Sub-micrometer focusing of intense 100 keV X-rays with multilayer reflective optics

High-energy X-rays serve as powerful tools for the non-destructive analysis of thick heavy metals, devices enclosed in protective casings, and materials subjected to high-pressure conditions. For high-energy X-ray applications, such as transmission X-ray imaging, X-ray fluorescence spectroscopy, and total-scattering measurements with pair-distribution function analysis, an incident X-ray beam with a high-energy resolution below 0.1% is not required. Instead, a "pink" beam with a moderate energy resolution of 1–10% is preferred, as it enhances photon flux. Focusing such a high-flux beam on a small region enables analysis with high spatiotemporal resolution.

Several types of devices have been developed to focus high-energy X-rays above 50 keV, including Fresnel zone plates (FZPs), multilayer Laue lenses (MLLs), compound refractive lenses (CRLs), and total-reflection Kirkpatrick–Baez (K–B) optics. Both FZPs and CRLs are on-axis devices that maintain a simple optical geometry; however, they exhibit chromatic aberration, which reduces throughput. MLLs offer high diffraction efficiency and a small focal spot size but are also subject to chromatic aberration and have a small acceptance aperture. We note that the chromatic aberrations of these devices are proportional to the photon energy E (E^2) for the FZPs and MLLs (CRLs), which limits the ability to generate a small, intense focus with a pink beam due to constraints on the numerical aperture (NA). While total-reflection K–B optics exhibit achromatic properties, their critical angle decreases significantly for high-energy X-rays, leading to reduced spatial acceptance and low throughput. In contrast, multilayer K–B optics can be designed to accommodate a reasonably wide bandwidth of a few percent at a specific photon energy, facilitating the generation of an intense, small focus with large spatial acceptance, large NA, and high reflectivity.

In this study, we developed a 100 keV K–B focusing system comprising laterally graded multilayers deposited on high-precision figured mirrors [1]. The focusing mirror system features a wide bandwidth of 5% and a high peak reflectivity of 74%. The system's performance was evaluated at the undulator beamline SPring-8 **BL05XU** [2], which generated an intense 100 keV X-ray beam with a bandwidth of 1%.

Figure 1 illustrates the layout of the main optical components within the optics hutches (OH1 and OH2). In this study, the 19th harmonic of the 5.3 keV fundamental radiations, with an energy width of 0.93%, was utilized. The entire spectrum of the 19th harmonic was extracted using a double multilayer monochromator (DMM). To suppress the total-reflection low-energy component (< 30 keV) reflecting from the DMM, attenuators were employed. As shown in the bottom left of Fig. 1, a photon flux of 3 × 10^{13} photons/s with an energy bandwidth of 1% was achieved at 100 keV.

We designed laterally graded multilayer focusing mirrors (Fig. 2) with a $[W/C]_{50}$ coating to generate a sub-micrometer beam in the vertical direction. A comparable size in the horizontal direction was

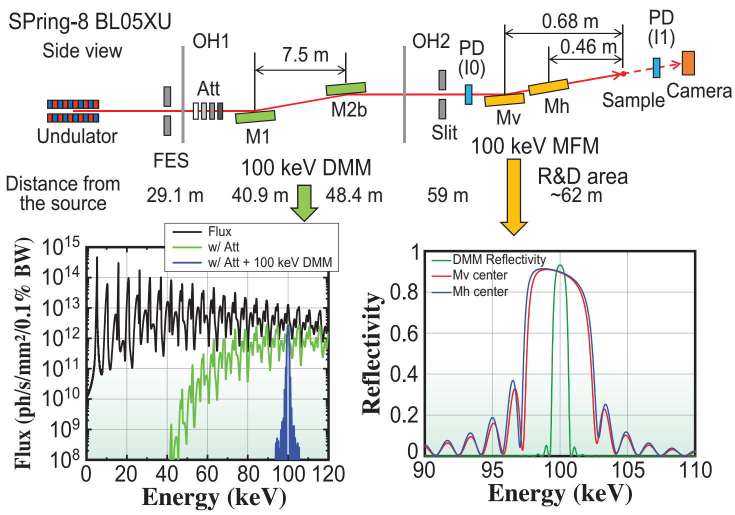

Fig. 1. Layout of the main optical components in the optics hutches (OH1 and OH2) at BL05XU. FES: front-end slit, Att: attenuators, DMM: double multilayer monochromator, MFM: multilayer focusing mirror, and PD: photo diode detector. Bottom left: The calculated undulator spectrum, along with attenuators, and DMM. Bottom right: Reflectivity curves of the DMM, vertical (Mv) and horizontal (Mh) focusing mirrors.

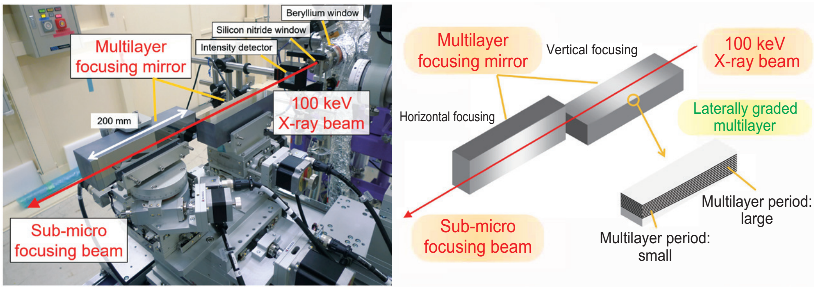

Fig. 2. Photograph and schematic of the developed 100 keV multilayer focusing mirrors.

achieved by restricting the horizontal size of the front-end slit (FES), which acted as a secondary source. The multilayer focusing mirror was designed with a bandwidth of approximately 5% along its entire length to fully encompass the DMM bandwidth (1%), as shown in Fig. 1 (bottom right), while allowing sufficient tolerance for potential alignment and/or multilayer deposition errors.

The mirror substrate surfaces were finished by JTEC Corporation, while the multilayer coatings were deposited at our SPring-8 in-house laboratory. The deposition system, based on DC magnetron sputtering, was designed to coat substrates up to 600 mm in length and 50 mm in width. To achieve uniform long coatings and thickness gradients, the substrates were moved in front of the sputtering sources during deposition. The multilayer deposition process had an error margin of approximately ±1%, which was acceptable given that the reflection energy width of the multilayer was as wide as 5%.

The focusing mirrors were installed in OH2, as shown in Fig. 2. The mirror system operated in an atmospheric environment without a vacuum or gas chamber. We evaluated the system's performance by measuring reflectivity, focusing beam size, and photon flux. The peak reflectivity was 74% for two bounce reflections. The beam profiles of the focusing beams were characterized using the knife-edge scanning method with tantalum blades. In the high spatial resolution mode, with the 20 μm horizontal width of FES, the beam size was measured to be 0.25 μm (V) × 0.26 μm (H), as shown in Figs. 3(a,b), with a corresponding flux of 6×10^{10} photons/s. In high flux mode, with the horizontal FES opened to 1.5 mm, the focusing beam size was measured to be 0.32 μm (V) × 5.3 μm (H), achieving a high flux of 1×10^{12} photons/s. To evaluate imaging performance, we conducted scanning transmission imaging of a tantalum Siemens star chart (XRESO-100, NTT Advanced Technology Corporation) with a tantalum thickness of 1 μm in high-spatial resolution mode, as shown in Fig. 3(c). The structure of the 200 nm line and space was successfully resolved.

For a 4th-generation synchrotron light source, such as the forthcoming SPring-8-II, which features a smaller horizontal source size, a small horizontal focus can be achieved without relying on a secondary source formed by FES, thereby significantly enhancing the available photon flux. Additionally, the undulator spectrum consists of single peaks without satellite profiles. The multilayer K–B focusing system enables the selective extraction of a specific harmonic with an energy bandwidth of a few percent, further increasing the beam intensity.

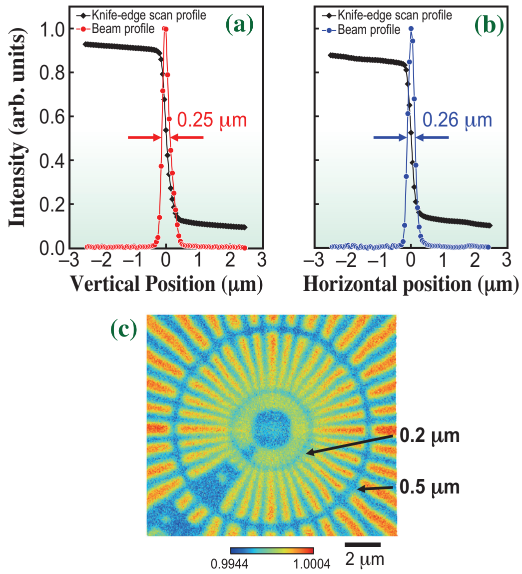

Fig. 3. Measured focusing beam size and observation result of the test chart.

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References

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