BL20B2
Medical and Imaging I

1. Introduction

BL20B2 is a medium-length beamline with a bending magnet source. It is composed of an optics hutch (OH), upstream experimental hutch 1 (EH1) located 42 m from the source, and downstream experimental hutches 2 (EH2) and 3 (EH3) located more than 200 m from the source. EH1 is located in the storage ring building, whereas EH2 and EH3 are located in the Medium-Length Beamline Facility.

BL20B2 is mainly used for X-ray imaging techniques such as X-ray micro-tomography and real-time radiography. In EH1, high-spatial-resolution and ultrafast imaging experiments, which require a high photon flux density, are performed. In comparison, X-ray imaging experiments with a wide field of view are performed in EH2 and EH3 using an X-ray beam with a large cross section. In addition, X-ray phase-contrast imaging based on the high spatial coherence of the beam generated over a large propagation distance from the source is also performed. Recently, double-multilayer monochromators (DMMs) for X-ray energies of 40 keV and 110 keV have been installed as a new beamline optical system [1, 2]. As the activities in FY2022, high-energy X-ray micro-laminography (micro-LG) using the DMM for 110 keV was developed as a novel X-ray imaging technique in the high-energy X-ray region [3]. In addition, the application to the nondestructive and high-resolution observation of dense and thick planar objects was demonstrated.

2. Development of high-energy X-ray micro-laminography

In the case of dense and thick planar objects such as flat fossils, it is difficult to observe the inner structure because strong X-ray absorption occurs along the longitudinal direction. This prevents conventional tomographic observation even when using high-energy X-rays. In comparison, X-ray micro-LG is a promising tool for nondestructive three-dimensional (3D) observation. X-ray micro-LG is capable of observing the region of interest even in a large-area flat object merely by tilting the rotational axis from a normal direction to the X-ray beam. A schematic drawing of the difference between X-ray micro-tomography (micro-CT) and X-ray micro-LG is shown in Fig. 1.

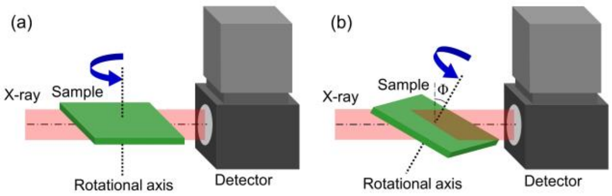

Fig. 1. Schematic drawings of measurement setups for (a) X-ray micro-CT and (b) X-ray micro-LG.

High-energy X-ray micro-LG was developed at EH2 and EH3, which are far from the source, to utilize the high degree of spatial coherence of the incident X-ray beam, as it is more advantageous for observing the sample with X-ray phase contrast. A key factor in the laminographic measurement is the tilt of the rotational axis of the sample. Thus, a goniometer was installed on the sample stage to tilt the rotational axis. The goniometer could be operated with the tilt angle (Φ) from 0 degree, which is normal to the X-ray beam, to 30 degrees for X-ray micro-LG. Therefore, a laminographic setup could be quickly switched to a tomographic one to compare the resulting images of the same sample. X-ray transmission images were recorded with a lens-coupled visible-light conversion-type X-ray imaging detector. Here, two kinds of detector configuration were employed for observations with different spatial resolutions and fields of view. For the wide field of view observation, the effective pixel size and the field of view were 12.4 μm and 50.8 mm, respectively. On the other hand, the effective pixel size and the field of view were 4.22 μm and 17.3 mm, respectively, for the high-resolution observation. In both configurations, a high-definition CMOS camera (C13949-50U, Hamamatsu Photonics) was used. A filtered back-projection (FBP) method considering the tilt angle of the rotational axis was used for reconstructing a sectional image in X-ray micro-LG [4], while a conventional FBP method was used for X-ray micro-CT.

3. High-resolution observation of dense and thick planar objects

As a demonstration of high-energy X-ray micro-LG, high-resolution observation of flat fossils, which could be a promising application, was conducted. Here, two kinds of planar fossil were employed: a fossilized cockroach preserved near the surface of laminated limestone and a platy fossil including gastropods. The flat fossil set on the sample stage is shown in Fig. 2(a). A plastic container with elastic membranes was employed to hold the sample in the tilted condition during the laminographic measurement.

In the projection image in X-ray micro-LG, an effective vertical field of view (FOV_v) of more than $FOV_h \times \sin\Phi$ is basically required to reconstruct a full-field sectional image, where FOV_h is the horizontal field of view in the projection image that is equal to the image width of the sectional image. When FOV_h is 50.8 mm, FOV_v should be larger than 25.4 mm at the tilt angle of 30 degrees. However, the effective vertical beam width of 110 keV X-rays at the sample position was limited to approximately 10 mm. To overcome this limitation, the sample was scanned along the vertical direction step by step at every 360 degree rotation, as shown in Fig. 2(b). In the case of the measurement with FOV_h of 50.8 mm, the sample was scanned five times stepwise at 8 mm per step. Then, five-part subprojection images were combined to make a single projection image with an FOV_v of 40 mm before reconstruction.

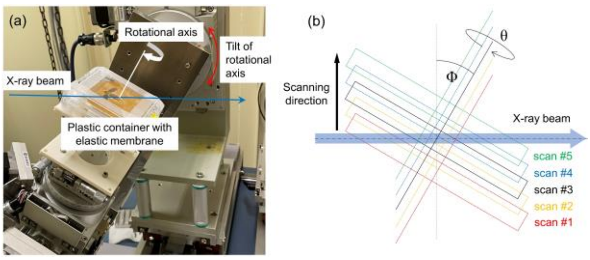

Fig. 2. (a) Actual measurement setup for observing a flat fossil set in a plastic container. (b) Schematic drawing of the wide field of view observation with a vertical sample scan.

A wide field of view sectional image of the fossilized cockroach parallel to the planar surface of the matrix is shown in Fig. 3(a). The measurement conditions were as follows: 7200 projection images taken with 360-degree rotation, 150 ms exposure time, and 30-degree tilt angle. Microscale structures in the whole body of the fossilized cockroach could be clearly observed. For comparison, the same sample was measured with X-ray micro-CT. A sectional image obtained from the tomographic measurement is shown in Fig. 3(b). The image quality suffered from streak-like artifacts due to strong X-ray refraction at the planar surface. In addition, the elastic membrane holding the sample in the plastic container (indicated by arrows) could be recognized, whereas the membrane could not be seen in the sectional image obtained by X-ray micro-LG. This is because the membrane was regarded to be an almost transparent and uniform material in the X-ray micro-LG projection images, like a thin filter, and caused practically no interaction with the X-ray beam. As a result, an excellent image quality could be obtained by X-ray micro-LG.

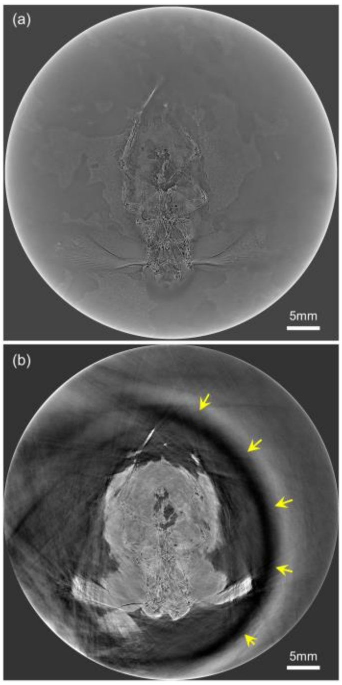

Fig. 3. Sectional images of a fossilized cockroach obtained by (a) X-ray micro-LG and (b) X-ray micro-CT. The same sectional planes are presented.

To demonstrate the observation of fossils in a dense planar matrix, a gastropod shell in the matrix was measured with the high-resolution detector. A sectional image of the shell obtained by X-ray micro-LG is shown in Fig. 4(a). The measurement conditions were as follows: 7200 projection images taken with 360-degree rotation, 200 ms exposure time, and 30-degree tilt angle. Detailed structures in the shell could be clearly observed. For comparison, the same region was measured with X-ray micro-CT. A sectional image obtained by X-ray micro-CT is shown in Fig. 4(b). Because of lower X-ray transmission and undesired interactions with the surrounding matrix, the image quality was considerably degraded in the tomographic image. The magnified images shown in Figs. 4(c) and 4(d) present the difference in the image quality in more detail

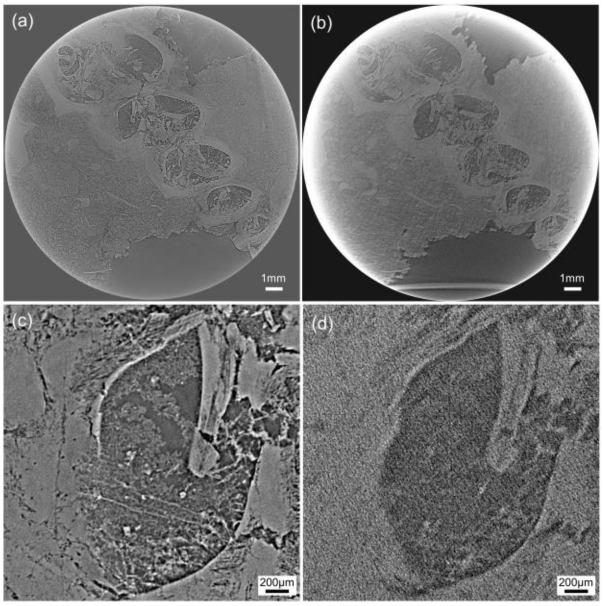

Fig. 4. Sectional images of a gastropod shell obtained by (a) X-ray micro-LG and (b) X-ray micro-CT. Magnified images at upper middle region of the sectional images obtained by (c) X-ray micro-LG and (d) X-ray micro-CT.

4. Conclusion

High-energy X-ray micro-LG using a high-photon-flux X-ray beam from the DMM was developed. By comparing the quality of the sectional images obtained by X-ray micro-LG and X-ray micro-CT, the validity and superiority of high-energy X-ray micro-LG for observing dense and thick planar objects such as flat fossils were successfully demonstrated. The high penetration power of the high-energy X-rays has potential for various applications. In addition, local structures in the region of interest can be easily observed in the tilted geometry of X-ray micro-LG, as shown in Fig. 4(a). This is an advantageous feature for easily achieving multiscale observations. Further optimization of the measurement conditions in both X-ray micro-CT and X-ray micro-LG will lead to further expansion of high-energy X-ray imaging applications.

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References:

[1] Koyama, T. Senba, Y. Yamazaki, H. Takeuchi, T. Tanaka, M. Shimizu, Y. Tsubota, K. Matsuzaki, Y. Kishimoto, H. Miura, T. Shimizu, S. Saito, T. Yumoto, H. Uesugi, K. Hoshino, M. Yamada, J. Osaka, T. Sugahara, M. Nariyama, N. Ishizawa, Y. Nakano, H. Saji, C. Nakajima, K. Motomura, K. Joti, Y. Yabashi, M. & Ohashi, H. (2022). *J. Synchrotron Rad.* **29**, 1265–1272.

[2] Uesugi, K. Hoshino, M. Koyama, T. Yamazaki, H. Senba, Y. Takeuchi, T. Yumoto, H. Ohashi, H. Yamada, J. Osaka, T. Sugahara, M. & Yabashi, M. (2022). *J. Phys.: Conf. Ser.* **2380**, 012120.

[3] Hoshino, M. Uesugi, K. & Imai, T. (2023). *J. Synchrotron Rad.* **30**, 400–406.

[4] Hoshino, M. Uesugi, K. Takeuchi, A. Suzuki, Y. & Yagi, N. (2011). *Rev. Sci. Instrum*. **82**, 073706.