Development of X-ray imaging detector for 200 keV X-ray microtomography

High-energy X-ray microtomography is a promising tool for observing inner fine structures of metallic samples and large rocks containing fossils in three dimensions without the need to cut them into small pieces. A synchrotron-radiation-based high-energy X-ray beam with plentiful flux and a relatively high degree of spatial coherence can be better serve for high-spatial-resolution X-ray microtomography compared with laboratory-based computed tomography systems. Recently, 200 keV high-energy X-ray microtomography using a white beam from a bending magnet source has become available at SPring-8 **BL28B2**. The high-energy X-ray spectrum at around 200 keV can be extracted by using an absorber composed of heavy metal plates: a tungsten plate with a thickness of 0.5 mm and a lead plate with a thickness of 2 mm [1]. The 200 keV high-energy X-ray microtomography has been applied to the observation of, for example, metallic cultural heritages and fossils.

Because of the high penetration power of a high-energy X-ray beam, large objects filled with dense materials are the primary targets of high-energy and high-spatial-resolution X-ray microtomography. A dedicated X-ray imaging detector, which allows a wide field of view (FOV) observation, was developed for using these applications. In addition, a high-definition CMOS camera was introduced to realize high-spatial-resolution X-ray microtomography while keeping the wide FOV [2].

An X-ray imaging detector employing a lens-coupled visible-light conversion-type system to allow for the flexibility to change the effective pixel size and FOV has been developed [3]. Photographs of this detector are shown in Fig. 1. A large-format camera lens (Planar 135/3.5, Carl Zeiss) was used as the first lens to enable wide-FOV imaging without vignetting. The focal length, which is almost equal to the distance from the scintillator to the lens, is 135 mm, and the *F* number is 3.5. The first lens is moved along the optical axis of visible light by a linear actuator to adjust the focus of the image. This system employs an "L-shaped" configuration in the horizontal plane to reduce the X-ray scattering from the prism mirror caused by high-energy X-rays passing through the scintillator. A high-definition industrial CMOS camera, C13949-50U (4096 (H) × 3008 (V) pixel format, 3.45 μm/pixel, dynamic range of 4565:1, full-well capacity of 10,500 e^-, Hamamatsu Photonics), was used to achieve a wide FOV with a smaller effective pixel size. The second lens, which had a focal length of 35 mm (AI Nikkor 35 mm f/1.4 S, Nikon), was set just in front of the CMOS camera. In this case, the effective pixel size was 12.98 μm.

In high-energy X-ray imaging, selecting an optimal scintillator is an important issue to realize efficient and high-spatial-resolution measurements. This is because high-energy X-rays of around 200 keV are easily transmitted through even thick scintillators. Although a thick scintillator provides a high conversion efficiency from X-rays to visible light, the achievable spatial resolution in the thick scintillator becomes lower than that in a thin scintillator. By evaluating several scintillators in terms of their efficiency and imaging property using the modulation transfer function, a $Lu_3Al_5O_{12}:Ce^+$ (LuAG) ceramic of 500 μm thickness is found to be a good candidate for 200 keV high-energy X-ray microtomography when the effective pixel size is 12.98 μm.

As a demonstration of high-energy X-ray microtomography using the developed detector, an

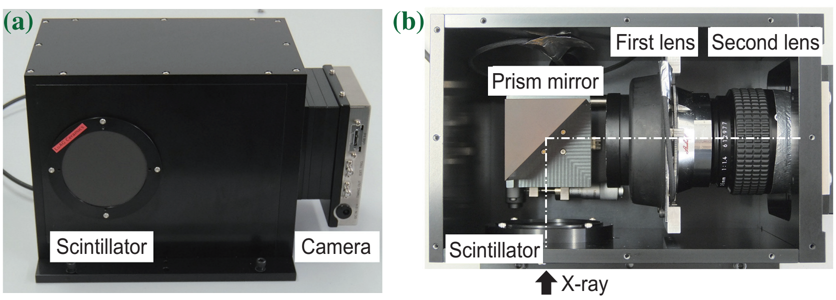

Fig. 1. Photographs of the developed X-ray imaging detector. **(a)** Exterior view and **(b)** top view showing the interior.

elliptical nodule containing a fossil was observed. A photograph of the nodule is shown in Fig. 2(a). The propagation distance from the nodule to the X-ray imaging detector was set to 3 m. Then, the effective pixel size was 12.15 μm, which is slightly smaller than the pixel size shown above. This is because the projection image was slightly magnified by the relatively long propagation distance. In this case, the horizontal FOV in the image was calculated to be 49.8 mm. Since the effective beam size along the vertical direction in the 200 keV region was approximately 1.5 mm at the sample position, the nodule was scanned along the vertical direction at 1.42 mm per step to observe the whole shape. Cross-sectional images in three orthogonal directions are shown in Figs. 2(b)–2(d). The inside of the nodule was clearly observed. The three-dimensional view of the fossil of a shell at the center of the nodule is shown in Fig. 2(e). The fine structure of the nodule as well as the fossil inclusion could be clearly observed with the developed X-ray imaging detector.

As a merit of the lens-coupled X-ray imaging detector, the effective pixel size and FOV can be easily changed by replacing the second lens. In this detector, the effective pixel size of a few microns can also be achieved by using a second lens with a large focal length. The high-spatial-resolution observation of the local fine structure in a large object will be an outstanding feature of synchrotron-radiation-based high-energy X-ray microtomography. The optimal measurement conditions will be explored in future work.

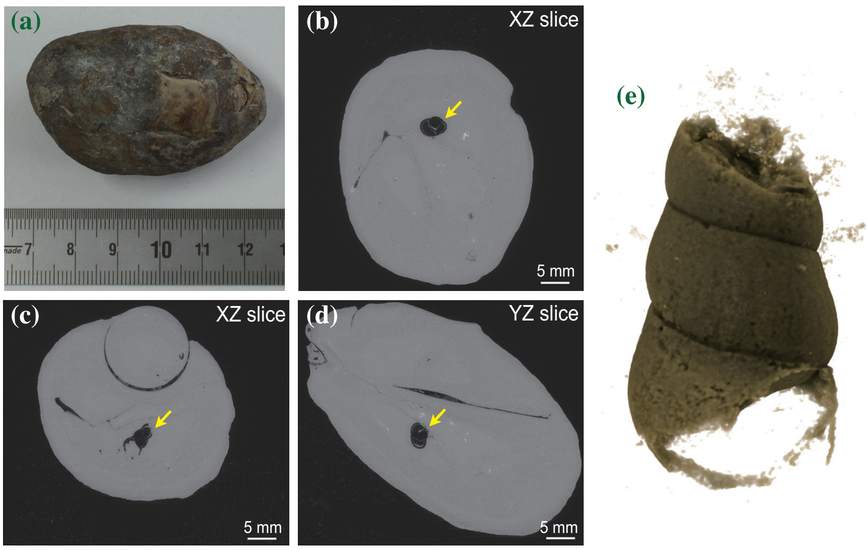

Fig. 2. **(a)** Photograph of the nodule. Cross-sectional images of the nodule in the **(b)** XY, **(c)** XZ and **(d)** YZ planes. Here, the XY plane is normal to the rotational axis in the tomographic measurements. Number of projections: 7200. Exposure time: 25 ms. Thirty tomographic scans were required to observe the whole shape. **(e)** Three-dimensional view of the shell indicated by arrows in the cross-sectional images.

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References

[1] M. Hoshino *et al.*: AIP Advances **7** (2017) 105122.
[2] *M. Hoshino, K. Uesugi and N. Yagi: J. Synchrotron Rad.* ***27*** *(2020) 934.*
[3] K. Uesugi *et al.*: J. Synchrotron Rad. **18** (2011) 217.