Microfocusing of 50 keV Undulator Radiation with Two Stacked Zone Plates

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Introduction

The success of high-spatial-resolution studies of materials with micron-sized x-ray beams at third-generation synchrotron facilities is due to the radiation brilliance of undulator sources combined with the availability of microfocusing optics such as Fresnel zone plates, compound refractive lenses, and Kirkpatrick-Baez mirrors. Although the focusing of x-rays to micron and even submicron dimensions is currently routine [1], it is so primarily at lower energies (< 20 keV), and not at higher energies (40–100 keV) where x-ray optics generally tends to become more challenging due to the sub-angstrom wavelengths. Motivated by possible applications such as trace heavy-element detection by K-shell spectroscopy, fluorescence from dense materials, and bulk microdiffraction for stress measurements, an attempt to focus 50 keV undulator radiation using two, closely juxtaposed zone plates was carried out and is reported here. Since the fabrication of zone plates puts limits on the thickness of the refractive material on the alternate, thick circular zones, and given that the π-rad refractive phase shift desired for maximum efficiency requires greater thickness at high energies, the stacking of more than one zone plate is necessary to increase focusing efficiency. The technical challenge of implementing such a scheme is achieving the required submicron relative alignment stability to make the two (or more) zone plate elements act as one.

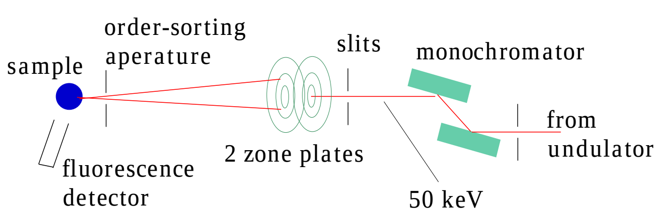

Figure 1: Illustration of the microfocusing setup at the 1-ID beamline.

Stacked Zone Plate Setup and Performance

The microfocusing optics configuration is sketched in Fig. 1. The 50 keV undulator radiation incident on the zone plates was delivered by a Si(111) double-crystal monochromator. The focal spot coincided with the sample position and was located 1 m downstream of the two zone plates, separated by a few millimeters, which in turn were positioned 60 m from the source. An small order-sorting aperture, immediately before the sample, isolated the first-order focal spot from the zone plates.

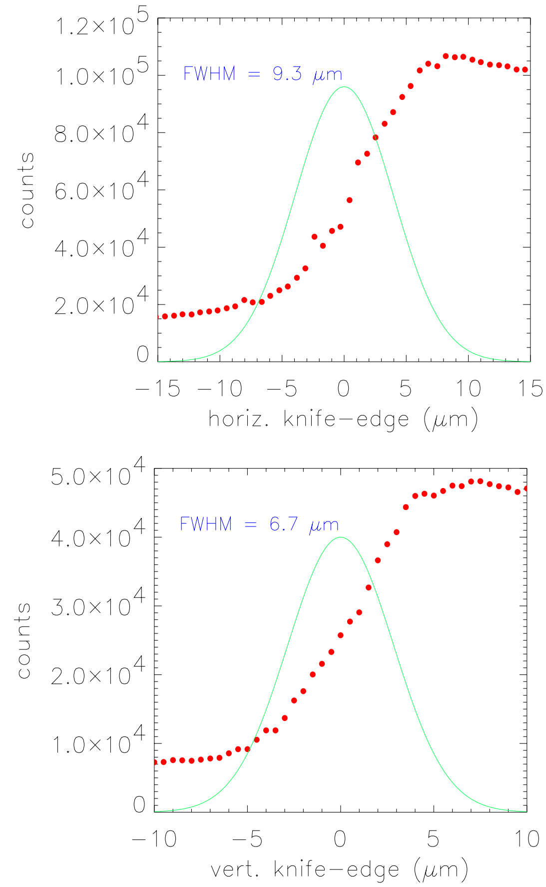

Figure 2: Horizontal and vertical focal spot profiles measured with Au knife-edge fluorescence scans.

For a typical fabricated zone plate consisting of a Si substrate and where the material deposited for the alternate retarding zones is Au, the optimal Au thickness (giving π-rad shift) for 50 keV is 9.8 μm. Since the production of 9.8-μm-thick structures having sub-μm transverse extents, as required for the outermost zones in a device of reasonable spatial acceptance, is prohibitive due to the aspect ratio, two zone plates were employed, each one having retarding zones of 3.3-μm-thick Au. The resulting doubled thickness of 6.6 μm, still being insufficient to provide constructive focal interference between the open and retarding zone sets, should result in a slightly decreased efficiency that is .76 of the optimum efficiency (associated with 9.8-μm thickness, keeping other parameters unchanged). However, the use of a single, 3.3-μm-thick Au zone plate at 50 keV should result in a considerably re-

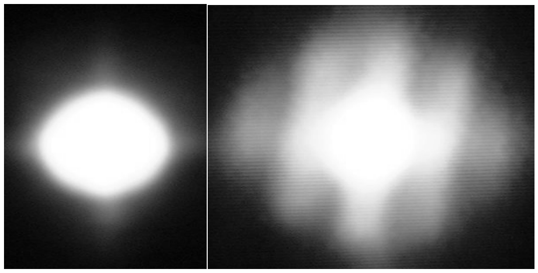

Figure 3: View of beam beyond the focus with the two zone plates perfectly aligned (left) and slightly misaligned (right) by a few hundred nanometers.

duced efficiency that is .26 of the efficiency from optimum thickness.

The two, identical zone plates had a compound structure, meaning that each consisted of an inner and outer family of zones geometrically laid out so that the first-order focal spot from the inner family gets diffracted to the exact same location as the third-order spot from the outer family. The inner-zone family occupied an 80-μm-diameter region, and the outer family filled an annular region extending from 80- to 200-μm diameter. The calculated diffraction efficiencies for these two separate zone families, treating the stacked system as one, are 30% and 3.3%, for the first- and third-order parts, respectively. But since the third-order set of zones occupies over five times the area as the first-order set, the proper area-weighting gives the stacked pair an overall efficiency of 7.5%, meaning that of the x-ray flux intercepted within the 200-μm outer diameter, 7.5% gets directed to the focal spot. The measured efficiency was 4.7%, with a flux of 3×10^8 ph/s at the focus.

Based on a 60:1 demagnification of the source, the expected size (FWHM) of the focal spot is 14 μm horizontally and 1 μm vertically, not quite in agreement with the knife-edge scan measurements (Fig. 2) which gave 9 and 7 μm, respectively. The discrepancy is particularly large in the vertical dimension, and could be due to a combination of mechanical vibrations and the distortion of the source's vertical brilliance by the vertically diffracting monochromator subject to the high heat load of closed-gap undulator radiation.

The measured efficiency and spot size together imply a flux density gain of 24, a figure of merit quantifying the flux in the focal spot normalized relative to the flux one would get through an aperture having the focal spot size, but without any focusing optics.

In order for the two zone plates to behave as one, the second zone plate must be placed well within the near-field diffraction distance of the first, and their relative transverse positions must be adjusted properly to within a few hundred nanometers so as to directly line up the zones of the two elements. The system of motion stages used to execute such precise alignment and provide the desired stability over many hours will be described elsewhere. The operational determination of the exactly aligned condition was done visually (see Fig. 3), by looking at the CCD camera image of the beam striking a scintillating crystal a few meters downstream of the rest of the setup, taken through a magnifying microscope objective. When the two zone plates are nearly perfectly aligned, the image shows an interference fringe pattern, with the fringe spacing becoming infinite as the stacking alignment becomes perfect.

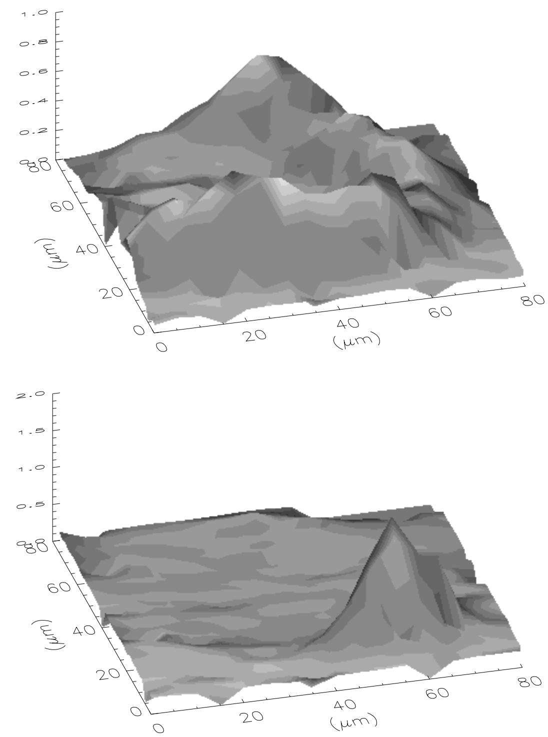

Figure 4: Fluorescence determination of the distributions of La (top) and Zr (bottom) within a small inclusion in mica.

The microfocusing setup was used to obtain a two-dimensional fluorescence map of a geological specimen consisting of a small, rare-earth-rich inclusion in a cleaved slice of natural mica. The distributions of La and Zr concentrations measured by their K-fluorescence are shown in Fig. 4.

The assistance of A. Mashayekhi, J. Pollmann, and A. Pyzyna is acknowledged. Use of the APS was supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under Contract No. W-31-109-Eng-38.

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