# Experimental Study for the Feasibility of a Crystalline Undulator

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We present an idea for creation of a crystalline undulator and report its first realization. One face of a silicon crystal was given periodic microscratches (grooves) by means of a diamond blade. The x-ray tests of the crystal deformation due to a given periodic pattern of surface scratches have shown that a sinusoidal-like shape is observed on both the scratched surface and the opposite (unscratched) face of the crystal; that is, a periodic sinusoidal-like deformation goes through the bulk of the crystal. This opens up the possibility for experiments with high-energy particles channeled in a crystalline undulator, a novel compact source of radiation.

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The energy of a photon emitted in an undulator is in proportion to the square of the particle Lorentz factor $\gamma$ and in inverse proportion to the undulator period $L$. The minimal period $L$ achieved presently with the electromagnetic undulators is limited to several millimeters [1], with a corresponding restriction to the photon energy on the order of $\hbar\omega = 2\pi\hbar\gamma^2 c/L$. Crystalline undulators (CU) with periodically deformed crystallographic planes offer electromagnetic fields in the order of 1000 T and could provide a period $L$ in the submillimeter range. This way one can also achieve substantial oscillation amplitudes $A$ for the particles channeled in the undulator and thus increase the radiation intensity.

Currently, bent crystals are largely used for channeling extraction of 70-GeV protons at IHEP (Protvino) with efficiency reaching 85% at intensity well over $10^{12}$ particle per second, steered by silicon crystal of just 2 mm in length [2]. A bent crystal (5 mm long) is installed into the yellow ring of the Relativistic Heavy Ion Collider where it channels Au ions and polarized protons of 100–250 GeV/u as a part of the collimation system [3].

With a strong world-wide attention to novel sources of radiation, there has been broad theoretical interest [4–12] in compact crystalline undulators, with some approaches covering also nanotechnology to make use of nanotubes to guide radiating particles. The performance of CU is limited by scattering (on lattice electrons and ions) and by channel curvature. Positrons of $E = 0.5$–$0.8$ GeV are dechanneled in Si(111) over length $L_D \approx 0.5$–$1.0$ mm. For electrons, nuclear scattering shortens $L_D$ significantly. At some low $E$, increased scattering makes $L_D$ as short as $\approx L$; that sets a lower limit on $E$ for any given CU. On the other hand, channel curvature radius $R$ should be larger than Tsyganov radius $R_T$ (preferably, $E/R \leq$ 1–2 GeV/cm); this sets a higher limit on $E$, respectively.

Kaplin *et al.* first proposed the idea of crystalline undulator in 1979 [4,5]; the same authors have suggested the historically first idea [5] of how one could realize a CU, namely, by applying ultrasonic waves for periodical deformation of crystal lattice. A more recent idea [11] was to use graded-composition strained layers in superlattices like $\mathrm{Ge}_x\mathrm{Si}_{1-x}$ with periodic variation of $x$, based on Ref. [13]. Another proposal [14] was to induce periodical strains in the crystal by covering its surface with periodically placed strips of $\mathrm{Ge}_x\mathrm{Si}_{1-x}$ grown onto a Si substrate. However, these ideas are still pending realization.

In 70-GeV proton channeling experiments [15], it was found that accidental microscratches on a crystal surface cause a deformation of the crystallographic planes to substantial depths, down to a few hundred microns as depicted in Fig. 1(a). The plane deformation can be reconstructed by profile analysis for protons channeled in crystals (Ref. [15], p. 120). The analysis showed that protons near a scratch are channeled by deformed crystal planes. Therefore, this effect could be profitably used for creation of a CU by making a periodic series of microgrooves on the crystal surface as shown in Fig. 1(b).

For the first experimental proof of the method, a special diamond blade scratched one face of a silicon plate with a set of parallel grooves. A sample with dimensions of $50 \times 17 \times 0.48$ mm$^3$ was prepared from a commercial silicon wafer. The large polished faces of the sample were parallel to crystal planes (001), other faces were parallel to planes (011) and (01-1). On one of the large faces, 16 grooves were made with 1 mm period along the 50 mm edge. The grooves had 100 $\mu$m width and the same depth.

The prepared sample was carefully investigated with the help of the single-crystal diffractometer, part of the two-crystal x-ray spectrometer described in [16]. The setup is shown in Fig. 2. The x-ray (Mo $K_{\alpha 1}$, 17.4 keV)

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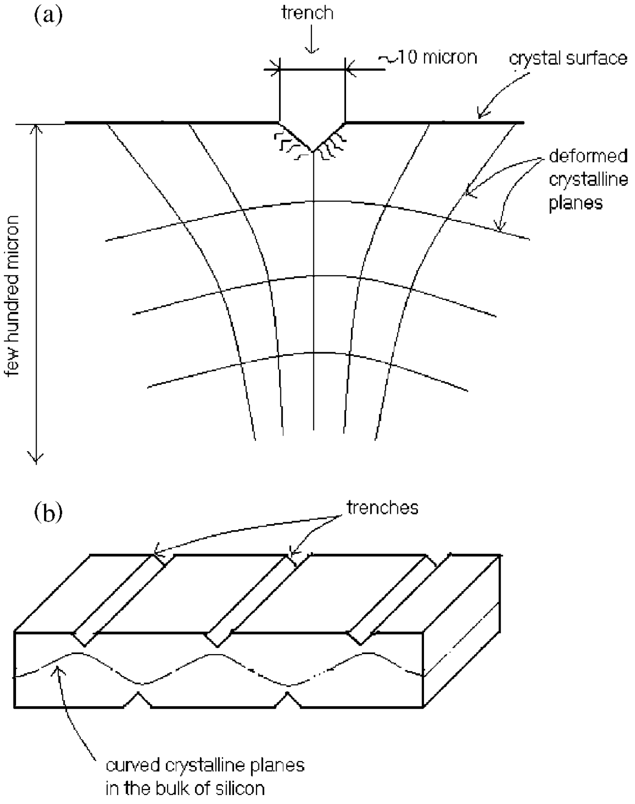

FIG. 1. (a) Angular distortion of the crystal planes near a surface scratch (groove). (b) Scheme of proposed crystalline undulator.

beam was collimated to 2 mm height and 40 $\mu$m width before incidence on the sample surface. The sample could be translated with an accuracy of 1 $\mu$m and 1 arcsec by use of a standard theodolite. A NaI counter with a wide-acceptance window detected the diffracted radiation. The count rate of diffracted quanta is maximal under the Bragg condition, achieved by rotation of the sample.

Two parameters were measured for each x-ray beam position: intensity of the diffracted beam and the angular position of the sample corresponding to a half intensity of the diffracted beam. The intensity is proportional to the integral reflectivity of the crystal at the point of x-ray beam diffraction, and is very sensitive to crystal deformations. In the present studies, the sensitivity of this parameter to the bending of crystal planes in the diffraction area was a fraction of 1 arcsec. The angular position of the sample is related through the Bragg law to the orientation of crystal planes and to the magnitude of interplanar distance; the accuracy of angle readings was a fraction of 1 arcsec. The change in the second parameter along the $x$ axis is completely due to the change in the orientation of crystal planes. Sensitivity of this parameter to plane orientation was 2 arcsec.

Figures 3(a) and 3(b) show the measured intensities and angles as functions of the beam incidence position at the surface with grooves. On the same absolute scale, the position of grooves is shown as well. The periodic angular deformation of the crystal planes reaches an order of 40–50 $\mu$rad. The plane deformation amplitude is in the order of 40 Å as obtained by analysis of the angle-versus-position function of Fig. 3(b).

Figures 4(a) and 4(b) show the corresponding values for the opposite (unscratched) face of the crystal, on the same absolute scale as in Fig. 3(a) and 3(b). One can see in Figs. 3 and 4 that peak positions on the opposite sides

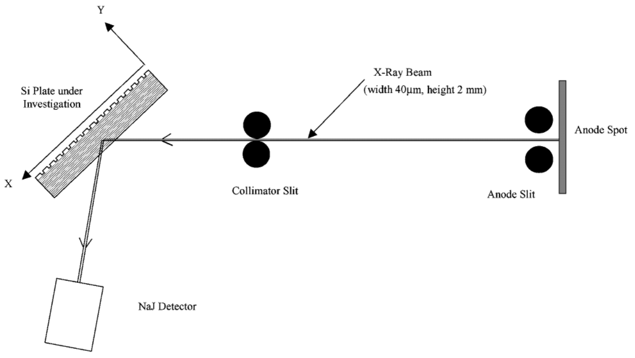

FIG. 2. Scheme of one-crystal mode of reflection-type measurements.

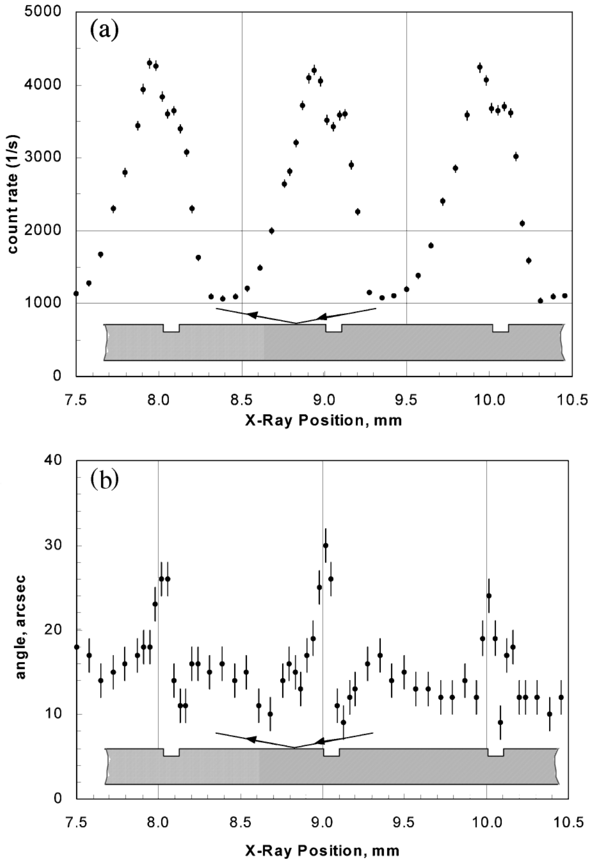

FIG. 3. (a) Intensity of diffracted beam versus the position of the incident x-ray beam along the $x$ axis, for crystal side with grooves. (b) Rotation angle of the sample versus the position of the incident x-ray beam along the $x$ axis, for crystal side with grooves.

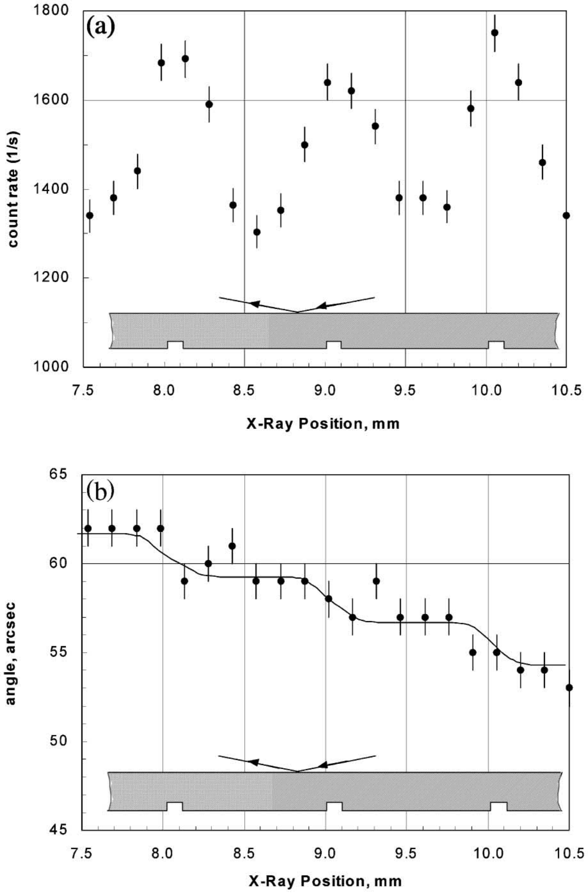

FIG. 4. (a) Same as in Fig. 3(a), but for the crystal side without grooves. (b) Same as in Fig. 3(b), but for the crystal side without grooves.

match each other and match the groove position as well; the systematic error for the absolute position in Figs. 3 and 4 is 50 μm. On the unscratched side, the local periodic deformations are smaller, just under 10 Å. If interpolated between the two faces, deformation amplitudes of order of 20 Å are expected in the bulk of the crystal.

The channel can be more distorted near the groove, where local $R$ approaches $R_T$. This could affect the channeled beam distribution near the groove. As fine structure in Figs. 3(a) and 3(b) shows, there is a local stress pattern across a groove. It was shown [15] with a 70 GeV beam that the pattern of plane distortions near a scratch is as shown in Fig. 1, not in the opposite sense.

As proven by the present experimental study, it is feasible to manufacture a crystalline undulator for channeling of radiating particles with a submillimeter period and with the amplitude of channel oscillations in the order of 20–40 Å, which is highly interesting for a novel radiation source [10–12]. Based on this success, an experiment on photon emission from a crystalline undulator is being planned at the Laboratori Nazionali di Frascati with 0.5–0.8 GeV positrons. The present grating spacing $L = 1$ mm is too large in that case, $L \approx L_D$. For the experiment we plan to produce a grating spacing $L \approx 0.1$ mm to obtain CU with $\approx 10$ periods and undulator parameter $K \approx 0.3$ (with equivalent field of $\approx 300$ T); the expected CU photon energy is $0.95E^2[\mathrm{GeV}] \times L^{-1}[\mathrm{cm}](1 + K^2/2)^{-1} = 50$ KeV. For comparison, channeling radiation in this crystal produces photons of $\approx 2$ MeV as the period of channeling oscillations is $\approx 40$ times shorter than $L$. Therefore, the spectra of undulator and channeling radiation in our crystal are well separated.

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[1] J. R. Schneider, Nucl. Instrum. Methods Phys. Res., Sect. A **398**, 41–53 (1997).
[2] A. G. Afonin *et al.*, Phys. Rev. Lett. **87**, 094802 (2001). See also http://crystalbeam.narod.ru.
[3] R. P. Fliller III *et al.*, in Proceedings of the European Particle Accelerator Conference, Paris, 2002 (to be published).
[4] V. V. Kaplin, S. V. Plotnikov, and S. A. Vorobiev, Zh. Tekh. Fiz. **50**, 1079–1081 (1980).
[5] V. V. Kaplin, S. V. Plotnikov, and S. A. Vorobiev, in *Abstracts of the 10th Conference on the Application of Charged Particle Beams for Studying the Composition and Properties of Materials* (Moscow State University, Moscow, 1979), p. 28.
[6] V. G. Baryshevsky, I. Ya. Dubovskaya, and A. O. Grubich, Phys. Lett. **77A**, 61–64 (1980).
[7] H. Ikezi, Y. Lin, and T. Ohkawa, Phys. Rev. B **30**, 1567–1568 (1984).
[8] S. A. Bogacz and J. B. Ketterson, J. Appl. Phys. **60**, 177–188 (1986); S. A. Bogacz, Part. Accel. **42**, 181 (1993).
[9] G. B. Dedkov, Phys. Status Solidi (b) **184**, 535–542 (1994).
[10] A. V. Korol, A. V. Solovev, and W. Greiner, Int. J. Mod. Phys. E **8**, 49–100 (1999).
[11] U. Mikkelsen and E. Uggerhoj, Nucl. Instrum. Methods Phys. Res., Sect. B **160**, 435–439 (2000).
[12] R. O. Avakian, L. G. Gevorgian, K. A. Ispirian, and R. K. Ispirian, Nucl. Instrum. Methods Phys. Res., Sect. B **173**, 112–120 (2001).
[13] M. B. H. Breese, Nucl. Instrum. Methods Phys. Res., Sect. B **132**, 540–547 (1997).
[14] R. O. Avakian, K. T. Avetyan, K. A. Ispirian, and E. G. Melikyan, Nucl. Instrum. Methods Phys. Res., Sect. A **492**, 11–13 (2002).
[15] V. M. Biryukov, Yu. A. Chesnokov, and V. I. Kotov, *Crystal Channeling and Its Application at High-Energy Accelerators* (Springer, Berlin, 1997).
[16] S. G. Skornyakov, A. I. Smirnov, and G. P. Solodov, “Precision Measurements of the WL$\beta$1, WL$\beta$3, MoL$\beta$1, MoL$\gamma$1 X-ray Wavelengths with Two-Crystal Spectrometer” (to be published).