Magnifying effect by neutron diffraction on cylindrically bent perfect crystal (BPC) of Si in fully asymmetric diffraction geometry

P Mikula, V Ryukhtin and J Šaroun
Nuclear Physics Institute ASCR, v.v.i., 250 68, Řež, Czech Republic
mikula@ujf.cas.cz

Abstract. Low absorption of neutrons in Si crystal enables using the fully asymmetric diffraction geometry (FAD) of the single crystal slab in which neutron beam can pass inside a rather long distance more than ten centimetres. A practical exploitation of this property can be namely in the case of bent perfect crystals when due to the homogeneous deformation a neutron beam can meet, on the path, the diffraction condition only once and its attenuation is mainly brought about by absorption or incoherent scattering. In this paper a large one dimensional magnifying property of the FAD geometry of the cylindrically bent perfect crystal slab of Si is demonstrated. This property can be used in high resolution small angle neutron scattering as well as in neutron imaging.

1. Introduction
It is well known that depending on geometry of the single crystal and the diffractometer performance one can easy manipulate e.g. with resolution, cross-section, focusing properties of the diffracted beam in the scattering plane. In the case of manipulation of the cross-section of the beam, the simplest way is to use asymmetric diffraction geometry, which has been studied many times and described in many text books related to neutron or X-ray diffraction. Namely, it is often used for special monochromator systems on scattering instruments using synchrotron radiation. The extremum case of the asymmetric diffraction geometry is so called fully asymmetric diffraction geometry (FAD geometry). Such unique diffraction geometry employing the crystal of a large length is only practical in neutron diffraction. Neutrons have a high penetration ability and namely perfect Si crystals are very suitable for such experiments and studies. Two contrasts can be distinguished: the FAD geometry with the output beam compression and the opposite one - the FAD geometry with the output beam expansion. In the case of the former one e.g. a wide incident polychromatic beam is impinging the crystal and a narrow (compressed beam) is diffracted when passing the crystal perpendicularly to its thickness e.g. along its longest edge. This alternative was already tested in the eighties for exploitation in designing of new types of neutron monochromators [1-3]. In the latter case a narrow beam enters the bent-crystal slab through the end face and, after passing along the longest edge of the slab, the diffracted monochromated beam is expanded to a large cross section. Such FAD geometry has been then successfully employed in the high resolution double bent crystal (1,-1) SANS diffractometer with the FAD analyzer as a second crystal [4-6] which provided a substantial enlargement of the range of analyzed angles and a possibility to use a one dimensional position sensitive detector for the analysis...
of the SANS signal instead of the step-by-step analysis with the conventional symmetric diffraction geometry of the crystal analyzer. Recently, double bent crystal dispersive \((n,m)\) arrangement with the second FAD crystal in the the output beam expansion diffraction geometry has been studied for imaging of refraction edge effects [7-9]. However, the FAD geometry can also be used for one dimensional magnifying as it is demonstrated in the following chapters.

2. Experimental performances
The experiments were carried out on the double crystal SANS diffractometer operating at the the neutron wavelength of \(\lambda=0.21\) nm and the neutron optics diffractometer operating at \(\lambda=0.162\) nm which are installed at the medium power reactor LVR-15 in Rez and figure 1 shows schematically the diffractometer arrangements and the detail of the FAD diffraction transforming the angular deviation \(\Delta \theta\) from the mean position, e.g. in the middle of the FAD-crystal, to the linear spatial shift \(\Delta x\). The arrangement related to figure 1b exploits a premonochromator - bent perfect Si(111) crystal slab - providing the monochromatic beam of a rather low collimation (no Soller collimators are used) and of a relatively large \(\Delta \lambda\) spread.

Figure 1. Schematic view of the basic diffractometer performances (a) and (b) used in the experiments and schematic sketch showing the detail of the FAD geometry of the Si crystal (c).

3. Experimental results

3.1. Double bent crystal \((1,-1)\) setting
The double-crystal setting as schematically displayed on figure 1a is used for high resolution SANS measurements. In this case the curvature of both Si crystals is changeable and permits the choice of an optimum resolution required by a SANS experiment. Neutrons diffracted somewhere in the irradiated volume in the vicinity of the middle of the first bent crystal can be secondarily diffracted in the equivalent spatially limited volume in the second FAD Si-crystal. This diffraction volume, namely, its length (roughly expressed as \(\Delta x/\sin 2\theta\)) along the longest edge of the FAD crystal slab, depends on the relative values of the bending radii \(R_1\) and \(R_2\) of both crystals. For demonstration of the magnifying effect small holes in Cd sheet were used as a sample (see figure 2). Figure 3 displays the image of two vertically situated holes of the diameter of 0.7 mm with the mutual distance of 19 mm situated just in front of the face of the FAD crystal for two different radii of curvature and for \(R_2=20\) m. 2d-PSD used for imaging was situated at the distance of \(0.9\) m from the middle of the FAD crystal. It can be clearly seen that there is a strong one dimensional magnification in the horizontal scattering.
plane. Some vertical magnification is brought about by the vertical divergence of the monochromatic beam. Individual displayed fein lines in each hole image belong to the wires of the 2d-PSD detector having spatial vertical resolution about 2.5 mm. 1 channel corresponds to 0.09 mm.

3.2. Three axis Si(111)+(n,-m) diffraction performance with the third FAD crystal slab

In this case, the bent Si(111) crystal, due to its large lattice constant, can be considered as premonochromator for the next quasidispersive double crystal (n,-m) setting when providing rather divergent monochromatic beam of a large \( \Delta \lambda \) spread (see Fig. 1b). However, the used quasidispersive (n,-m) setting improves considerably \( \Delta \lambda \) as well as \( \Delta \theta \) resolution. The effect of cross section manipulation of the diffracted beam is demonstrated in figure 4 by imaging vertically arranged small holes in a Cd sheet situated just before the front face of the FAD crystal in the place of slit S\(_2\). It can be seen from figure 4 that the FAD crystal works as a one dimensional magnifying glass. For larger radii of curvatures of the FAD crystal the spreading of the beam inside of it can be several centimetres. In this case the imaging plate (IP) was at a distance of 10 cm from the FAD crystal. The beam was relatively high, nearly 4 cm. Radius of curvature of the Si(220) slab was 36 m and the radii of FAD Si(311) slab was 9 m. After that we imaged only one hole from the middle of the sample with a nearly released bending of the FAD crystal (\( R \approx 100 \) m) and the radius of Si(220) slab of 36 m (see figure 5). Similarly to the previous case described in paragraph 3.1, the magnifying factor depends on the relative combination of curvatures of the Si(220) and FAD crystal slabs. Generally, it can be said that the value of magnifying factor increases with the value of the radius of the FAD crystal slab. In the case of the larger hole (\( \phi = 0.7 \) mm) the influence of the vertical divergence making the image "thicker" is

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Figure 3. Image of two vertically situated holes of the diameter of 0.7 mm with the mutual distance of 19 mm for \( R_{FAD} = 56 \) m and \( R_{FAD} = 131 \) m, respectively.

Figure 4. The photo of the sample used in the vertical position (left) and the magnified image of the holes taken by means of the FAD analyzer and IP.

Figure 5. Magnified image of the 1 mm hole IP for a nearly released bending of the FAD crystal.
clearly visible. It should also be pointed out that the enlarged cross section of the monochromatic beam has locally much higher spatial resolution. High resolution properties of the double-diffracted beam in the scattering plane (in our case it is horizontal plane) can also be proved in the case of imaging some linear objects. In the present case we imaged the rectangular edges of Ti and Al plates (see figure 6). Inspection of figure 6 reveals that at the edges of the samples a typical refraction of neutrons takes place. It has been found that its observation depends on the curvature of the crystals and a proper distance of IP from the sample.

4. Conclusion
It has been demonstrated that the fully asymmetric diffraction geometry of the bent perfect crystal employed in the nondispersive (1,-1) and quasidispersive (n,-m) double-crystal settings permits a considerable one dimensional magnifying of small objects in the scattering plane. It is in fact a spatial enlargement of the analyzing angular scale. The observed slight increase of the height of the image is brought about simply by the vertical divergence of the neutron beam. As the neutron beam should pass inside the FAD crystal along its longest edge, thanks to low attenuation factor, perfect crystal of silicon appears as the best one for application. The choice of the crystal slabs was given mainly by some fixed experimental conditions. Of course, that some other settings employing the FAD second crystals could also be used for other neutron wavelengths. For design and optimization of such double bent crystal settings, Monte Carlo simulations are desirable.

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References
[1] Mikula P, Kulda J, Vrána M and Chalupa B 1984 J. Appl. Cryst. 17 189.
[2] Mikula P, Chalupa B, Kulda J, Vrána M, Sedláková L and Michalec R 1985 J. Appl. Cryst. 18 135.
[3] Mikula P, Kulda J, Horalík L, Chalupa B and Lukáš P 1986 J. Appl. Cryst. 91 324.
[4] Lukáš P, Mikula P, Šaroun J and Strunz P 1994 Nucl. Instrum. Methods in Phys. Research, A 338 111.
[5] Šaroun J, Lukáš P, Mikula P and Alefeld P 1994 J. Appl. Cryst. 27 80.
[6] Hempel A, Eichhorn F, Reichel P and Boede W 1995 Nucl. Instrum. Methods in Phys. Res. A 381 466.
[7] Mikula P, Vrana M, Seong B S, Woo W, Em V and Korytár D 2014 IOP Publishing Journal of Physics: Conference Series 528 012004.
[8] Mikula P, Vrana M, Šaroun J, Pilch J, Seong B S, Woo W and Em V 2014 J. Appl. Cryst. 47 Part 2, 599.
[9] Mikula P, Vrana M and Korytár D 2015 Physics Procedia 69 320.