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Real-time radiology in the microscale

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Abstract

We present several examples of the applications of a novel microradiology approach based on phase contrast enhancement using unmonochromatized synchrotron X-rays. The approach-mostly implemented and realized at the International Consortium on Phase Contrast Imaging and Radiology (ICPCIR) Beamline at the Pohang Light Source in Korea and on the NSRRC B01A wavelength shifter beamline in Hsinchu, Taiwan, allows the real-time analysis of a variety of phenomena on the micron and submicron scale due to the efficient use of the high-synchrotron X-ray intensity and the coherence. The practical examples concern the examination and investigation of microscopic inhomogeneities, local morphology, etc., in materials science, industrial technology, medicine, the life sciences and other areas.

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1. Introduction

Radiography techniques based on the (real part of the) index of refraction are becoming important analytical tools for real-time process monitoring in life sciences, materials science, medicine, physics, chemistry and other disciplines [1–11]. The theoretical background and the practical implementation were discussed in several recent articles [3]. We recently commissioned two synchrotron beamlines, 7B2 X-ray microscopy beamline at Pohang Light Source (Pohang, Korea) and B01A SWLS (superconducting wavelength shifter) beamline at National Synchrotron Radiation Research Center, (NSRRC) Hsinchu, Taiwan under the management of International Consortium of Phase Contrast Imaging and Radiology (ICPCIR) based on a careful analysis of the longitudinal coherence requirements for such techniques [1,12]. That enabled us to eliminate the need for

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monchromatization, thus, leaving much more flexibility for time and spatial resolution. We present here some of our recent and most significant results.

2. Technical background

Phase contrast radiography is a rather generic term [1–10] identifying a class of contrast mechanisms based on the difference in the X-ray refractive index rather than on the absorption coefficient. The simplest mechanism is refraction contrast: the edges between different object regions with different refractive index slightly deviate from a well-collimated X-ray beam. This produces a sharp enhancement of the edges in the image. In a different regime, the enhancement is produced by a mechanism similar to Fresnel edge diffraction of visible light [2–6]. In the general case, the mechanisms are superimposed to each other with different relative weights.

Extensive theoretical and computer modeling of the contrast phenomena revealed several important features [1]. A collimated beam is of course required since the contrast depends on the definition of the X-ray direction. For similar reasons, the source size must be sufficiently small to avoid penumbra effects. From a practical point of view, the source size must not exceed a few ten microns. The PAL and NSRRC sources are, therefore, perfectly adequate for this task. Another important requirement to obtain high quality phase contrast enhancement is longitudinal coherence. Our own theoretical and experimental validation demonstrated that this requirement is quite weak: a relative wavelength bandwidth not exceeding ≈ 1 is sufficient to observe the edge enhancement.

In view of this ongoing technical progress and of the importance of a non-destructive microscopic tool for materials science and the life sciences, we formed a international consortium called ICPCIR and proposed to construct synchrotron beamlines taking advantage of the new results. The main objective of the ICPCIR facility is to perform phase contrast X-ray microscopy and microradiology experiments on a variety of different systems. Several years of previous research [1] including many pioneering work of several groups [2–10] provided the background for the beamline design with some important and non-conventional features.

The goal to optimize the use of synchrotron X-rays without sacrificing the image quality in the phase contrast regime led to a fundamental strategic decision for the ICPCIR beamlines: the elimination of the monochromator. The benefit is a huge increase in the flux delivered to the object in comparison with monochromatized beamlines. As a result, several interesting experimental techniques become feasible: images can be taken in real time with a speed already exceeding 1 image per millisecond and with excellent lateral resolution ($< 1\,\mu$m).

Such features are critical for a number of practical applications. We can mention, for example, the non-destructive study of the structure of unique paleontological samples; the real-time monitoring of electrodeposition processes [11]; the three-dimensional imaging of cells and of their structure [12]; the study of the microchemistry of concrete formation; the investigation of different processes used by the microelectronics industry; the study of the pathological effects of small particles in the atmosphere. Many other interesting examples could be added to the list and they all have requirements of high imaging speed for dynamic studies and/or of reducing the damage to the samples due to long X-ray exposures [1].

In addition to the elimination of the monochromator, other important technical features of the beamline are the elimination of hard-X-ray optical components except windows, the large beam size suitable for large field of view imaging (approximately up to 10×4 cm of useable flux at the object point), the flexibility, the easy and safe operation and the rapidity in changing experiments.

Fig. 1 shows the scheme of one of the ICPCIR beamline—the X-ray microscopy line at PLS, and, in the inset, the radiology system. The source is the 7B2 bending magnet port of the PLS storage ring, with a size of $45\,\mu$m (vertical) and $120\,\mu$m (horizontal), equipped with a radiation shutter.

The imaging techniques implemented on the beamline are influenced [1–6,13–15] by the ratio