A Condenser Scanner for Artifact-Free, Large Field of View, Full-Field X-ray Microscopy at Synchrotrons

J. Rudati\textsuperscript{a}, J. Irwin\textsuperscript{a}, A. Tkachuk\textsuperscript{a}, J. C. Andrews\textsuperscript{b}, P. Pianetta\textsuperscript{b}, and M. Feser\textsuperscript{a}

\textsuperscript{a}Xradia Inc., 5052 Commercial Circle, Concord, CA 94520, USA
\textsuperscript{b}SLAC, Menlo Park, CA 94025, USA

Abstract. Most full-field microscopes at synchrotrons exhibit a highly peaked illumination in the center of the field of view for stationary condenser and objective optics. This illumination pattern is typically reference-corrected by division with an image without the sample to correct for the uneven illumination. However, this correction does not rectify problems such as the poor signal-to-noise ratio away from the center and the variation in image quality across the field of view due to the unbalanced illumination. These non-uniformity issues affect imaging strategies that stitch several fields of view together as is needed for large samples. We present the implementation of a condenser scanner that time-averages the illumination on the sample, leading to vastly improved image uniformity and the avoidance of image artifacts.

Keywords: Condenser scanner, nano-CT
PACS: 68.37, 07.85

INTRODUCTION

Synchrotron x-ray microscopes have an x-ray illumination system (synchrotron beamline and microscope condenser optic) that produces an uneven and quite often peaked profile, as shown in Fig. 1(a). The reason for this is the high degree of collimation of the synchrotron beams that result in very small focal spots when focused by the condenser lens. We have developed a capillary condenser scanner for distributing the illumination evenly over large fields of view (Fig. 1(b)). The scanner physically translates the condenser parallel to the beam axis vertically and horizontally in a predetermined Lissajou pattern. Since there is no absorbing material introduced in the beam path (as with a rotation diffuser used in many x-ray microscopes [1]), there is no attenuation. The full incoming beam is used to illuminate the sample. Coherence artifacts are eliminated by time-space averaging both the focal spot intensity and the distribution of the angular components of the incoming beam. This results in a time-averaged illumination pattern that is very even in intensity and produces a faithful image of the sample without shadowing artifacts, which are common when the angular distribution in the illumination is not balanced.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Illumination patterns (a) highly peaked with the scanner OFF; (b) enlarged and smoothened with the scanner ON. Exposure time: 1 second; photon flux: \( \sim 7 \times 10^9 \) x-ray photons/s incident on camera; photon energy: 9 keV.}
\end{figure}
CON DENSER SCANNER DESIGN

The optical setup of a transmission x-ray microscope (TXM) is analogous to that of an optical microscope (Fig. 2(a)). A zone plate or a reflective capillary condenser is used to focus an x-ray source (from a synchrotron or otherwise) onto the sample field of view (FOV) [2]. The objective lens (a gold zone plate) produces a magnified image of the specimen on an x-ray camera.

![Image of optical setup](image)

**FIGURE 2.** (a) Optical setup of a transmission x-ray microscope – not to scale. (b) Typical condenser chamber holding four condensers.

In the x-ray microscope on SSRL’s beamline 6-2 ([3, 4]), the capillary condensers are cylinder shaped, can be up to 170 mm long, and are about 3 mm in diameter (see Fig. 2(b)). The dimensions vary with the source, energy used, and imaging mode. The condenser is scanned in order to more evenly distribute the focused x-rays on the sample [5]. To avoid a misalignment caused by the scanner, the goal is to scan the capillary condenser vertically and horizontally while keeping it parallel with the incoming beam (no yaw or pitch rotations). This is achieved by using a stiff flexure design [6] (with two piezoelectric actuators on each corner) for each axis (Fig. 3). The flexures are attached to the condenser chamber, appropriately keeping in mind the center of mass.

![Image of design drawings](image)

**FIGURE 3.** Design drawings showing stiff scanner flexures (with the four piezoelectric actuators) holding the condenser chamber.

**Scanning Parameters**

The signal that drives the piezoelectric actuators is carefully controlled. The oscillation’s peak-to-peak amplitude must be slightly smaller than the FOV so that no flux is wasted. At SSRL’s 6-2 beamline the oscillation is 30 μm for a FOV of 34 μm. The frequency depends on the exposure time (which is determined by the sample composition and
thickness). For every image, an integer number of oscillations of the scanner must be completed. A Lissajous pattern is used with horizontal frequency typically of 5 Hz and vertical frequency of 4 Hz and a 90° phase offset. This corresponds to a minimum cycle time of 1 s. Hence, exposure times must be a multiple of 1 s. This scanning pattern was chosen because it matches well the square shape of the camera’s chip (Fig. 4).

![Figure 4. Lissajous pattern driving the scanner shown in an oscilloscope.](image)

**Scanner Limitations**

The scanner’s maximum frequency of 30 Hz limits the minimum exposure time to 200 ms for the scanning pattern presented in this paper. This is not yet a problem since typical exposure times are larger. The maximal field of view can be as high as 100 μm with appropriately designed optics. Finally, for other imaging modes like Zernike phase contrast (ZPC) care must be taken to keep the scan range small enough to not affect imaging performance. For ZPC this means that the overlap of the illumination and the phase ring must be maintained.

**IMAGES AND RESULTS**

The scanner enables a large field of view mode. Currently a 34-μm field of view (with a 2k × 2k camera) is easily achieved at SSRL’s BL 6-2. Without the scanner, 16 μm was the maximum useable field of view with severe intensity drop-off at the edges. As one would expect, scanning the condenser does not affect the microscope’s resolution, as shown in Fig. 5. In this example, the zone plate used has a 30-nm outermost width and 11% diffraction efficiency. The overall magnification is 500 (50 x-ray, 10 visible). The exposure time is 0.5 seconds and the x-ray photon flux is $2 \times 10^{10}$ photons/s on the camera.

![Figure 5. X-ray microscope image of the star test pattern (200-nm-thick gold imaged at 9 keV) taken with scanner on shows artifact-free imaging and evenness of contrast and 30-nm resolution or better (Star’s finest feature size is 30 nm in the pattern and diameter is 30 μm).](image)

The scanner’s main goal is to spread the available illumination over a larger field of view in order to have an even signal-to-noise ratio (SNR). This ensures equivalent detectability of faint features in the whole image. It is also helpful for proper flat-field correction, lessens the effect of unstable beamline optics, and enables sample density calculations.

Figure 6(c) shows the SNR vs pixel of the illuminating beam with the scanner OFF. The per pixel average and variance is computed from 100 images taken with exposure time of 1 s. As expected, the large variation closely follows the illuminating beam (Fig. 6(a)). A much more even SNR is obtained throughout the whole field of view with the scanner ON as shown in Fig. 6(d). Faint indications of ‘hot spots’ (or areas with more illumination) are still
visible. These are caused by the Lissajou pattern crossing over its own path or slowing down at the turning points in the corners.

![SCANNER OFF and ON Mean Counts](attachment:fig6.png)

**FIGURE 6.** Illumination and SNR for images with the scanner off and on. Images (a) and (b) are the average of 100 images. Images (c) and (d) are the mean/variance of each pixel. (a) and (c) correspond to the scanner OFF and (b) and (d) to the scanner ON.

**CONCLUSIONS**

A condenser scanner has been developed to precisely reproduce and quickly paint the x-ray beam focused by a condenser optic in the sample plane to fill the image field without the absorptive losses of a diffuser. It has been shown that a constant SNR can be maintained over the whole field of view. The time-space averaging nature of the scanner eliminates image artifacts typically seen when the angular distribution in the illumination is not balanced within the field of view. The scanner can also time/space average the speckles produced by coherent beams. The homogeneous illumination produced allows proper flat-field correction of the images, lessens the effect of unstable beamline optics, and is therefore key for accurately measuring the optical density of a material and for finding faint features equally across the whole field of view.

**ACKNOWLEDGMENTS**

The authors would like to acknowledge and thank Michael Bajura and Gregory Boverman for their significant contributions to this paper.

**REFERENCES**

2. A. Tkachuk et al., Z. Kristallogr. 222, 650 (2007).
6. Xradia Inc. module. 4385 Hopyard Road, Suite 100, Pleasanton, CA 94588.