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EMISSION OF PHOTONS AT THE INTERACTION OF A HIGH ENERGY POSITRON BEAM WITH A PERIODICALLY DEFORMED CRYSTAL*

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Abstract

Periodically deformed crystals have long attracted attention as "crystalline undulators" [1-8]. In the experiment carried out at the U-70 accelerator, the radiation of positrons moving in a periodically deformed crystal was observed. Experimental evidence has been obtained for an undulator peak in a radiation spectrum, which is qualitatively consistent with calculations. It is shown that most of the emitted energy is due to hard photons with energies of tens of MeV as a result of channeling and reflection of particles, whose spectral density is several times higher than the radiation in an amorphous target.

INTRODUCTION

Intense X-rays are currently used for research in biology, medicine, materials science, and many other areas of science and technology. The traditional way to obtain such beams (with energies of several keV and higher) is the use of special magnets - undulators at accelerators [9]. The energy of the photons generated in the undulator is proportional to the square of the Lorentz factor of the gamma particle and inversely to the period of the undulator L.

Unlike conventional undulators with a period of several centimeters, "crystal undulators" have a period of the submillimeter range and are capable of generating photons hundreds of times harder. In [10], a crystalline undulator was created for the first time, and in [11], an indication was obtained of the existence of an undulator peak in radiation. At the same time, background radiation from channeled particles with higher radiation energies was observed. Later it was shown that unchanneled above-barrier particles emit strongly on trajectory segments that are close to tangents to curved crystallographic planes (as a result of the "volume reflection" process [12-14]). In this work, we tried to measure the emission spectrum in a wide range of energies and to understand what proportion of this spectrum is undulator radiation. Figure 1 shows the difference between the trajectories of channeled particles in a crystalline undulator and trajectories in a conventional undulator. In a crystal, the sinusoidal motion of particles with a period of the deformation of the planes (~ 100 μm) is modulated by frequent oscillations (with a period ~ 1 μm) during channeling between curved crystallographic planes. The radiation due to channeling with frequent oscillations is many times tougher, but its spectral density is lower than undulator radiation due to the deformation of the planes.

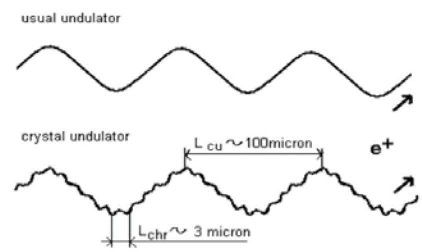

Figure 1: Particle trajectories in a conventional undulator (top) and in a crystalline undulator (bottom).

In addition, as noted above, the above-barrier particles, when their trajectories reach tangents to curved planes, perform aperiodic oscillations (Fig. 2) and also radiate strongly [12]. The techniques described below were used to measure the emission energy spectrum in a wide range.

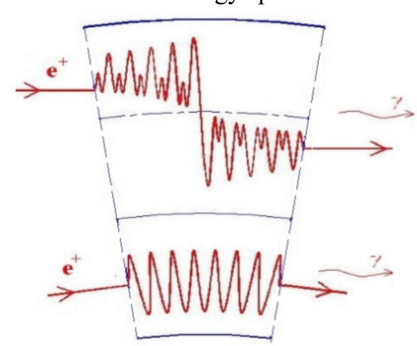

Figure 2: Trajectories of above-barrier particles near the tangent to curved planes (top); the trajectories of channeled particles in the same section are shown below.

CRYSTALLINE TARGET

In [10], the possibility of creating a crystalline undulator — a periodically bent crystal — by double-sided application of mechanical grooves was shown for the first time. A schematic of an undulator with applied grooves, developed at IHEP according to this principle, is shown in Fig. 3. The period of double-sided application of grooves d must be no less than the thickness of the crystal plate h so that sinusoidal deformations penetrate in deep into the entire thickness of the crystal, according to the Saint-Venant principle, known from the theory of elasticity [15]. The first data on radiation with a crystal undulator were obtained with a positron beam with an energy of 10 GeV at IHEP [11]. However, most electron accelerators, where crystal undulators can be used, operate at energies below 6 GeV.

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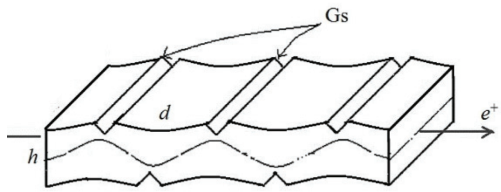
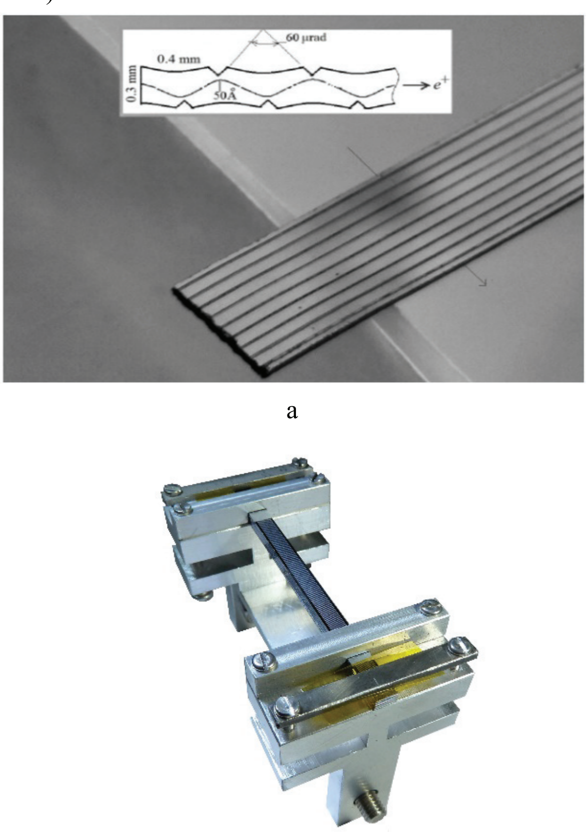


Figure 3: Schematic representation of a crystal undulator: Gs - grooves, d - period of grooving, h - thickness of the crystal plate, e+ - positron beam. The sinusoid shows curved crystallographic planes in the thickness of the crystal.

We have prepared new samples of crystalline undulators (Fig. 4a), optimized for lower energies of positrons, which can be achieved at operating electron accelerators. To capture most of the beam, several identical grooved plates were combined into an array in one holder (Fig. 4b). The experiment with new samples of undulators was carried out on the CRYSTAL setup at a positron energy of 6 GeV. With the achieved parameters, namely, a period of 0.4 mm, an amplitude of 50 Å, the number of periods is 8, it was planned to obtain an undulatory peak of photons about 0.6 MeV (experimental and calculated data will be presented below).



a

b

Figure 4: Crystalline undulator for a 6 GeV positron beam: a - its photograph and a schematic representation of its cross section (inset); b - appearance of the array of plates in one holder (crystal target in the assembly).

EXPERIMENTAL SETUP AND RESULTS

The experiment was performed in the 4a beamline of the U70 accelerator (Fig. 5). A positron beam with an energy of 6 GeV and an intensity of ~ 10^4 particles per cycle was directed to a crystalline device located in a goniometer.

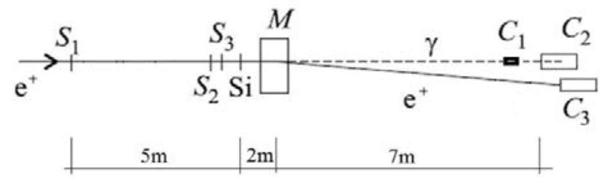


Figure 5: Schematic of the Crystal setup. S_1 – S_3 scintillation counters, C_1 – C_2 calorimeters for determining the energy of generated photons, C_3 – calorimeter for determining the energy of positrons after the magnet M. Si – crystal radiator in the goniometer.

The goniometer step was 0.02 mrad for horizontal rotation. The telescope of scintillation counters S_1, S_2, S_3 separated the fraction of particles entering the crystal radiator and formed an angular divergence σ_x ~ 0.5 mrad and σ_y ~ 1.0 mrad. Moreover, the last counter had a cross section of 2 × 30 mm, which coincides with the transverse dimension of the crystal assembly, and was mounted at the end of the radiator and could move with it in the goniometer due to the fiber-optic connection to the PMT. A vertically deflecting magnet M with a magnetic-path length Bl = 0.33 T×m separated the emitted photons and interacting positrons. The C_1 yttrium calorimeter was adapted to register photons in the 60 keV - 2 MeV region, the main BGO detector C_2 could register gamma quanta with energies of several MeV and above (the calorimeters were not used at the same time). In addition, the C_3 - Shashlyk electromagnetic calorimeter [16] registered positrons. The energy spectrum of the positron beam was measured with a Shashlyk calorimeter with a resolution of several percent. The C_1 calorimeter was also used to quickly find the planar orientation of a crystal target.

First, the main plane (111) was found, along which silicon strips were cut and bent, by rotating the horizontal angle φ_x. In Figure 6 shows the orientation dependence of the C_1 count on the horizontal angle of the goniometer.

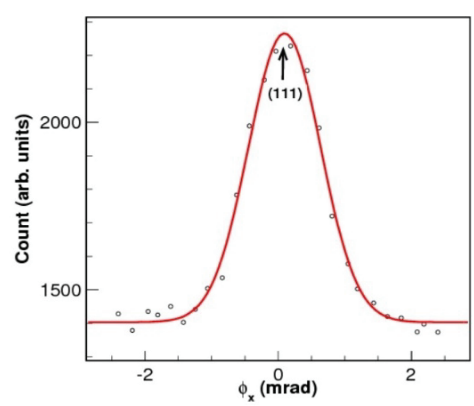


Figure 6: C_1 counting rate depending on the horizontal angle of crystal rotation.

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The spectra of emitted energy and energy losses of positrons were measured for two positions of the goniometer: in-plane orientation and disoriented state of the crystal target. In the case of a disoriented state, the crystal is equivalent to an amorphous radiator with a length of 3.5% of the radiation length. In Figure 7 shows the spectra of the emitted energy E × dN / dE for the above two cases of orientation of the crystal target, measured by the calorimeter C_2. The spectrum of the radiated energy for the disoriented state is shown by the horizontal line as for an amorphous medium. For an oriented state of a crystalline target, the emitted energy increases several times due to the generated photons with energies of the MeV range. Calculations show that channeling radiation predominates up to ~100 MeV; above this energy, radiation from above-barrier particles predominates in the spectrum.

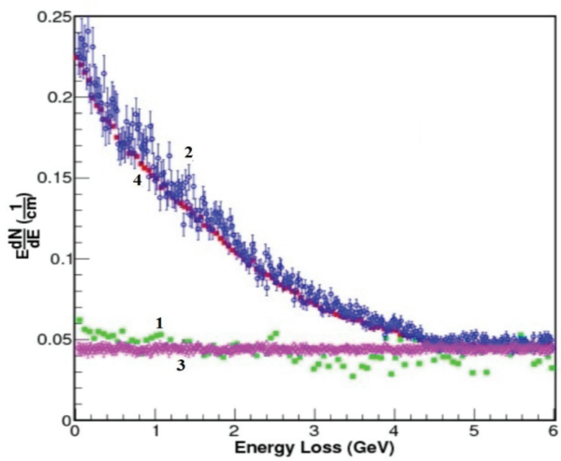

Figure 7: Measured spectra of the radiated energy in different positions of the crystal radiator: 1 - disoriented state, 2 - in-plane orientation; 3, 4 - the corresponding calculation results are shown.

Against this background of high emitted energy and processes of multiple photon production, undulator radiation in the soft spectral region is not visible. To register undulator radiation, it was decided to use another calorimeter based on yttrium aluminate $YAlO_3$. The signal at the yttrium detector adapted for recording undulator radiation was distorted. Calculations show that these distortions arise due to the presence of accompanying coherent radiation during channeling and reflection of particles. At a positron energy of 6 GeV in channel 4a, this creates a multiplicity factor of about 3, which is much higher than 1. Thus, most of the undulator events (0.5 photons per 1 positron) are accompanied by several photons of higher energy and are recorded with distortions. However, using a special selection of events with low energy losses of the primary positron using the Shashlyk calorimeter (about 10% of all statistics), we obtained spectra that are experimental confirmation of the existence of an undulator peak in the 0.6 MeV energy region.

The data on the emitted energy in the C_1 calorimeter, taking into account our selection criterion, are presented in Fig. 8 in comparison with the calculation results confirming the presence of a radiation peak at this energy. This comparison is possible only at a qualitative level, since the instrumental function of the detector was not taken into account (limited detection efficiency of gamma and Compton tail). It should be noted that the calculations of undulator, channeled, and above-barrier radiation were carried out using algorithms and programs [12, 17], where they are described in detail.

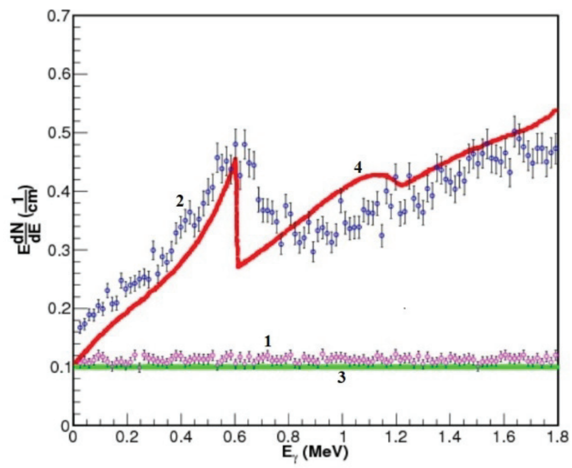

Figure 8: Spectra of the emitted energy in a crystalline target: 1 - experiment, 3 - calculation for the disoriented case; 2 - experiment, 4 - calculation for the oriented case of crystal target.

The setup scheme used will be upgraded in the next sessions of the accelerator operation. In particular, it is planned to use a narrow collimator to limit the angular distribution of gamma radiation. It is also proposed to apply the Compton scattering technique in order to restore the undistorted gamma spectrum.

CONCLUSION

The experiment observed the emission of positrons in a periodically deformed crystal. Under high background conditions of a due to the process of multiple production of photons, we received an experimental indication of the existence of an undulator peak in radiation at a qualitative level, which was confirmed by calculations. It is shown that most of the emitted energy is due to hard photons with energies of tens of MeV as a result of channeling and reflection of particles whose spectral density is a multiple of the radiation in an amorphous target. It is shown that most of the emitted energy is due to hard photons with energies of tens of MeV as a result of channeling and reflection of particles, whose spectral density is several times higher than the radiation in an amorphous target. It is this property of a periodically deformed crystal that makes it a promising source of radiation of high-energy photons and can be used in accelerators (for example, for transillumination of thick objects). The developed crystal radiators also have the prospect of being used for collimating beams at large electron-positron colliders [18], and can be used in special electromagnetic calorimeters (for example, in space).

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