EUROPEAN SYNCHROTRON RADIATION FACILITY

INSTALLATION EUROPEENNE DE RAYONNEMENT SYNCHROTRON

ESRF

Experiment Report Form

The double page inside this form is to be filled in by all users or groups of users who have had access to beam time for measurements at the ESRF.

Once completed, the report should be submitted electronically to the User Office using the **Electronic Report Submission Application:**

http://193.49.43.2:8080/smis/servlet/UserUtils?start

Reports supporting requests for additional beam time

Reports can now be submitted independently of new proposals – it is necessary simply to indicate the number of the report(s) supporting a new proposal on the proposal form.

The Review Committees reserve the right to reject new proposals from groups who have not reported on the use of beam time allocated previously.

Reports on experiments relating to long term projects

Proposers awarded beam time for a long term project are required to submit an interim report at the end of each year, irrespective of the number of shifts of beam time they have used.

Published papers

All users must give proper credit to ESRF staff members and proper mention to ESRF facilities which were essential for the results described in any ensuing publication. Further, they are obliged to send to the Joint ESRF/ ILL library the complete reference and the abstract of all papers appearing in print, and resulting from the use of the ESRF.

Should you wish to make more general comments on the experiment, please note them on the User Evaluation Form, and send both the Report and the Evaluation Form to the User Office.

Deadlines for submission of Experimental Reports

- 1st March for experiments carried out up until June of the previous year;
- 1st September for experiments carried out up until January of the same year.

Instructions for preparing your Report

- fill in a separate form for each project or series of measurements.
- type your report, in English.
- include the reference number of the proposal to which the report refers.
- make sure that the text, tables and figures fit into the space available.
- if your work is published or is in press, you may prefer to paste in the abstract, and add full reference details. If the abstract is in a language other than English, please include an English translation.

ESRF	**Experiment title: Differential phase contrast tomography of biological specimens in aqueous solution using a shearing interferometer**	**Experiment number**:
Beamline: ID19	**Date of experiment**: from: 06 July 2005 to: 10 July 2005	**Date of report**: 30 August 2005
Shifts: 12	**Local contact(s)**: Peter Cloetens	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

Franz Pfeiffer* (Paul Scherrer Institut), Christian David* (Paul Scherrer Institut), Christian Gruenzweig* (Paul Scherrer Institut), Oliver Bunk* (Paul Scherrer Institut), Marco Stampanoni* (Paul Scherrer Institut), Amela Groso* (Paul Scherrer Institut), Konstantins Jevimovs* (Paul Scherrer Institut), Peter Cloetens* (ESRF)

Report:

Conventional radiography and tomography are very successful non-destructive methods to look inside rather thick samples simply by detecting the attenuation of x-rays with a spatially resolving detector. However, a number of interesting samples are very difficult to image with sufficient contrast. For example the detection of tumours in soft tissue is very difficult with x-rays as the difference in *absorption* between healthy tissue and a tumour is extremely small. A look at the x-ray refractive index shows, that even in such cases the difference in *phase shift* is usually considerable. Thus a variety of x-ray phase contrast imaging methods have been developed to improve the contrast of low absorbing samples [1].

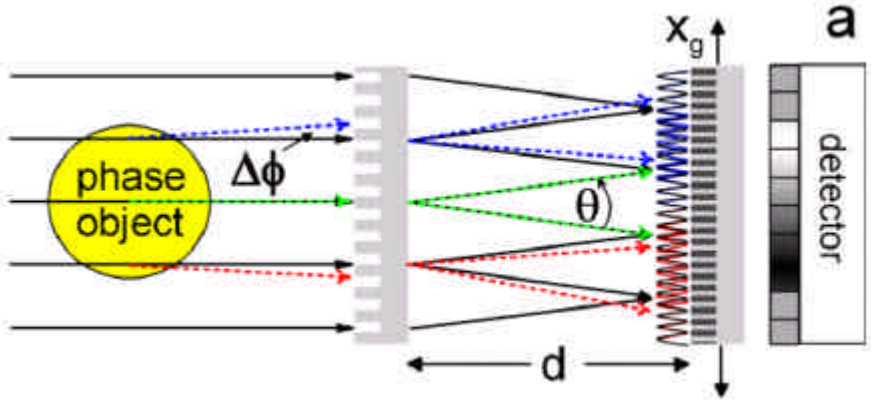

Figure 1: *Principle of the x-ray interferometer. The beam splitter grating splits the incident beam essentially in two diffraction orders which form a periodic interference pattern in the plane of the analyzer grating. A phase object in the incident beam will cause small refractions resulting in a change of the locally transmitted intensity through the analyzer.*

We have recently developed an interferometric x-ray imaging technique based on diffraction gratings [2-5]. The method is capable of detecting wavefront distortions of an incident wave caused by the phase shift gradients of a sample in a quantitative way and with extreme sensitivity. The set-up is very simple, robust, easy to align, and can be scaled up to large fields of view. These properties make the method very interesting for medical applications.

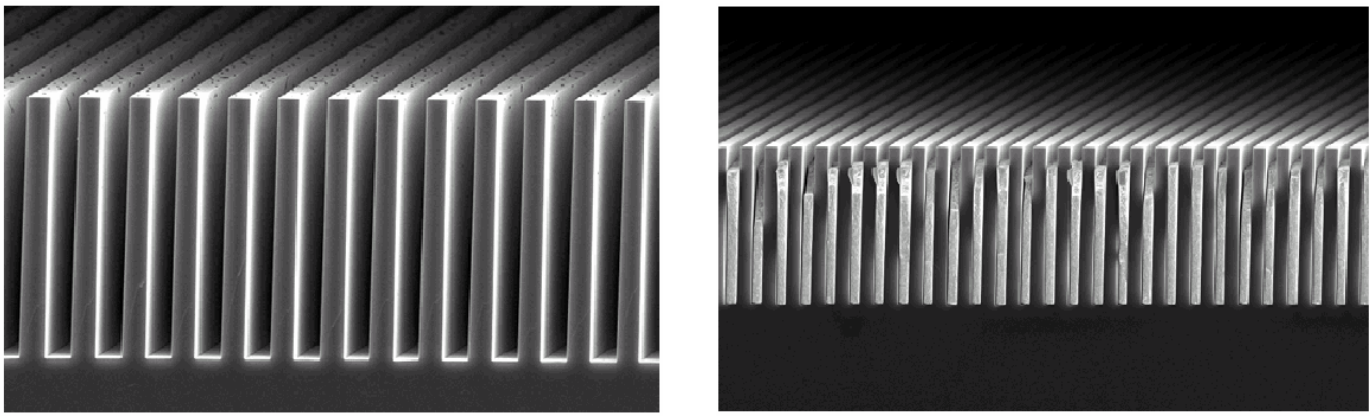

Figure 2: *Scanning electron micrographs of cross sections through the used gratings. The silicon beam splitter grating consists of p-phase shifting lines with a period of 4 micron, while in case of the 2 micron period analyzer grating the grooves were filled with gold by electroplating.*

The interferometer used in the experiement MI-764 consisted of a phase grating G1 (i.e., a grating whose lines show negligible absorption but substantial phase shift) and an amplitude analyzer grating G2 (Fig. 1). The first grating acts as a beam splitter and divides the incoming beam essentially into the two first diffraction orders, which form a periodic interference pattern in the plane of the analyzer grating. Neither the period nor the lateral position of these fringes depends on the wavelength of the radiation used. Perturbations of the incident wave front induced by refraction on an object in the beam, lead to local displacements of the fringes. The analyzer grating acts as a transmission mask for the detector and transforms local fringe position into signal intensity variation (Fig. 1). The detected signal profile thus contains quantitative information about the phase gradient of the object. Figure 2 shows scanning electron micrographs of cross sections through the gratings used. The height of the 4 μm period phase grating was chosen to give π phase shift for 17.8 keV radiation. The height of the gold absorbers in the analyzer grating is 12 μm, which results in a transmission of less than 10% at this energy. To separate this phase information from other contributions to the signal, such as absorption in the sample, inhomogeneous illumination or imperfections of the gratings, a phase-stepping approach used in visible-light interferometry was adapted to this setup. One of the gratings is scanned in the direction *x* perpendicular to the grating lines over one period of the grating, and for every point of the scan an image is taken. The intensity signal *I(x,y)* in each pixel in the detector plane oscillates as a function of the grating position.

The phases $f(x,y)$ of the intensity oscillations in each pixel are related to the wave-front phase profile $F(x,y)$, the X-ray wavelength l and the period g of the absorption grating and the distance d between the two gratings by

$$j = \frac{d\,l}{g}\frac{\partial \Phi}{\partial x} \qquad (1).$$

Importantly, $f(x,y)$ contains no other contributions, particularly no absorption contrast. The phase profile of the object can thus be retrieved from $f(x,y)$ by a simple one-dimensional integration. In the general case where the wave front impinging on the object already shows some distortion, the background phase distribution should be measured with the object removed from the beam and then subtracted. Even in cases where the range of phase values exceeds $2p$ by far, such as in the example in Fig. 3, the method still works well because the measured quantity $f(x,y)$, essentially the first derivative of $F(x,y)$ (Eq. 1), will not exceed $2p$ as long as the phase gradients in the sample are not too steep. This is a clear advantage over methods that record $F(x,y)$ directly, as in this case the phase shifts in the image are mapped onto an interval of $[0,2p]$. This gives images consisting of interference fringes that require complicated phase unwrapping algorithms for a quantitative interpretation.

The described method was applied to image an animal organ, a rat heart, which was placed in a container filled with a 4% aqueous formalin solution. We used the wiggler source at beam line ID19 of the ESRF. The detector consisted of a Gadox scintillator optically coupled to a FRELON CCD camera. The field of view was 14x14 mm^2. The image resolution was determined by the point spread function of the CCD and the scintillator to ~7.5 micron.

Figure 3 shows the absorption, differential phase contrast, and integrated phase image of the sample. Due to the limited size of the synchrotron beam of 15 mm in the vertical direction, the image has been stitched together from two sub-frames. In absorption contrast (left), only some fatty tissue is visible, whereas the complete organ with many details can be seen in the differential phase contrast image (center). Quantitave phase image images (right) were obtained by applying linewise integration to the differential phase contrast data.

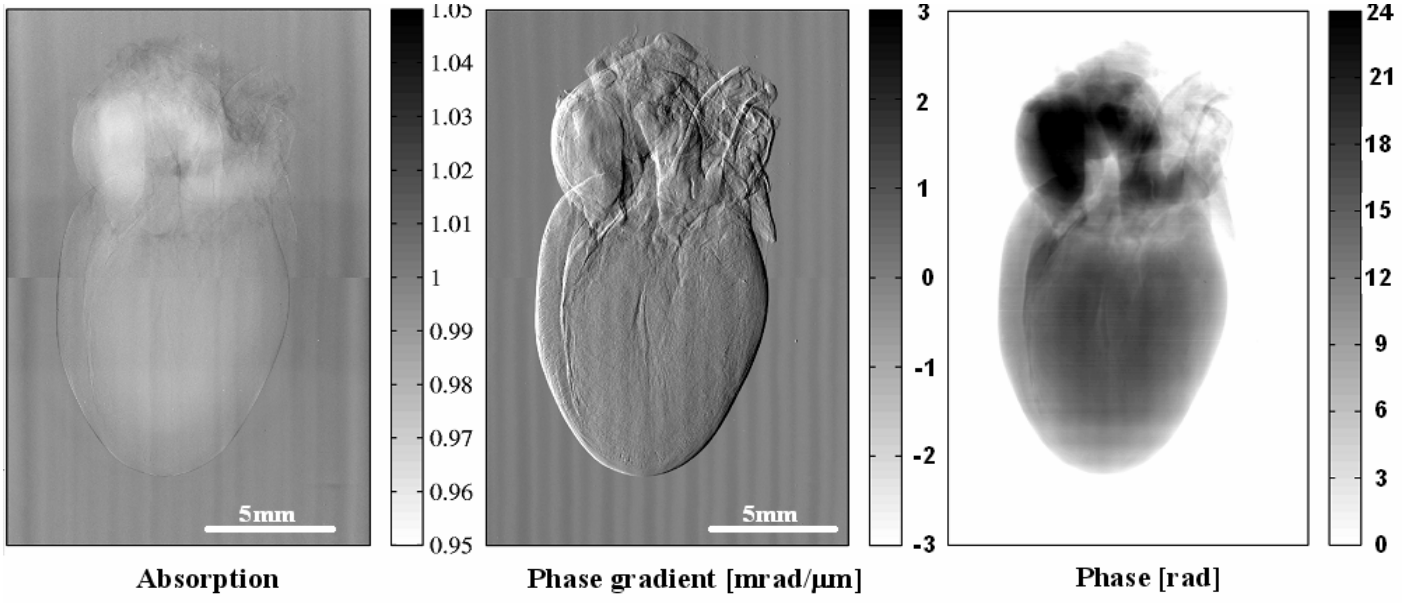

Figure 3: *X-ray micrographs of a rat heart placed in a formalin solution. The photon energy is 17.8 keV. The absorption image shows much less contrast compared to the phase gradient image. The method gives quantitative information, thus a phase image can be obtained by integration of the phase gradient in horizontal direction.*

The experimental results show that a grating interferometer can be used for qualitative or quantitative two-dimensional x-ray phase radiography of specimens in aqueous solution. The possibility to make large gratings of high quality and efficiency, suggest that hard X-ray phase imaging with grating interferometers can find application in areas where phase imaging would be desirable, but is currently not widely used. In particular, the possibility to combine the instrument with imaging systems of an even larger field of view let us envisage applications in such fields as medical and biological imaging.

References:

1. A. MOMOSE,
   Phase-sensitive imaging and phase tomography using X-ray interferometers,
   Optics Express 11, 2303 (2003).

2. C. DAVID, B. NOEHHAMMER, H. SOLAK, AND E. ZIEGLER,
   Appl. Phys. Lett. **81**, 3287 (2002).

3. T. WEITKAMP, A. DIAZ, B. NOEHAMMER, F. PFEIFFER, M. STAMPANONI, AND C. DAVID,
   Moire interferometry formulas for hard x-ray wavefront sensing,
   SPIE Int. Soc. Opt. Eng. **5533**, 140 (2004).

4. T. WEITKAMP, A. DIAZ, B. NOEHAMMER, F. PFEIFFER, T. ROHBECK, AND C. DAVID,
Hard x-ray phase imaging and tomography with a grating interferometer,
SPIE Int. Soc. Opt. Eng. **5535**, 137 (2004).

5. T. WEITKAMP, A. DIAZ, C. DAVID, F. PFEIFFER, M. STAMPANONI, P. CLOETENS, ET AL.,
X-ray phase imaging with a grating interferometer,
Opt. Express **13**, 6296-6304 (2005).