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Multimode X-Ray Tomography at the Mediana Station of the Kurchatov Synchrotron Radiation Source

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Abstract—The synchrotron radiation used in X-ray tomography enables us to vary the recording conditions within wide limits due to the continuous spectrum and the beam's high brightness and collimation. The possibilities of multimode X-ray tomography at the Mediana station of the Kurchatov synchrotron radiation source, including tomography and microtomography based on white and "pink" beams, imaging with the help of a monochromatic beam, and measurements via axial and refractive phase-contrast methods, are described. The presented results of the reconstruction of different objects have been obtained under different recording conditions.

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INTRODUCTION

X-ray tomography, i.e., the technique of obtaining the 3D images of objects, is commonly used in the nondestructive testing of objects, biology and medicine, mineralogy and paleontology, and many other fields of research. In tomographic measurements, a series of images of the sample are recorded with the help of one- or two-coordinate detectors while the sample is rotated through angles of 0–180 deg around the axis perpendicular to an incident beam. Afterward, mathematical processing (3D image reconstruction) is carried out. X-ray tomography always poses problems concerned with both the selection of optimal conditions of recording, such as the spatial resolution, field of view, and radiation energy, and application of phase-sensitive methods to enhance the contrast. In measurements based on synchrotron radiation (SR), the recording conditions can be varied over a wide range due to spectrum continuity and the high brightness and collimation of a beam. In this paper, the possibilities of multimode X-ray tomography are described as applied to the Mediana station of the Kurchatov Synchrotron Radiation source and illustrated by several examples.

EXPERIMENTAL

The specific feature of the Mediana station is that a white beam is extracted from the storage ring and delivered into the experimental area. With allowance for beryllium windows, the source's radiation spectrum has a maximum near 13 keV at a nominal electron energy of 2.5 GeV, and its rapidly descending high-energy part extends up to 80 keV and more. The spectrum of radiation incident on the sample can be varied using crystal monochromatization and by the application of filters and mirrors. Moreover, changes in the spectrum can also be attained by varying the source parameters: the number of high-energy photons decreases abruptly if the energy of electrons generated in the storage ring is 1.6 GeV instead of the nominal value of 2.5 GeV. The soft component of the spectrum is suppressed by beryllium windows in the extraction channel and with the help of additional aluminum filters. As a result, the SR beam has a spectral peak at an energy of 12 keV, the width of which at half height is about 6 keV. In the "pink" beam mode, the maximum intensity is less by two orders of magnitude, but the estimated integral gain exceeds the value inherent to a monochromatic beam by a factor of approximately 300. A beam reflected from a mirror provides a similar spectrum shape. The radiation spectra calculated for a storage-ring beam, the output beam from a copper filter, and a pink beam are shown in Fig. 1.

An optical bench intended for mounting of the slits and the positioning devices for the samples and detectors, as well as a refraction introscopy block, are arranged along the beam path [1] (Fig. 2). Along with beam control, the simplicity of varying the experimental scheme permit us to prepare the different types of beams for the experiment and, accordingly, vary its parameters. Absorption tomography can utilize white, filtered, pink, and monochromatic beams; in-line phase-contrast tomography relies on pink and monochromatic beams; and refraction tomography is performed with the help of only a monochromatic beam.

The height of an SR beam is small (about 2 mm). Hence, large objects under study must be scanned, except for the use of a refraction scheme with an asymmetric crystal, in which the field-of-view height grows in proportion to the degree of asymmetry and is 3–5 cm.

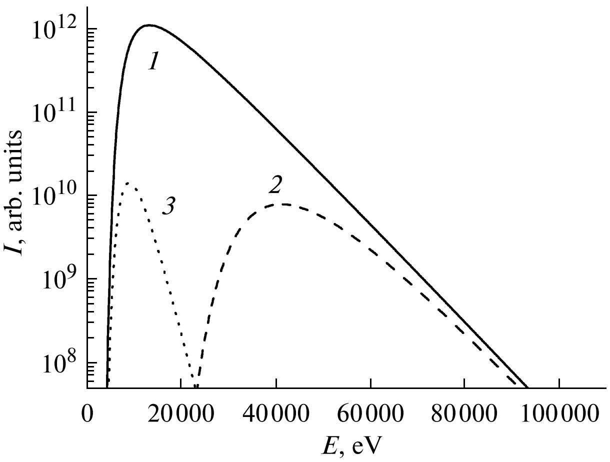

Fig. 1. Radiation spectra calculated for beams that have been passed through (*1*) storage-ring windows and (*2*) a copper filter 2 mm thick and (*3*) a pink beam.

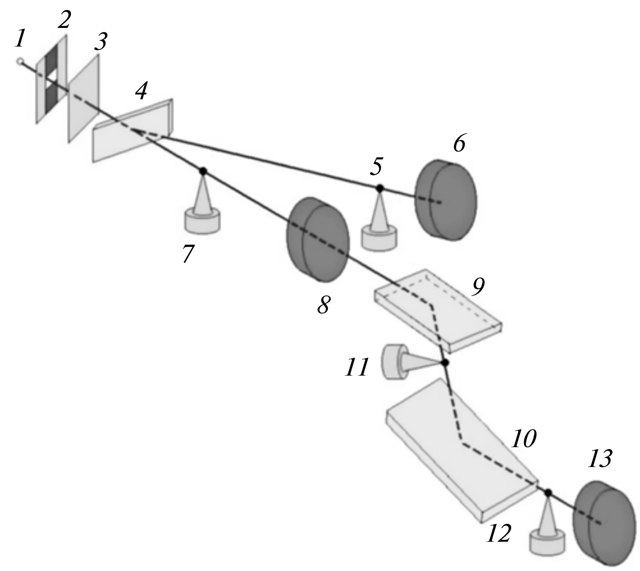

Fig. 2. Diagram of the setup involving the SR source *1*, slits *2*, filters *3* used in the monochromatic-beam mode, crystal *4*, sample *5*, detectors *6* intended for the white and pink beams, sample *7*, detector *8* used in the refraction-contrast mode, crystals *9* and *10*, possible sample positions *11* and *12*, and detector *13*.

To record the experimental data, i.e., projections, two-coordinate detectors based on polycrystalline (CsI) and monocrystalline ($Bi_4Ge_3O_{12}$) scintillators and 1024 × 1024 CCD cameras are used with the spatial resolution being varied from 2 to 10 μm. As a rule, the measurements consisted in the recording of 360 projections, an empty beam, and the dark current of the detector. Primary processing of the projection (noise elimination, evaluation of the background and beam inhomogeneities, and normalization) was carried out by means of the macros of the ImageJ program [2], and cross sections were reconstructed from the projections via the convolution and back-projection method based on the fast Fourier transform and the standard radial filter [3].

WHITE-BEAM TOMOGRAPHY

The simplest experimental method is the use of the white beam. In this case, the experimental setup comprises slits, filters, sample positioning devices, and a detector. A white beam is suitable only if rather thick objects are examined with X-rays. In addition, the soft component of the spectrum remains unusable and can be excluded by means of an absorbing filter. A disadvantage of the method is the difficulty in achieving a high spatial resolution because the fluorescence region of a monocrystalline scintillator increases at large energies and the polycrystalline scintillator resolution is limited by the grain size.

As an example of tomography based on a white beam, let us consider the results obtained by investigating the structure of notebook batteries. Measurements were performed under exposure to a direct SR beam, and the low-energy part of the spectrum was removed with the help of Al and Cu filters (Fig. 1, curve *2*). The spatial resolution of recording was 20 μm. The reconstructed cross section is presented in Fig. 3. It is clearly seen that the battery has a spiral structure composed of electrode and electrolyte layers. The battery state can be controlled according to the structural homogeneity, the absence of foreign impurities, and other criteria.

MONOCHROMATIC-BEAM TOMOGRAPHY

In the "classical method" of tomographic experiment based on SR, measurements are performed with the use of monochromators. As a rule, double-crystal monochromators are used. In spite of obvious advantages, these devices provide lower flexibility in terms of the selection of experimental conditions. Hence, the scheme with a single-crystal monochromator reflecting in the horizontal plane was chosen to implement tomographic measurements at the Mediana station. Its drawback is a high level of background, but its influence can be estimated during projection processing. An important issue is the selection of a monochromator crystal.

Highly perfect silicon crystals often serve as SR monochromators. However, they are known to have low reflectivity. On the other hand, crystal perfection is necessary to preserve high spatial resolution. Hence, a germanium crystal with a mechanically polished surface and a uniform field of view without substantial defects was chosen as the close-to-optimal variant. Its intensity exceeded the intensity of perfect silicon by approximately 4. When the radiation energy was $E =$

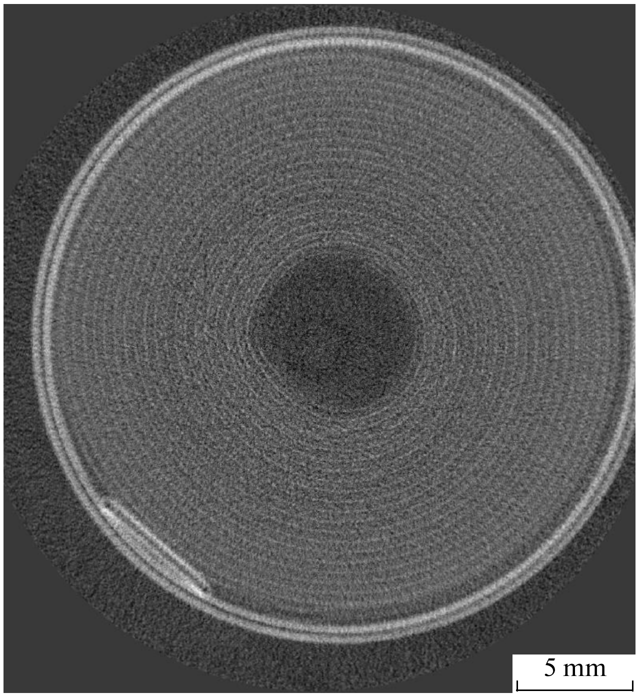

Fig. 3. Axial cross section of the 3D battery image.

12 keV, the best attained spatial resolution was 3 μm. At $E = 17$ keV, the resolution worsened to 5 μm.

As an example of tomography using a monochromatic beam, let us consider the results of investigating a natural diamond crystal with a size of 2 mm and impurities whose shape and distribution were of interest. The spatial resolution was 10 μm. The exposure time per one projection was 5 s. The reconstructed cross section and an arbitrary projection of the 3D crystal model constructed from a set of cross sections by means of the edge detection function are depicted in Fig. 4.

PINK-BEAM TOMOGRAPHY

When weakly absorbing thin samples (i.e., biological objects) are examined, it suffices to use a beam with an energy of about 10 keV. In this case, the requirements for monochromaticity are not high. Hence, a pink beam is an optimal variant. Together with the measurements using the white beam, this experiment is the fastest. The exposure time was 200 ms at a resolution of 2 μm. In our case, the recording rate was limited by the detector readout speed. Phase contrast (pronounced object contours) is observed if the distance between the object and the detector is 10–100 cm [4].

The above-discussed method was used to obtain an image of the head of a northern house mosquito (Fig. 5). Note that both external details (e.g., antennae) and features of the internal structure of the object are well seen in the image and the reconstructed projection.

REFRACTION-CONTRAST TOMOGRAPHY

In the investigations of weakly absorbing samples or objects with components characterized by a small difference in densities, enhanced contrast can be achieved by the use of refraction introscopy [5]. The main experimental difficulty of the method is the long (several hours) retaining of crystals in the reflection position at a narrow (about 0.5 arcsec) rocking curve. This difficulty was surmounted by actively stabilizing the intensity with the help of a feedback system involving a video camera that recorded the beam on a phosphor screen and a piezodrive that continually ensures the maximum reflection of the crystals.

In the demonstration experiment, a plastic mouse statuette 2 cm high was chosen as the object. Considerable refraction contrast is observed in projections at the edges of the mouse image, leading to strong image contouring in the reconstructed cross section (Fig. 6).

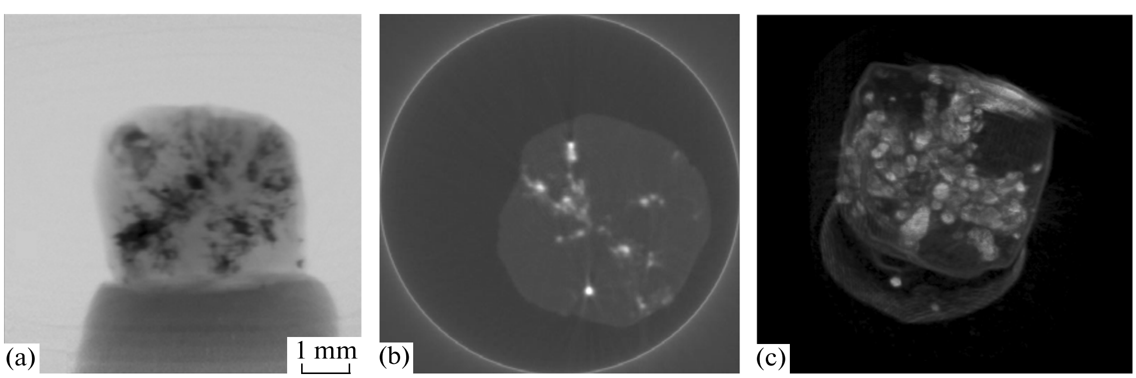

Fig. 4. Tomographic reconstruction of the structure of a diamond crystal with impurities: (a) the initial projection, (b) reconstructed cross section, and (c) the arbitrary projection of the 3D image.

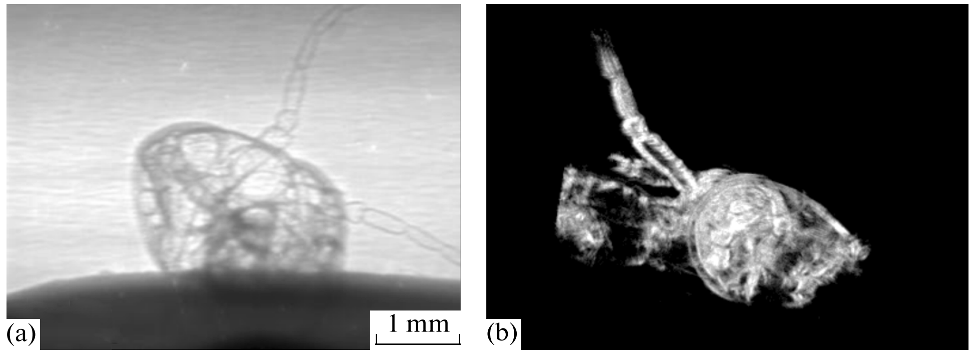

Fig. 5. Tomographic reconstruction of the head of a northern house mosquito: (a) the initial projection and (b) the arbitrary projection of the 3D image.

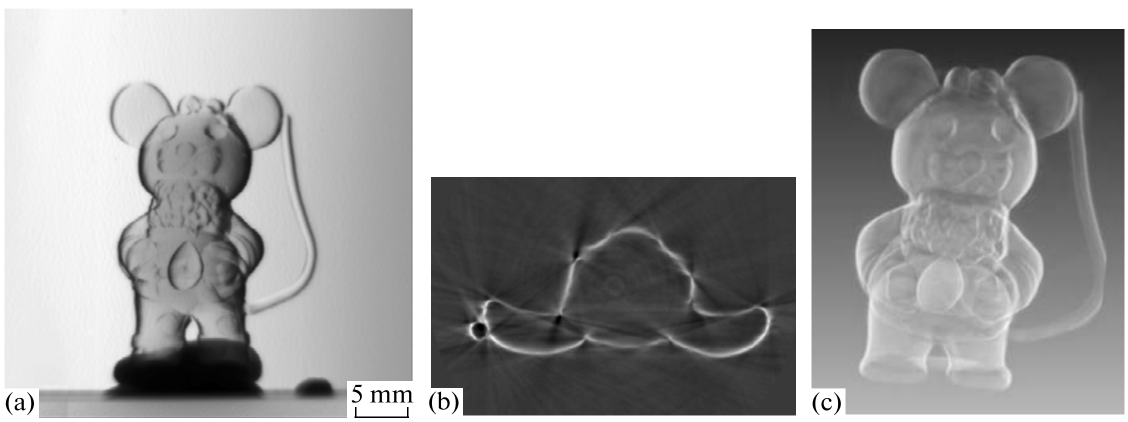

Fig. 6. Tomographic reconstruction of the mouse statuette: (a) one of the projections, (b) tomographic cross section, and (c) the arbitrary projection of the 3D image.

In our case, such excess contrast gives rise to artifacts of reconstruction. However, as can be expected, refraction-contrast tomography measurements should qualitatively increase the sensitivity in detecting the small density variations of the object if the difference between the refractive indices is less by an order of magnitude.

CONCLUSIONS

Nondestructive methods for obtaining 3D images of the internal structures of objects, which were implemented at the Mediana station of the Kurchatov synchrotron radiation source with the help of tomography, permit us to vary the recording conditions within wide limits. This is caused by the fact that the experimental scheme's parameters can be optimized with allowance for the features of the object under study. The presented results make it possible to infer that these methods are promising and deserve further development.

ACKNOWLEDGMENTS

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