X-ray beam deflection control with a flexible capillary

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Abstract. X-ray beam deflection control method using a single flexible glass capillary is proposed to illuminate a fixed sample at a target position with different incidence angle. A 700 mm-long capillary with a bore diameter of 50 micron and an outer diameter of 2 mm, which gives suitable flexibility for the critical curvature, was employed for the test experiment in SPring-8. The X-ray beam with a wavelength of 0.1 nm was introduced into the capillary, whose axis at the input side was finely adjusted to be parallel to the X-ray beam axis with swivel-, rotation- and translation stages. The divergence angle of output beam was measured and is 1-2 mrad. By moving the output-side capillary-support transversely to the beam axis, the beam deflection angle was changed over the range of about 80 mrad. The maximum throughput was larger than 60 % in efficiency, and $8 \times 10^{10}$ photons/s in flux. Mapping with the beam deflection system has also been demonstrated for X-ray absorption measurement of a test sample composed of copper and nickel films. The materials were identified by changing the X-ray photon energy around their absorption edges.

1. Introduction
When a sample is irradiated by a synchrotron radiation X-ray beam, the incidence angle and the illuminated position is adjusted generally by controlling the sample orientation and position. However, the beam direction should be controlled in the cases that the sample must be fixed when the sample is in liquid phase or is attached with heavy equipments and/or rigid environment. Then, X-ray beam deflection control method using a flexible glass monocapillary is proposed to illuminate a fixed sample at a target portion with different incidence angle and adjustable timing.

Capillary optics has been developed for X-ray beams, neutrons and the other particles [1,2], chiefly for focusing optics [3]. As an X-ray beam propagates with multiple total reflections inside the capillary, the curvature is limited due to its small critical angle for total reflection, $\theta_c$. The available curvature radius, $R$, is given as,

$$R \geq \frac{2d}{\theta_c^2}, \quad \text{with} \quad \theta_c \approx \sqrt{2\delta}$$

(1)

where $d$, the bore diameter, and $1-\delta$ is the refraction index of a capillary material. Through the geometrical consideration, the relation, (1), gives the beam deflection by $\theta$ displacement by $x$, and optical delay along to the original direction by $\Delta t$, as,
\[ \theta \leq l \theta_c^2 / (2d), \]
\[ x \leq l^2 \theta_c^2 / (4d), \]
\[ \Delta \theta \leq l^3 \theta_c^4 / (24cd^2), \]

where \( l \) is the length of the capillary, and \( c \) is the speed of light inside the capillary.

For a monocapillary made of a borosilicate glass which has \( \theta_c \approx 2.3 \text{ mrad} \) at an X-ray wavelength of 0.1 nm, the dimension of 0.7 m in length and 50 \( \mu \text{m} \) in bore diameter was designed to demonstrate the beam deflection angle, \( \theta \), by about 40 mrad. In this paper, we report the experimental results on the acceptance angle, the output divergence, and the throughput of an X-ray beam when a monochromatized synchrotron radiation beam is introduced into the monocapillary. A demonstration experiment of X-ray absorption mapping for a test sample composed of metal films is also shown as a simple application of the beam deflection system.

2. Experimental

A 700 mm-long capillary with a bore diameter of 50 \( \mu \text{m} \) and an outer diameter of 2 mm (IFG inc.), which gives suitable flexibility for the critical curvature, was employed for the test experiment at an undulator beamline, BL19LXU [4], of RIKEN, SPring-8. The wavelength of the X-ray beam was tuned to be 0.1 nm by using a Si 111 double-crystal monochromator. The X-ray beam collimated with a slit was introduced into the capillary, whose axis at the input side was finely adjusted to be parallel to the X-ray beam axis by using swivel-, rotation- and translation stages with stepper motors as shown in Fig. 1. The capillary was simply supported by a flat table not to tail down due to the flexibility. A stepper motor system controls the position of a point support at the output side to move it in the horizontal direction. The output beam profile was monitored with an area detector (100 mm by 100 mm) of a flat panel (Hamamatsu) with a pixel size of 50 \( \mu \text{m} \). The divergence and deflection angles of output beam were measured by monitoring the beam profile with changing the flat panel position in the direction parallel to the incident beam. In the measurement of output intensity and the demonstration experiment of mapping, the flat panel was replaced by an ion chamber.

![Figure 1. Experimental setup for X-ray beam deflection with a flexible monocapillary.](image)
3. Results and discussion

3.1. Beam deflection
By moving the output-side capillary-support transversely to the beam axis, the beam position on the flat panel was changed as keeping its profile as shown in Fig. 2. From the displacement, $x$, for various flat panel position, the deflection angle, $\theta$, was estimated and is plotted in Fig. 3. The deflection was achieved over the range of about 80 mrad with an intensity variation less than 50%. The maximum throughput was larger than 60% in efficiency, and $8 \times 10^{10}$ photons/s in flux, at the straight condition, $\theta=0$.

![Figure 2](image1.png)  
**Figure 2.** The X-ray beam profiles through the glass capillary ($x=0$ mm and 10 mm) detected with a flat panel detector when the capillary-detector distance was 70 mm.

![Figure 3](image2.png)  
**Figure 3.** Normalized throughput intensity dependent on the deflection angle of output beam.

3.2. Acceptance angle and beam divergence
Acceptance angle at the input side of the capillary was measured for adjustment to guide a monochromatized X-ray beam. As the numerical aperture for the capillary is estimated to be $\pm \sqrt{2} \delta$, the acceptance angle width is estimated to be about 5 mrad for a borosilicate glass. Figure 4 shows the $\omega$ - and $\phi$-dependence of throughput intensity. Both the vertical and horizontal acceptance angles are consistent with the estimated value.

The divergence angle of output beam was also measured from the beam profile to be 1-2 mrad, as shown in Fig. 5. The multiple reflections with around the critical angle, where reflectance decreases,

![Figure 4](image3.png)  
**Figure 4.** The acceptance angles at the input end.

![Figure 5](image4.png)  
**Figure 5.** Output beam divergence for various deflection angles.
reduce the beam intensity in the component having a relatively large divergence. As a result, the output beam divergence is smaller than the critical angle and becomes smaller for larger deflection angle due to increase in the number of reflections.

3.3. Mapping of X-ray absorption spectrum

As a demonstration of mapping using the beam deflection system, absorption measurements with scanning in one direction has been conducted for a test sample composed of copper and nickel films, the form of which is shown as an inset of Fig. 6. The sample was positioned downstream of the end of the capillary by 5 mm, like a flat panel in Fig. 1. The illuminated position was controlled by moving the capillary-support close to the end with a precision of \(1 \mu m\). An ion chamber with an effective area of larger than \(1 \text{ cm} \times 1 \text{ cm}\) was placed behind the sample. Figure 6 shows the absorbance at various positions of the fixed sample. The absorbance was measured with a spatial resolution of \(55 \mu m\), for the photon energies of 8.0 keV, 8.7 keV, and 9.3 keV, in order to distinguish the materials according to their absorption edges. Figure 7 (a) and (b) show the X-ray photon energy dependence of absorbance at positions of \(x=1.5 \text{ mm}\) and \(x=-3.0 \text{ mm}\) in Fig. 6, which identifies the materials to be nickel and copper, respectively.

![Figure 6. Absorbance of a sample composed of copper and nickel films, which depends on the capillary scanning position, x, for the photon energies of 8.0 keV, 8.7 keV, and 9.3 keV. The capillary end was scanned with a step of 25 \(\mu m\).](image)

![Figure 7. X-ray photon energy dependence of absorbance at positions of (a) nickel (x=1.5 mm in Fig. 6) and (b) copper (x=-3.0 mm) films. The photon energy was scanned with a step of 10 eV.](image)

4. Summary

X-ray beam deflection control method using a single flexible glass capillary has been proposed and demonstrated to illuminate a fixed sample at a target position with different incidence angle. This method is expected to be widely applied for transportation of X-ray beam, two-dimensional X-ray mapping for a fixed sample, and tuning the X-ray pulse timing using a curved capillary to delay the arrival time. This work was supported by A-STEP, Japan Science and Technology Agency, and JSPS KAKENHI Grant Number 24651109.

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