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Observation of horizontal focusing of X-rays using a toothed-crystal monochromator

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The behaviour of a toothed-crystal monochromator for synchrotron radiation was studied for the first time on the GILDA CRG beamline at the ESRF. A new kind of horizontal focusing was observed which may be attributed to the properties of inclined diffraction. We have also observed a vertical focusing of the beam, the nature of which remains unexplained.

Keywords: inclined X-ray monochromators; sagittal focusing.

1. Introduction

The toothed-crystal monochromator (Hrdý, 1992; Hrdý & Pacherová, 1993) is a modified version of the inclined monochromator (Hrdý, 1992; Khounsary, 1992), which was proposed for high-power synchrotron radiation beams from bending magnets and wigglers.

In the inclined monochromator the incoming beam impinges on a crystal cut in such a way that the plane containing the normal to the crystal surface and to the diffracting crystallographic planes is perpendicular to the diffraction plane (or the plane of incidence), *i.e.* the plane containing the incoming beam and the normal to the diffracting planes. The diffraction is still symmetric, but the irradiated area on the crystal is increased by a factor $1/\cos\beta$, β being the angle between the crystal surface and the diffracting crystallographic planes. In this way higher power can be handled than with a flat crystal: calculations show that for a 5 kW wiggler output power the temperature on the crystal surface can be reduced from an unrealistic value of thousands of kelvin to less than 473 K, only inclining the crystal surface with respect to the incoming beam. In the toothed crystal $\cos\beta$ varies from positive to negative values along the crystal cross section (Fig. 1). In such a geometry a higher power can be handled while keeping the dimensions of the crystal reasonably small. Whereas the simple inclined geometry has already been successfully tested at the APS (Macrander *et al.*, 1992; Lee *et al.*, 1992), experiments with toothed crystals, to our knowledge, have not yet been reported.

A second relevant characteristic of the toothed crystal is its potentiality to demonstrate the focusing of the beam in the sagittal plane. The effect had been anticipated by Hrdý & Pacherová (1993) in a detailed study of the properties of diffraction from an inclined crystal. In their work the authors applied the dynamical theory of diffraction to the case of inclined diffraction with the intent of demonstrating that an inclined double-crystal monochromator behaves like a symmetrically diffracting monochromator, with the advantage of reducing the power density on the crystal. The dynamical theory of diffraction is normally treated by introducing a dispersion surface and boundary conditions into a diffraction diagram in reciprocal space. In contrast to conventional Bragg diffraction (symmetrical or asymmetrical), where the situation is completely described by a two-dimensional diffraction diagram as the problem is coplanar (the normal to the surface belongs to the diffraction plane), in inclined diffraction a three-dimensional diffraction diagram must be used. The authors show that the diffracted beam is slightly deviated from the diffraction plane, and that this deviation increases in going through the angular range of diffraction creating a small divergence in the direction perpendicular to the diffraction plane. A simple procedure is shown for the evaluation of the angular deviation. However, to our knowledge, no experimental evidence of this phenomena has been reported.

In this paper we report the first evidence of synchrotron beam deviation induced by inclined diffraction. By using a toothed crystal the deviation effect is visualized as a 'sagittal focusing' effect, as the two sides of the teeth act as two equal but oppositely inclined crystals, each side deviating the beam by the same quantity but in opposite directions, perpendicular to the diffraction plane. Also reported is the first experimental study of the thermal behaviour as a function of power load of a toothed crystal.

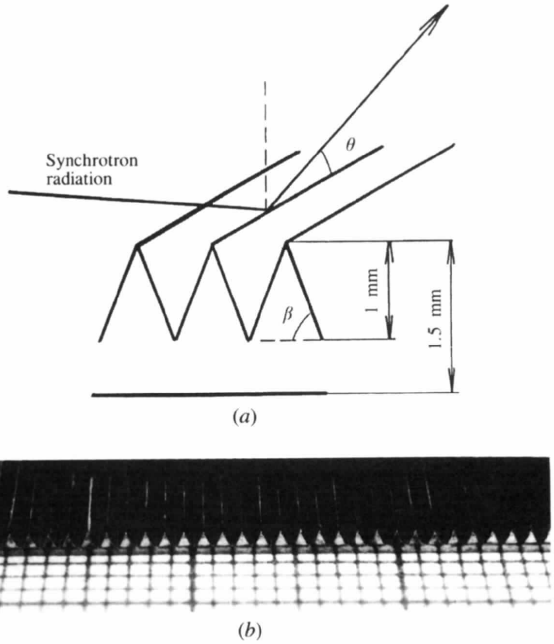

Figure 1
Silicon toothed crystal. (*a*) Schematic view: (111) crystallographic planes are on the horizontal plane. The length and the width of the crystal are 65 and 45 mm, respectively. The angle of inclination, β, of the teeth is 67.5–70°. (*b*) Photograph of the crystal.

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2. Experiment

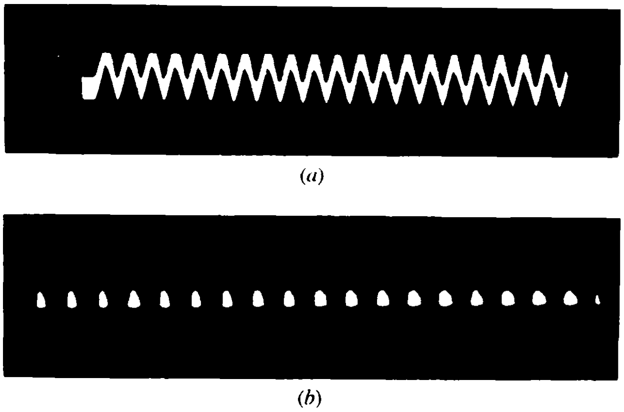
The experiment was performed on the GILDA beamline (Pascarelli *et al.*, 1995) at the European Synchrotron Radiation Facility (ESRF) in Grenoble. The machine operated in a 16-bunch mode, with an average current of 60–65 mA. A very simple toothed Si(333) crystal (Fig. 1) was used as the first crystal of the GILDA monochromator (Pascarelli *et al.*, 1996); it was attached to a cooled Cu plate through Ga–In eutectic. The second crystal of the monochromator was a 2 mm-thick flat Si(511) crystal with the surface parallel to the diffracting planes. In order to evaluate the thermal behaviour of the toothed crystal the experiment was then repeated using a flat first crystal, a 1 mm-thick Si(333) crystal, with the other two dimensions identical to those of the toothed crystal. Both (333) crystals were prepared at POLOVODIČE a.s. in Prague.

For the study of the thermal behaviour a series of rocking-curve profiles were measured at 8.4 keV ($\theta = 45^\circ$) under different thermal conditions. The power load was gradually increased by opening the vertical slits from 0.5 to 4 mm and by increasing filter transmission from a global power transmission of 25% (100 µm of Cu) to a transmission of 100% (no filters) so that the power density, defined as the power incident on a unit surface perpendicular to the beam direction, changed from 0.05 to 0.4 W mm^{-2}.

For the investigation of the beam deviation properties, photographs of the monochromatic beam using the toothed crystal were taken at different distances from the monochromator at 8.4 and 16.0 keV.

3. Results and discussion

The thermal behaviour of the toothed crystal was compared with that of the equivalent flat crystal by comparing rocking-curve-profile widths and intensities in the different thermal load conditions. In preliminary unpublished measurements using an X-ray tube the widths and intensities of the rocking curves relative to toothed and flat crystals were found to be comparable. Table 1 reports FWHM values obtained as a result of the best Gaussian fit of the measured rocking-curve profiles for the two crystals. Rocking curves recorded with the toothed crystal have slightly lower FWHM values when the slits are equal to 0.5 mm, but no significant difference was found with larger slit values. This is in agreement with the expected behaviour of the toothed crystal. In fact, due to the particular shape of the illuminated footprint, an improvement in thermal behaviour with respect to a flat crystal can be expected only if the vertical dimensions of the beam are smaller than the height of the teeth, *i.e.* 1.0 mm or less. These rather preliminary results also support the theoretical conclusions of Hrdý & Pacherová (1993), showing that it is possible to combine the inclined and symmetrical diffraction. Further, a more detailed study of the thermal behaviour of the toothed monochromator is obviously needed using vertically focused radiation or the radiation from a wiggler.



(*a*)

(*b*)

Figure 2
Photographs of the monochromatic beam at (*a*) 0.6 m and (*b*) 10 m from the monochromator using the toothed crystal as the first crystal. An Si(511) flat crystal was used as the second crystal.

Table 1
FWHM values obtained as a result of the best Gaussian fit of the measured rocking-curve profiles.

Slits (mm)	Cu filters (µm)	Flat FWHM (µrad)	Toothed FWHM (µrad)
0.5	100	15	10
	0	13	10
4.0	100	13	11
	0	17	17

The results relative to the investigation of the beam deviation properties are summarized in Fig. 2. In Figs. 2(*a*) and 2(*b*) we show the images of a 16 keV beam at 0.6 and 10 m from the monochromator, respectively, using a 1.0 mm slit. Fig. 2(*a*) shows a toothed profile which reflects the toothed surface of the crystal. The vertical dimension of the image is 2 mm, in accordance with the Bragg angle and the height of the teeth. Fig. 2(*b*) is, however, completely different: instead of showing a toothed profile, the radiation is horizontally concentrated into a row of spots with a vertical dimension of ~0.8 mm. This indicates the presence of beam deviation in the horizontal plane.

The rough horizontal 'focusing effect' may be explained in terms of the theoretical conclusion given by Hrdý & Pacherová (1993). There it was shown that the beam diffracted from an inclined crystal is slightly deviated from the diffraction plane (*i.e.* the plane containing the incident beam and the normal to the diffracting crystallographic planes) away from the surface of the crystal. Each tooth represents two inclined surfaces with opposite angles of inclination. The beam diffracted from each tooth is therefore split into two parts, each one deviated in opposite directions, towards the nearest channel, *i.e.* nearest space between teeth. The average angular deviation of the beam calculated for the above described diffraction conditions and the inclination angle of the toothed crystal ($\beta = 69^\circ$) is 2.65×10^{-5} rad, from which the splitting of the beam diffracted from each tooth can be calculated. At a distance of 10 m the theoretical value of the splitting is equal to 0.53 mm, in good agreement with the observed value 0.5–0.6 mm. This experiment supports, in a remarkable way, the calculated value.

Fig. 2 also shows that the vertical dimensions of the spots are ~0.8 mm, indicating the presence of a vertical focusing effect whose origin is not yet understood. Further investigations are necessary in order to understand the origin of the observed vertical focusing and to exclude any influence of deformation of the teeth, which may be caused by an increased temperature or by a clamping effect.

4. Conclusions

From the above discussion it follows that a longitudinal groove fabricated into a crystal can eventually focus an X-ray beam in the sagittal plane. This kind of 'inclined' focusing might be useful for narrow, *i.e.* undulator, beams. The V shape of the grooves in the toothed monochromator is, of course, the simplest of shapes, and produces only very imperfect focusing. To improve the focusing properties it is necessary to increase the slope of the wall of the groove as the distance from the axis of the groove increases ('inclined' lens). The presence of the groove moreover decreases the power density of the impinging radiation on the crystal surface. On the other hand the groove increases the vertical dimension of the diffracted beam. Apart from the vertical focusing observed in this experiment, the problem of reducing the vertical dimension of the beam may be solved, for example, by asymmetrical diffraction or by a vertically focusing mirror.

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