Crystal undulator as a new compact source of radiation

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Crystalline undulators with periodically deformed crystallographic planes offer coherent electromagnetic fields on the order of 1000 T and provide undulator period L in submillimeter range. We present an idea for creation of a crystalline undulator and report its realization. One face of a silicon crystal was given periodic microscratches (grooves) by means of a diamond blade, with a period ranging from 0.1 to 0.5 mm in different samples. The x-ray tests of the crystal deformation have shown that a sinusoidal-like shape of crystalline planes goes through the bulk of the crystals. This opens up the possibility for experiments with high-energy particles channeled in the crystalline undulator, a new compact source of radiation. The first experiments on photon emission in the crystal undulator are in preparation at IHEP (Protvino) with 2–15 GeV positrons and at LNF (Frascati) with 500–800 MeV positrons, aiming to produce undulator photons in the range of 50–500 keV. The results of Monte Carlo simulations for the planned experiments are presented as well.

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I. INTRODUCTION

Accelerator-based sources of hard-photon radiation are a rapidly developing field, as can be seen, e.g., from a topical issue of *Beam Line* [1]. Coherent radiation of a particle beam in an undulator is a popular choice. The energy of a photon emitted in an undulator is in proportion to the square of the particle Lorentz factor γ and in inverse proportion to the undulator period L: $\hbar\omega = 2\pi\hbar\gamma^2 c/L$. Typically, at the modern accelerators the period of the undulator in the synchrotron light sources is a few centimeters [1].

With strong worldwide attention to novel sources of radiation, there has been broad interest [2–10] to compact crystalline undulators. The crystalline undulators with periodically deformed crystallographic planes offer electromagnetic fields on the order of 1000 T and could provide a period L in the submillimeter range. This way, a hundredfold gain in the energy of emitted photons would be reached, as compared to a usual undulator.

The use of bent crystals for channeling extraction of beams from accelerators has been under development at several laboratories [11–15]. A collaboration of researchers working at the 70 GeV accelerator of IHEP has recently achieved a substantial progress in the efficiency of crystal-assisted beam deflection: extraction efficiency larger than 85% has been obtained at intensity as high as 10^{12} protons [16].

II. PECULIARITIES OF CRYSTALLINE UNDULATOR

Particle trajectories in a deformed crystal are more complicated than in a usual undulator (see Fig. 1). Undulator radiation is accompanied by a harder component (channeling radiation) due to channeling with a smaller period of oscillations $L_{chr} \sim 3\ \mu$m (for typical energies of a few GeV, where undulators are used). On the other hand the channeling component of particle motion in a crystalline undulator (CU) has the amplitude of oscillations also small $A_{chr} \sim 1$ Å. The resulting spectral density for the radiation of a particle moving in a CU is the subject of computation presented later in this paper.

The performance of a CU is limited by scattering (on lattice electrons and ions) and by channel curvature.

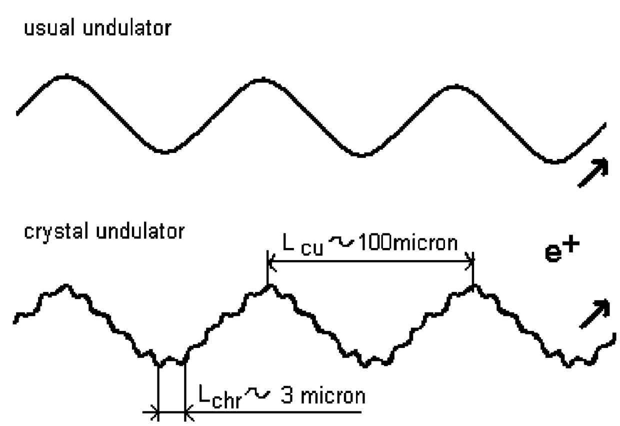

FIG. 1. Peculiarities of the crystalline undulator.

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Positrons of $E = 0.5$–0.8 GeV are dechanneled in Si(111) over length $L_D \approx 0.5$–1.0 mm; L_D grows with E almost linearly. 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 the Tsyganov radius R_T (preferably, $E/R \leq 1$–2 GeV/cm); this sets a higher limit on E, respectively.

III. METHOD OF CRYSTALLINE UNDULATOR CREATION

Different ideas were proposed for the creation of crystalline undulators [3–10], but they are still pending realization. Recently [2] we demonstrated experimentally by means of x rays that microscratches on the crystal surface make sufficient stresses for the creation of a crystalline undulator by making a series of scratches with a period of 1 mm. Presently, we have optimized this process and were able to produce an undulator with a period in submillimeter range and with a good amplitude. A series of undulators [(110) oriented silicon wafers] was manufactured with the following parameters: the length along the beam 1 to 5 mm, thickness across the beam 0.3 to 0.5 mm, ten periods of oscillation with step from 0.1 to 0.5 mm, and the amplitude on the order of 20–150 Å. Figure 2 shows a fragment of an undulator as seen in microscope. The trenches (about 50 μm wide) produced by micromachining on the surface of the undulator about 200 μm apart induce periodic deformations that propagate inside the bulk of the Si crystal. In order to visualize this phenomenon, we show in Fig. 3 a different viewing angle of the same fragment. Several ways of grooving (by rotating the blade and by a diamond scriber) were tried, and the optimization process continues. The size of the grooves and the pressure of the scriber are found empirically, aiming at producing maximal deformations while the crystal is not breaking yet. The characteristics of the undulators were tested with x rays as described in Ref. [2].

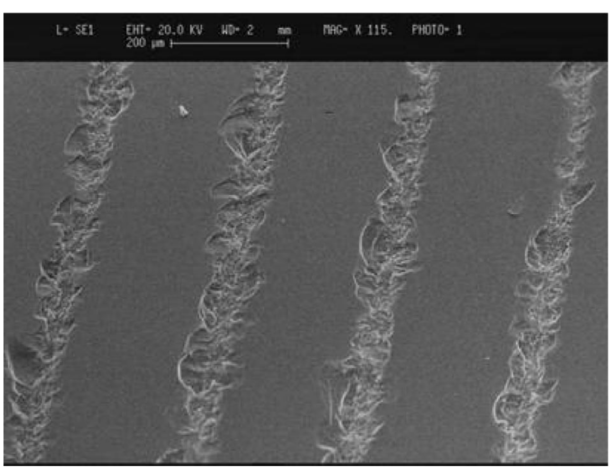

FIG. 2. Surface fragment of one of the manufactured crystal undulators seen by a microscope.

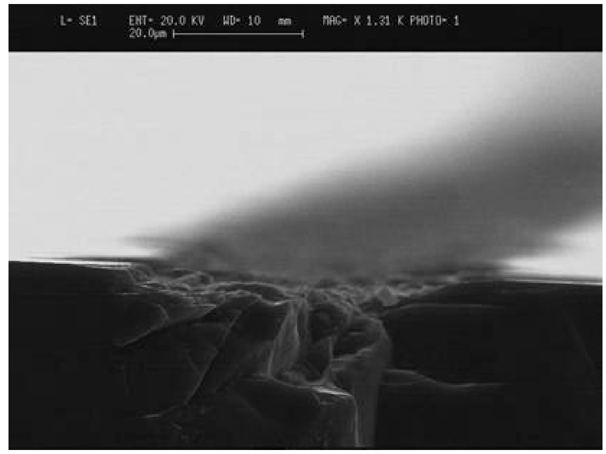

FIG. 3. Microscratch-induced deformations propagating in the bulk of the Si crystal.

The x-ray (Mo $K_{\alpha 1}$, 17.4 keV) beam was collimated to 2 mm height and 40 μm width before incidence on the sample surface. The sample could be translated with the accuracy of 1 μm and 1 arc sec 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 the rotation of the sample.

Figure 4 shows the measured angles as functions of the beam incidence position at the crystal surface. 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 mrad. The plane deformation amplitude is on the order of 20 Å as obtained by the analysis of the angle-versus-position function of Fig. 4, measured on the opposite (unscratched) face of the crystal. This means that a sinusoidal-like shape of crystalline planes goes through the bulk of the crystal. Naturally, deformation amplitude is reduced with the

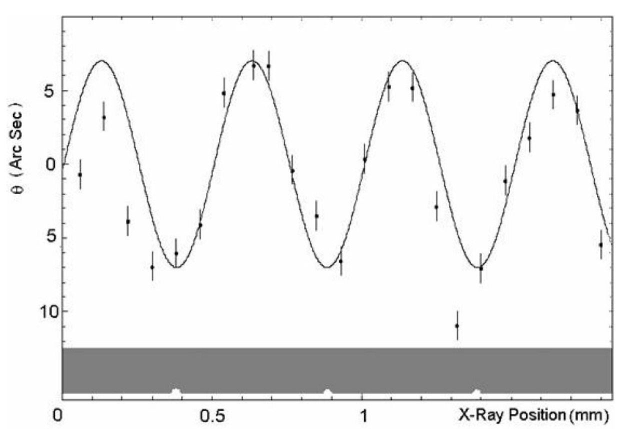

FIG. 4. X-ray test of one of the undulators.

depth in crystal. Therefore, crystal thickness should not be larger than the groove period. Besides, part of the crystal destroyed by grooving is not suitable for channeling. As it is difficult to obtain a clear theoretical picture of the disruptions, we directly tested crystal undulators for channeling of 70 GeV protons. Four CU wafers of thickness 0.3–0.5 mm, with 10 to 20 periods, were bent by means of devices described in Ref. [16]. The efficiency of proton deflection by CU wafers was compared to results of usual bent crystals of a similar size; the measurement technique is shown in Ref. [16]. The measurements showed that all CU crystals deflect protons with good efficiency and at least 70% of the crystal cross section is available for channeling (details of the experiment will be presented elsewhere). Experimentally established transparence for channeling of high-energy particles allows one to start a direct experiment on photon production from the positron beam in a crystalline undulator.

IV. SCHEME OF A PHOTON EMISSION EXPERIMENT

Our collaboration has two appropriate sites for an accelerator experiment on the generation of photons in a crystalline undulator. The two sites are LNF with the positron beam energy 500–800 MeV, and IHEP where one can arrange positron beams with the energy higher than 2 GeV. All equipment of the experiment is shown in Fig. 5.

In order to improve the background condition, one needs to place the crystalline undulator into vacuum. The crystal should be placed in a vacuum box, inside which a remotely controlled goniometer is positioned. The goniometer provides a horizontal translation of the crystal for its exposure into the beam within the limits of about 100 mm, with a step size of 0.1 mm. Also, it provides an angling of the crystal within ± 20 mrad with a step size of about 0.050 mrad. Right after the vacuum box, a cleaning magnet is positioned. The vacuum system is ended by a tube as long as 3 m, 200 mm in diameter, which has at the end a Mylar window 0.1–0.2 mm thick. The positron beam enters on the left side; undulator photons should be registered in front of the right side of the tube.

As a detector of photons, we use a crystal of NaI (Tl) of $\varnothing 1$ cm $\times$ 10 cm. To calibrate the γ detector, we use a radioactive source such as ^{241}Am with energy $E_\gamma =$ 59 KeV and ^{60}Co with energy $E_\gamma = 1.15$ MeV. The objective of the experiment is the observation of undulator photons emitted with expected energy in a crystalline undulator, the measurement of its spectrum, an experimental comparison to the case of a usual straight crystal, and the demonstration of the crystalline undulator work for the first time in the world.

First experimental results are expected soon, subject to the schedule of our accelerators.

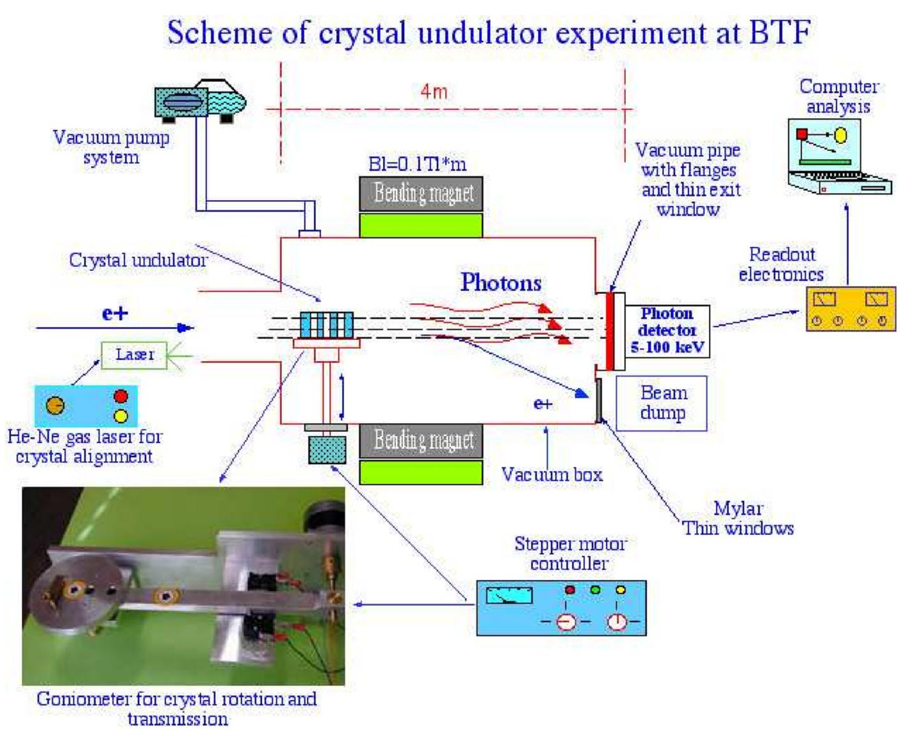

FIG. 5. (Color) The layout of the experiment on photon emission in the crystalline undulator.

V. EXPECTED PHOTON SPECTRUM

The calculations of radiation intensity were carried out for the (110) plane of the silicon single crystal. It is obvious that only channeled positrons can emit the low frequency radiation in the periodic above-considered structure. Thus the channeling radiation will take place as well, for this kind of crystal structures. In the general case, the character of the radiation of positrons can be determined by means of the dimensionless parameter [17] $\rho = 2\gamma^2 < v_p^2 > /c^2$, where $\langle v_p^2 \rangle$ is the mean squared transversal velocity of the particle. For the crystalline undulator $\langle v_p^2 \rangle$ is approximately equal to $\langle v_u^2 \rangle + \langle v_c^2 \rangle$ if the curvature of the trajectory is not large. Here $\langle v_u^2 \rangle$ and $\langle v_c^2 \rangle$ are mean squared transversal velocities for the undulator and channeling motion, respectively.

In the case when $\rho \leq 1$ the total radiation spectrum will be a simple additive combination of the (plain) undulator and channeling spectra. The total spectrum will be the sum of the contributions mostly corresponding to the two basic frequencies of both processes. In the case when $\rho \gg 1$ one can expect that the spectrum will be similar to the photon spectrum of synchrotron radiation.

At values of ρ slightly more than 1 the radiation spectrum has sufficiently complicated character and consists of some peaks. It should be noted that this case is more difficult for consideration. Besides, in a crystalline undulator, the dechanneling process and radiation of the above-barrier positrons are expected, and their influence on the photon spectrum is necessary to take into account. For calculations of the photon spectrum from the 800 MeV positron beam we selected the period and the amplitude of deformation of the silicon single crystal equal to 0.1 mm and 80 Å; these values we plan to obtain in the near future. In the case when parameter ρ is about or less than 1, one can calculate the expected photon spectra for the experiment in LNF.

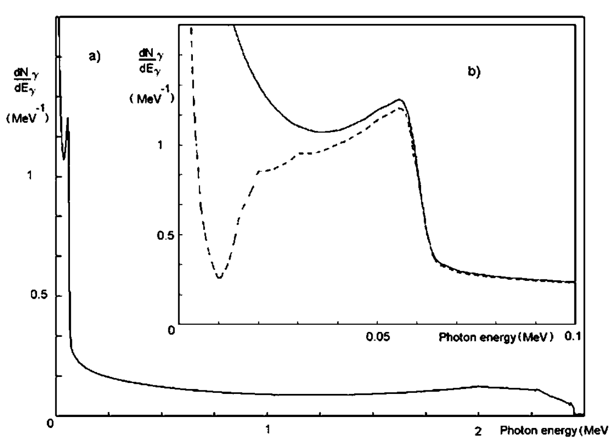

FIG. 6. The expected photon spectrum for 800 MeV positrons in the range 0–2.5 MeV (a) and 0–0.1 MeV (b). The dashed curve is the photon spectrum, where the absorption process of photons in the body of the undulator is taken into account. The curves are normalized on one positron passing through the undulator within the channeling angle.

Figure 6 illustrates the calculation of the spectral distribution of photons radiated in a crystalline undulator by 800 MeV positrons. One can see that the maximum of the distribution corresponds to approximately 55 KeV. The channeling radiation is computed in accordance with the paper [18] and these results are in good agreement with experimental data [19]. The distribution of the beam on the face of the crystal over the horizontal coordinate and angle (within channeling angle) in this computation was assumed uniform. The losses near the grooved surface were not taken into account because they are small. The small positive contribution above 2.4 MeV is both from the above-barrier particles and from the 2nd harmonics of the channeling radiation (this one is very weak). Our calculations take into account the following factors:

(1) channeling radiation and dechanneling process;

(2) finite length of the crystalline undulator, equal to 1 mm;

(3) radiation of the above-barrier positrons;

(4) absorption of gamma quanta in the undulator bulk (this process is calculated on the assumption that absorption in the undulator is similar to that in an amorphous silicon media [20]).

The channeling radiation is computed in accordance with the paper [18] and these results are in good agreement with experimental data [19]. Our calculations allow one to draw the following conclusions concerning the photon spectrum:

(1) A clear peak of the photon number can be observed in the range 30–60 KeV. The sum of the photons under this peak is equal to approximately 20% of all the photon spectrum (or 0.05 photons per positron). Most of the photons are due to channeling radiation. These photons are distributed in a wide range (up to 2.5 MeV) and their spectral density (per MeV) is 5 times lower than the undulator-photon density in the range with the undulator photons.

(2) The influence of the finite length of a single crystal and of the dechanneling process on the density and form of the undulator-photon spectrum is essential: the density is decreased 1.5–2 times and the maximum of the distribution is shifted from 61 to 55 KeV.

(3) The contribution of the radiation of the above-barrier positrons is insignificant and due to this fact a precise collimation of the positron beam is not required.

(4) The strong absorption process at the energies less than 30 KeV allows us to obtain better monochromaticity of undulator photons. The energies of the positron beams obtained at the IHEP accelerator in the direction of beam line No. 4 are 2–15 GeV. The calculated photon spectrum for the 3-GeV positron beam is shown in Fig. 7. In this case the ρ parameter is approximately 1. Our calculations were carried out for the (110) plane of a silicon single crystal. The length of the crystal undulator, amplitude,

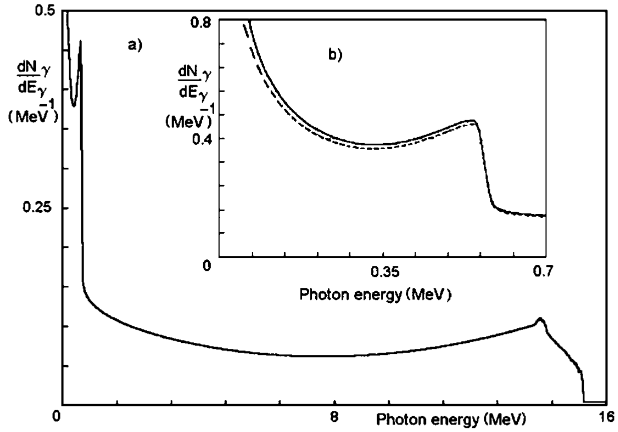

FIG. 7. The expected photon spectrum for 3 GeV positrons in the range 0–16 MeV (a) and 0–0.7 Mev (b). The dashed curve and the normalization are as in Fig. 6.

and period of the deformations were taken equal to 3 mm, 40 Å, and 0.15 mm, respectively. The calculated number photons in the range 100–600 KeV is 0.15 per one positron channeled through the crystalline undulator.

At positron beam energies higher than 3 GeV and at the selected parameters of the crystal undulator, the values of $\rho > 1$ are achieved and they can run up to 100 (for energies 10–15 GeV). For a usual undulator this case was solved analytically [17]. However, for a crystal undulator (where there are two practically independent frequencies of a particle motion) the finding of an analogous solution is important and actual problem. More detailed information concerning the calculations will be published elsewhere.

VI. CONCLUSION

Our studies on the creation and characterization of the periodically deformed crystalline structures and calculations of the expected photon spectra allow us to make the conclusion that a crystalline undulator will be able to produce intense x rays with the energies from 10 to 1000 KeV. The crystalline undulator would allow us to generate photons with the energy on the order of 1 MeV at the synchrotron light sources where one has at the moment only 10 KeV, and for this reason crystal undulators have interesting prospects for application.

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