# Coherent achromatic rotational reflective optics for ptychography (CARROT) at SPring-8 BL07LSU

With its high spatial resolution and various techniques for analyzing physical properties, X-ray microscopy has been applied in many fields, such as biology and materials science. Soft X-ray microscopy is particularly suited to investigating the physical properties of light-element-rich heterogeneous structures, such as biological cells and polymeric materials. For example, in combination with X-ray absorption spectroscopy, it has been used to map the chemical states of nanoparticles in magnetic bacteria [1] and to visualize the degradation mechanism of Li-ion battery materials [2].

Conventional soft X-ray microscopes have been developed using zone plates [3]. However, chromatic aberration of zone plates makes soft X-ray imaging of multiple elements difficult. In addition, the relatively short working distance makes it a challenge to apply a soft X-ray microscope to various *in situ*/*operando* applications. In this study [4], we developed a new soft X-ray microscope with Wolter mirror optics. The total reflection property of the Wolter mirror is ideal for spectroscopic measurements corresponding to the absorption edges of different elements at multiple wavelengths. We combined the Wolter mirror optics with the ptychography method [5] to achieve a high spatial resolution. Ptychography is a lensless imaging technique for reconstructing sample images from coherent diffraction patterns and can achieve high spatial resolution and sensitivity owing to the redundancy of input information.

Figure 1 shows a photograph and schematic diagram of the developed soft X-ray ptychography system. The system was constructed at the University of Tokyo Materials Science Beamline at SPring-8 **BL07LSU**. The orange cylindrical component in Fig. 1(a) is a 200-mm-long Wolter mirror newly developed as the illumination optics for soft X-ray ptychography. The system is named CARROT after Coherent Achromatic Rotational Reflective Optics for pTychography. The resolution of CARROT was evaluated using a test chart, and it was confirmed that a half-period resolution of 50 nm can be achieved with a broad photon-energy range from 250 eV to 2 keV while maintaining the focal position.

To demonstrate the application of CARROT, biological cell samples were measured with a 600 eV soft X-ray. The samples were Chinese hamster ovarian cancer (CHO-K1) cells grown on a 200-nm-thick silicon nitride thin film and chemically fixed with paraformaldehyde. The cells were approximately 5 μm thick. The internal structures of such thick cells are generally difficult to observe by electron microscopy without thinning. Figure 2 shows a typical example of a cell image observed with CARROT. The absorption and phase images of the cell are shown in the left and right areas of Fig. 2, respectively. The magnified images in the lower row are taken from areas corresponding to the dotted rectangles shown in the upper-right absorption image of the cell. Each magnified image corresponds to a pseudopodal structure of the cancer

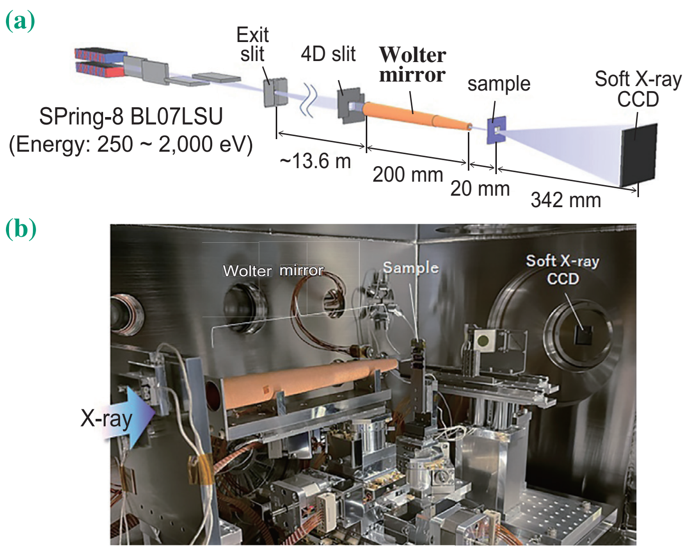


Fig. 1. Schematic diagram **(a)** and photograph **(b)** of CARROT at SPring-8 BL07LSU.

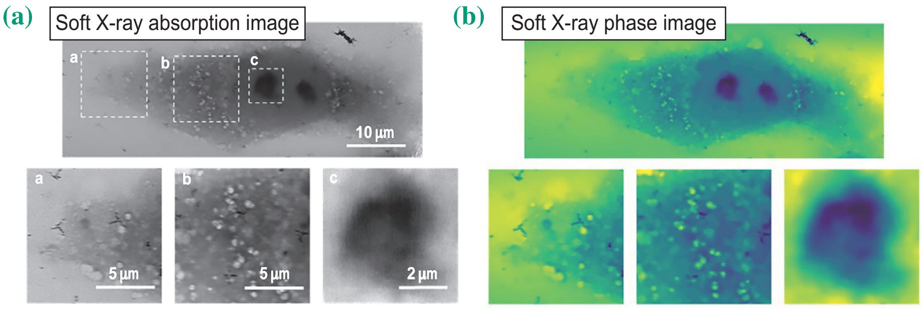


Fig. 2. Retrieved absorption **(a)** and phase **(b)** images of the CHO-K1 cell measured by CARROT. The retrieved image was measured at 600 eV.

cell, organelles such as the endoplasmic reticulum and mitochondria, and the nucleolus. Ptychography can quantitatively determine the amount of phase shift as well as the absorption rate of the sample in response to X-rays. Highly sensitive imaging of both absorption and phase is one of the advantages of ptychography compared with conventional soft X-ray microscopy. Intracellular structures of various thicknesses ranging from micrometers to nanometers, shown in Fig. 2, have been clearly imaged without saturation using highly sensitive absorption and phase imaging of soft X-ray ptychography with CARROT.

Figure 3 shows the phase images of the cell measured at 250 eV, 350 eV, 450 eV, 600 eV, and 1200 eV. Thanks to the achromatic feature of the Wolter mirror optics, we could seamlessly obtain the cell image at largely different wavelengths across the absorption edges of light elements. This demonstration measurement shows the ability to extend CARROT to combine soft X-ray ptychography with absorption spectroscopy of essential elements for biological samples such as carbon, nitrogen, and oxygen.

This element- and molecule-selective, high-resolution imaging technology is expected to be a powerful tool for the analysis of small molecules and other substances that are difficult to image with visible-light fluorescence microscopy.

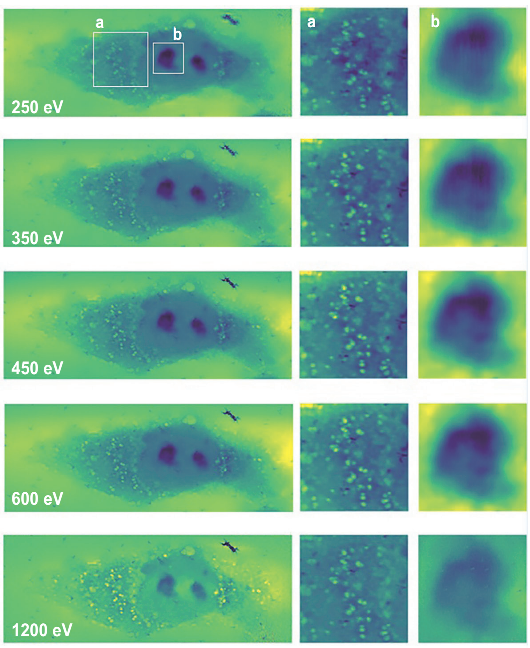


Fig. 3. Phase images of the CHO-K1 cell measured at 250 eV, 350 eV, 450 eV, 600 eV, and 1200 eV.

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