray magnifier and demagnifier into angle-resolved x-ray computed tomography to improve the spatial resolution and viewing field. From a practical application viewpoint, we have adopted one-dimensional optics rather than two-dimensional optics. A spatial resolution of 4 μm was realized at the bending-magnet beamline BL-15C of the Photon Factory. Both phase-contrast and apparent-absorption-contrast tomograms were successfully obtained at a magnification ratio of 20 at the vertical-wiggler beamline BL-14B. The apparent-absorption-contrast tomogram was observed to be clearer than the phase-contrast tomogram. Furthermore, phase-contrast and apparent-absorption-contrast tomograms for a sample larger than the viewing field of the x-ray CCD camera were successfully obtained by utilizing the x-ray demagnifier.

1. Introduction
X-ray phase-contrast imaging is a powerful method for observing the inner structure of biological and soft materials because it has a much higher sensitivity to low-Z elements such as carbon, nitrogen, oxygen, and sulfur than conventional absorption-contrast methods. At the Photon Factory (PF), two x-ray phase-contrast imaging techniques are mainly used: an interferometer-based method which is sensitive to the phase shifts produced by a sample [1, 2], and an analyzer-based method which is sensitive to the phase gradients (i.e. refractions) caused by a specimen [3]. In general, the former has a higher sensitivity than the latter, while the latter can cover a wider variety of samples than the former. In these methods, the spatial resolution is usually limited by the pixel size of the x-ray area sensor. Furthermore, the sample size is also limited by the viewing field of the x-ray camera. To solve these problems, we have introduced an x-ray magnifier and demagnifier into angle-resolved x-ray imaging and have successfully improved the spatial resolution and viewing field [4, 5]. In our previous research, the magnification ratio, m, was rather low (m = 5.47) and only phase-contrast tomograms were reconstructed [5]. In this paper we show results obtained at higher magnification ratios for both phase-contrast and apparent-absorption-contrast images to demonstrate the performance of the x-ray magnifier.

2. Principle of x-ray magnifier and demagnifier
In analyzer-based phase-contrast imaging, such as angle-resolved x-ray imaging, symmetrically cut crystals are often used for the analyzer. Magnification or demagnification of a sample image is easily realized by replacing the symmetrically cut analyzer with an asymmetric analyzer [5]. Figure 1 shows...
a schematic of the magnification and demagnification process. Note that magnification or
demagnification takes place in the plane that includes the incident beam and relevant reciprocal vector.
Then, \( m \) is given by

\[
m = \frac{\sin(\theta_B + \alpha)}{\sin(\theta_B - \alpha)}
\]

where \( \theta_B \) is the Bragg angle and \( \alpha \) is the angle between the crystal surface and diffracting plane. The
sign of \( \alpha \) is positive in Fig. 1 (a) and negative in Fig. 1(b), and \( m \) is tuneable through the wavelength
and angle \( \alpha \).

Figure 1. The process of (a) magnification and (b) demagnification.

Although Figure 1 shows only one-dimensional modifications, two-dimensional modifications can
also be realized by utilizing a pair of asymmetric crystals, where the diffraction plane of the second
crystal is perpendicular to that of the first. The throughput of this arrangement, however, is usually
very low and not suitable for practical use due to the narrow acceptance width in the horizontal plane.
Because of this disadvantage, we adopted the one-dimensional magnification–demagnification optics,
but we expect that two-dimensional magnification will become very useful at linac-based x-ray
sources such as x-ray free-electron lasers (XFELs) [6] and energy recovery linacs
(ERLs) [7], which can produce diffraction-
limited x-rays in both the horizontal and
vertical directions.

In practice, the achievable resolution is
limited by several factors such as the source
size, distance between the source and sample,
and pixel size of the camera. X-ray
penetration into the magnifier is also a spatial-
resolution limiting factor. Blurring of the
image due to this effect is usually on the order
of several micrometres but can be suppressed
by utilizing an extremely asymmetric
reflection where the penetration depth
becomes as small as several tens of
nanometres [8].

Figure 2. Estimated spatial resolution
obtained with the x-ray magnifiers.
3. Experiment and results

We first estimated the spatial resolution achieved with the asymmetric Si (220) magnifiers ($\alpha = 8^\circ$, $10^\circ$, and $14^\circ$) at the bending-magnet beamline BL-15C at the PF. Vertically magnified absorption-contrast images of x-ray test charts were observed with an x-ray CCD camera that consisted of a GdO$_2$:Tb scintillator, glass fibre plate, and CCD. The effective pixel size was 23 $\mu$m (H) $\times$ 23 $\mu$m (W). The spatial resolution was estimated from the modulation transfer function (MTF) as shown in Fig. 2; the spatial resolution was about 60 $\mu$m at $m = 1$, and the best resolution of 4 $\mu$m was obtained at $m = 40$ and $m = 80$, where the spatial resolution was limited mainly by the source size and x-ray penetration.

We then performed angle-resolved x-ray computed tomography (CT) experiments at the vertical-wiggler beamline BL-14B. The x-ray wavelength was set to 0.102 nm, and the top-view of the experimental setup is shown schematically in Figure 3. Samples were placed between the two main optical elements: a collimator and analyzer. To maximize the throughput and angular-resolution, the collimator, an asymmetric Si (220) crystal ($\alpha = 8^\circ$), and analyzer were arranged in the non-dispersive setting. The asymmetric collimator was used to expand the beam in the horizontal direction. To magnify the sample image, an asymmetric Si (220) analyzer ($\alpha = 14^\circ$, $m = 20$) was used. Sample images were observed using the same x-ray CCD camera.

![Figure 3](image)

**Figure 3.** The top-view of the experimental setup for the angle-resolved x-ray CT.

We used the analyzer scanning method to obtain both phase-contrast and apparent-absorption-contrast images. The samples were rotated around the vertical axis from 0° to 180° in steps of 0.72°. At each angle, 16 images were recorded by the x-ray CCD camera, rocking the analyzer through the Bragg diffraction condition in 1.0 arcsec steps. The exposure time for each image was 2 s. Figure 4 shows tomograms of the stalk of *Miscanthus sinensis*, which were much clearer than those obtained at $m = 1$. This result shows that one-dimensional magnification is quite useful for angle-resolved x-ray CT. Another interesting point is that the apparent-absorption-contrast image is clearer than the phase-

![Figure 4](image)

**Figure 4.** Magnified $m = 20$ (a) apparent-absorption-contrast and (b) phase-contrast tomograms of the stalk of *Miscanthus sinensis*.  

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*Figure 4.* Magnified $m = 20$ (a) apparent-absorption-contrast and (b) phase-contrast tomograms of the stalk of *Miscanthus sinensis*.  

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contrast image. This is because the apparent absorption contrast includes, strictly speaking, the phase contrast, absorption contrast, and scattering contrast.

We also performed angle-resolved x-ray CT experiments using a demagnifier ($m = 0.49$). The sample was an acrylic tube with a diameter of 10 mm. It is worth noting that it was almost impossible to carry out a tomographic reconstruction with the symmetric analyzer ($m = 1$) because the sample was larger than the viewing field of the x-ray CCD camera. By using the demagnifier, both phase-contrast and apparent-absorption-contrast tomograms were successfully obtained as shown in Figure 5.

![Figure 5. Demagnified $m = 0.49$ (a) apparent-absorption-contrast and (b) phase-contrast tomograms of an acrylic tube.](image)

4. Summary
An x-ray magnifier and demagnifier were successfully applied to angle-resolved x-ray CT to improve the spatial resolution and viewing field. From a practical application viewpoint, we adopted one-dimensional optics rather than two-dimensional optics. A spatial resolution of 4 $\mu$m was realized at the bending-magnet beamline BL-15C of the PF, and both phase-contrast and apparent-absorption-contrast tomograms were successfully obtained at a magnification ratio of 20 at the vertical-wiggler beamline BL-14B. We observed that the apparent-absorption-contrast tomograms are clearer than the phase-contrast tomograms. Furthermore, phase-contrast and apparent-absorption-contrast tomograms for a sample larger than the viewing field of the x-ray CCD camera were successfully obtained by utilizing the x-ray demagnifier ($m = 0.49$).

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