OBSERVATION OF PARAMETRIC X-RAY RADIATION EXCITED BY 50 GeV PROTONS AND IDENTIFICATION OF BACKGROUND RADIATION ORIGIN

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The experimental layout designed to study properties of focused parametric X-ray radiation generated by relativistic protons in a bent crystal and parametric X-ray radiation generated by relativistic ions and positrons at accelerator U70 is described. Preliminary results of measurements of spectra of characteristic and parametric X-rays observed at 50 GeV proton beam are shown and discussed. The origin of the background radiation that obstacles for detail research of the PXR properties at proton beam is identified. Moreover, the distribution of the ionization losses of relativistic charged particles in the X-ray detector similar to Landau distribution is measured and discussed.

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INTRODUCTION

The parametric X-ray radiation (PXR) of relativistic charged particles in crystals has been observed and studied experimentally in a number of papers (see, for example, reviews of some experimental research in Refs. [1, 2]). In particular, the PXR excited by relativistic protons in crystals has been observed in Refs. [3 - 5]. Therein, a significant background radiation in X-ray spectra was observed but the origin of the background was unclear. We have started experiments to observe the focused PXR emitted by protons in bent crystal [6] and PXR emitted by relativistic ions and positrons at accelerator U70; however, a significant background radiation hampers the detail research. In this paper we describe the experimental facility and report about the experimental observation of characteristic and parametric X-ray spectra and identify the origin of the background radiation at proton beam.

1. EXPERIMENTAL

The experiment has been performed at extracted proton beam in accelerator U70 at IHEP, Protvino, Russia. The beamline of the extracted proton beam and the experimental layout are illustrated in Fig. 1.

The proton beam is extracted from the accelerator U70 to the beamline № 4a by a Si crystal bent on 90 mrad. The extraction of the beam by a bent crystal is well described in [7]. The extracted by the bent Si crystal proton beam population is about 10^7 protons per a cycle. The BM1 are BM2 are the 6-m long bending magnets that provide a bending angle of the proton beam of 40 mrad. The copper collimators CH and CV of length 75 cm form a rectangular shape of the proton beam. The 2-m long quadrupole lenses (QH and QV) provide the beam divergence of about 100 μrad in both horizontal and vertical planes.

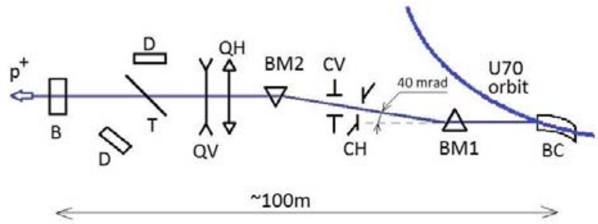

Fig. 1. The beamline and the experimental layout: The proton beam of energy 50 GeV is extracted from the U70 circular accelerator by a bent crystal BC. Then, the beam passes the bending magnet (BM1), horizontal and vertical collimators (CH and CV), bending magnet (BM2), quadrupole lenses (QH and QV), and target (T) mounted on a goniometer. The number of protons in the beam is registered by a fast scintillator counter (B). The X-ray detector (D) is shown at two locations

The proton beam profile measured in the vicinity of the target is shown in Fig. 2. The measurements were performed using the Dosimetry Film EBT2 and a scanner with the resolution of 20 μm.

The spectra were measured by a spectrometer consisting of an X-ray thermoelectrically cooled Si detector XR-100CR and a digital pulse processor PX4, both from Amptek. A 500 μm thick Si crystal detector with area of 6 mm^2 is equipped with a 0.3 mil Be window. The detector contains an inner collimator with area of 4.4 mm^2, which is opaque for soft X-rays but transparent for hard X-rays and relativistic particles. Due to intense background radiation we applied the shortest available in the PX4 peaking time 0.8 μs. The energy resolution of the spectrometer is about 260 eV at X-ray energy 5.9 keV. The measurements were performed during the extraction of the proton beam. The extraction time was 1 s executed every 9 s. The typical beam population was about (5…8)·10^6 protons per extraction.

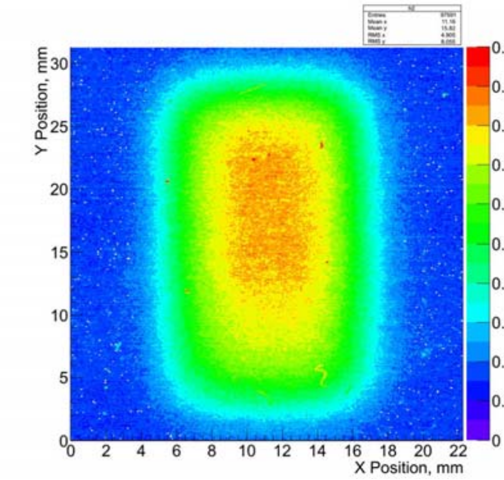

Fig. 2. The proton beam profile in the vicinity of the target

Crystalline targets were mounted on a goniometer with angular step of $2.18 \cdot 10^{-5}$ rad. The goniometer, the targets and the X-ray detector were assembled in air. The proton beam propagated from the vacuum tube to air through a Mylar foil. The distance from the Mylar foil to the target was about 1 m.

2. OBSERVATION OF CHARACTERISTIC X-RAY RADIATION

To make sure in our equipment we performed measurements of characteristic X-ray radiation (CXR) excited by 50 GeV proton beam in a copper target. The experimental setup is illustrated in Fig. 3.

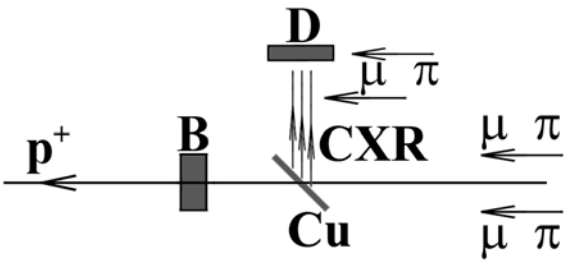

Fig. 3. The experimental setup for observation of characteristic X-ray radiation. Beam protons excite characteristic X-ray radiation in a copper foil. The spectrum of x-rays is measured by the detector D. The secondary relativistic particles like muons and pions accompanying the proton beam also cross the detector along its surface

As a target, we used a 20 μm thick Cu foil tilted at 45^0 angle with respect to the proton beam. The X-ray detector was installed at a 90^0 observation angle 60 cm away from the target. The measured spectrum is shown in Fig. 4 without the background subtraction.

In the spectrum shown in Fig. 4,a one can clearly see two spectral peaks with energies practically coinciding with reference energies of 8.0 and 8.9 keV of K_α and K_β CXR radiation of Cu respectively. The observation of the Cu CXR clearly demonstrates the possibility to measure X-ray spectra at the facility despite of the background radiation. In Fig. 4,b one can see the continuous background in the entire spectral range. The origin of this continuous background will be discussed below.

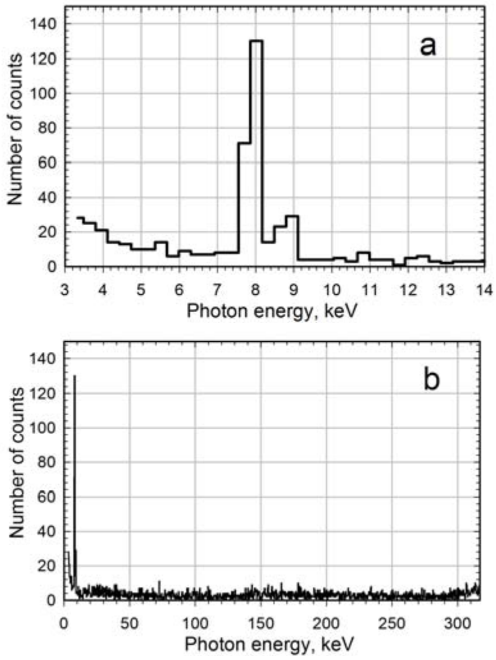

Fig. 4. The measured spectrum of characteristic X-ray radiation is shown without background subtraction in the range of 3…13 keV in Fig. a and in the range of 3…317 keV in Fig. b. Peaks with energies of 8.0 keV and 8.9 keV are due to K_α and K_β characteristic X-ray radiation from the Cu target

3. OBSERVATION OF PARAMETRIC X-RAYS

As a target, we used a flat 300 μm thick Si crystal slab with (111) crystallographic plane oriented parallel to the slab surface. The detector was installed at observation angle $\theta_{obs} \approx 19.9^0$ at distance 25 cm away from the target. The Si target was mounted on the goniometer and preliminarily aligned for observation of the PXR in Bragg geometry. The experimental setup for the PXR studies is shown in Fig. 5.

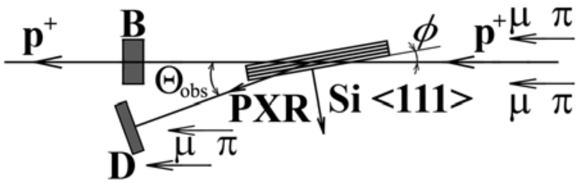

Fig. 5. The experimental setup for the PXR measurements

The transverse proton beam dimensions on the target were about 25 mm in vertical direction and 10 mm in horizontal direction. The experimental angular resolution was about 0.11 rad in vertical direction and 0.05 rad in horizontal direction. Both angular resolutions exceed typical angular size of the PXR reflection γ^{-1}, where γ is the relativistic factor. In our case $\gamma^{-1} = 0.019$ rad at proton beam energy 50 GeV. Therefore it is impossible to resolve clearly a fine structure of the PXR reflection yield in present experiment. Two spectra measured when the PXR reflection is aligned towards the detector and when the PXR reflection was aligned aside from the detector are shown in Fig. 6.

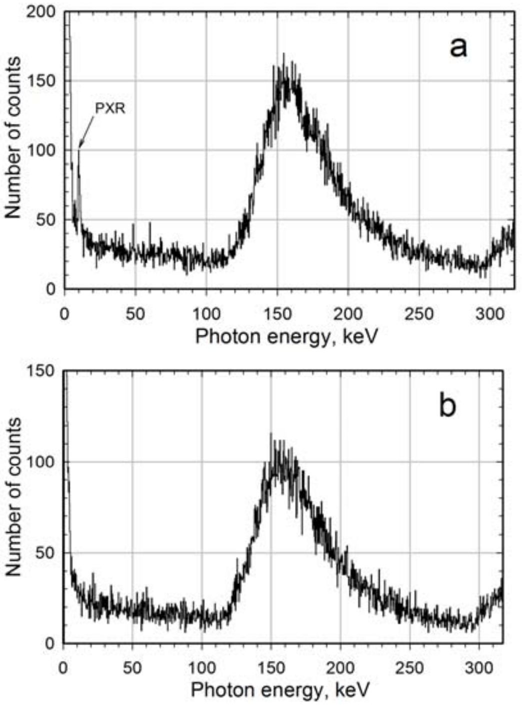

Fig. 6. Spectra without background subtraction measured when the PXR reflection is directed towards the detector (a) and when the PXR reflection is aligned aside from the detector (b). The arrow shows the PXR spectral peak

In Fig. 6,a one can see a spectral peak with the energy of 10.0 keV. However, the peak is absent in the same spectrum shown in Fig. 6,b measured at random crystal orientation. The energy of the measured peak coincident to the energy $\hbar\omega$ of the PXR reflection calculated by Eq. (9.5) [1] at the angle of crystal orientation of ϕ =8.7^0

$$\hbar\omega = \frac{\hbar \cdot g \cdot V \cdot \sin\phi}{1-\beta \cdot \sqrt{\varepsilon} \cdot \cos\theta_{obs}}, \qquad (1)$$

where g is the module of the reciprocal lattice vector for Si crystallographic plane (111), V is the proton velocity, $\beta = V/c$, ε is the permittivity, θ_{obs} is the observation angle. Thus, the spectral peak with the energy of 10.0 keV definitely appears due to the PXR reflection from Si crystallographic plane (111). Other experimental data on the PXR will be considered in more details elsewhere.

The PXR peak / background ratio in the spectrum shown in Fig. 6,a is about 1:1. This ratio is much worse then one in experiments at electron beams, where the peak / background ratio can reach values 100:1 or more [1, 2]. The origin of so high spectral background at proton accelerator and the wide asymmetric spectral peak with the maximum at energy of about 156 keV is considered below.

4. THE ORIGIN OF THE SPECTRAL BACKGROUND AND LANDAU DISTRIBUTION OF THE IONIZATION LOSSES

Let us consider the origin of the wide asymmetric spectral peak with the maximum of the peak at energy of about $E_{\max}^{\exp} = 155$ keV observed in Fig. 6. During the experiments we found that the properties of the peak at a fixed detector location are the same for an arbitrary target alignment or even without the target at all. This means that the peak belongs to some kind of background radiation in the experimental area. We suppose the peak and the spectral background are generated by secondary relativistic charged particles such as muons and/or pions, which are produced as a result of the interaction of beam protons with bending crystal, and/or the collimators and/or other components of the beamline shown in Fig. 1.

The shape of the measured spectral peak is very similar to the shape of the Landau or Landau-Vavilov distribution of ionization losses of charged particles in a slab, which one can see, for example, in Fig. 27.7 in [8] and in Fig. 3 in [9]. The secondary particles move almost parallel to the proton beam and pass in the X-ray detector, where they produce the ionization losses. We found that the energy in the maximum of the measured peak nearly coincides with the calculated value of $E_{\max}^{calc} = 154.7$ keV of the most probable ionization energy losses by ultra-relativistic particles in our Si detector. The calculation has been performed using Eq. (27.11) [8] for ultra-relativistic particles accompanying the proton beam

$$E_m^{calc} = \xi \left[\ln \frac{2mc^2\xi}{\left(\hbar\omega_p\right)^2} + j \right], \qquad (2)$$

where m is the electron mass, j=0.200, ω_p is the plasma frequency of the Si detector crystal, $\xi = (K/A)\cdot(Z/2)\cdot\left(x/\beta^2\right)$, $K = 4\cdot\pi\cdot N_A \cdot r_e^2 \cdot m \cdot c^2$, A is the atomic mass, Z is the atomic number, N_A is the Avogadro's number, x is the path in units $g\cdot cm^{-2}$, r_e is the classic electron radius. The particle path in the Si detector crystal at PXR experiment was $T/\cos\theta_{obs}$ =0.523 mm, where T is the Si crystal detector thickness.

A good agreement of the experimental and calculated values means that the spectral peak really is the result of the ionization losses in the detector by ultra-relativistic charged particles accompanying and moving almost parallel to the proton beam. Moreover, the additional confirmation is that the ionization peak is absent in the spectrum measured when the detector surface is parallel to the proton beam (Fig. 3) as it is seen in Fig. 4,b. In this case the ultra-relativistic charged particles pass through the detector along its surface and their path in the detector is about 2.45 mm. The most probable ionization losses calculated by Eq. (2) are 780 keV, which is out of the operating range of our spectrometer.

It is worth it to point out that in the PXR experiment the cooled Si detector was working simultaneously both as the X-ray detector that registers the PXR spectral peak with the energy of 10.0 keV and as the $\frac{dE}{dx}$ detector that registers the ionization losses of ultra-relativistic charged particles with the most probable energy losses of 155 keV. One can see both spectral peaks in the spectrum shown in Fig. 5,a. The relation of the number of the PXR quanta in the PXR spectral peak to the number of charged particles in the ionization spectral peak is about $1.0 \cdot 10^{-2}$.

The continuous spectral background with energies below 155 keV can be generated by the charged particles that cross the detector close to its edges. The reason for the growth of the number of counts in the vicinity of 300 keV is not clear yet, because we were unable to reduce the amplification gain in the spectrometric tract to observe energies above 300 keV. Nevertheless we can note that the growth is not only due to possible pile-up effect because a similar growth is observed in the spectrum shown in Fig. 4,b where the spectral peak with energy of 155 keV is missing.

5. SPATIAL DISTRIBUTION OF SECONDARY PARTICLES

The background arising due to the secondary ultra-relativistic particle interaction with the detector is the main obstacle in detailed research of the PXR effect. To find out an optimal place for the X-ray detector, we performed the measurements of the distribution of such particles around of the proton beam. The measurements were performed by the same detector aligned perpendicularly to the proton beam and installed at different distances from the beam. The experimental layout is shown in Fig. 7.

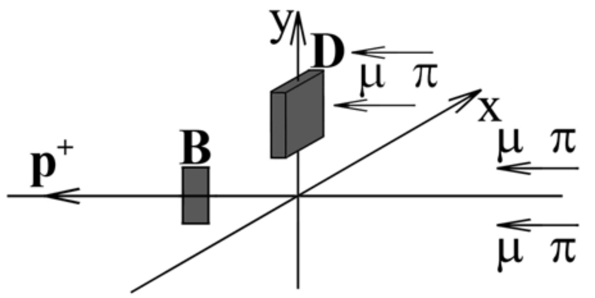

Fig. 7. The experimental setup for measurements of the spatial distribution of the secondary ultra-relativistic particles in horizontal and vertical directions

In the measurements, we registered the number of counts in the ionization spectral peak with energy in the maximum of about 145 keV as a function of the position of the detector. The measurements were performed for the same charge of the proton beam registered by the counter B. The results of the measurements of the number of counts in the ionization spectral peak after spectral background subtraction are shown in Fig. 8.

The measured spatial distribution of the secondary particles shows that their intensity is significant up to the distances of about 2 meters from the proton beam. The distribution is practically symmetric with respect to the proton beam trajectory in the horizontal plane. It means that the secondary particles are produced mainly in the proton beamline.

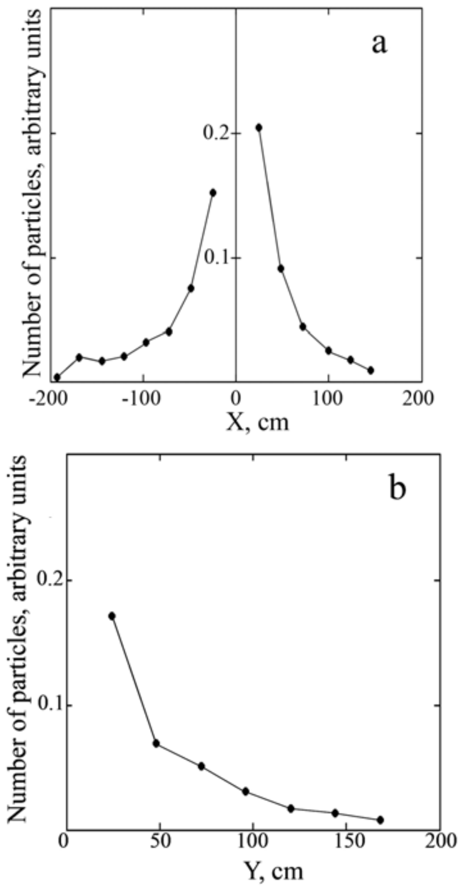

Fig. 8. The number of ultra-relativistic charged particles crossed the detector as a function of the distance from the proton beam to the detector in horizontal (a) and vertical (b) directions

6. RESULTS AND DISCUSSION

We succeeded in observation of X-ray radiation excited by 50 GeV proton beam despite of a strong radiation background. In particular, the clear spectral peaks of characteristic X-ray radiation from a copper target and the spectral peak of parametric X-ray radiation emitted from (111) crystallographic plane of a flat Si crystal in forward hemisphere in Bragg geometry were observed. In both cases the spectral peaks were observed on a significant spectral background.

The origin of the radiation background at the proton accelerator is identified. We found that the background is mainly due to secondary ultra-relativistic charged particles like muons and/or pions that are generated in the proton beamline. Besides, we have measured the distribution of ionization losses of the secondary particles in 500 μm Si detector and found that the distribution is very similar to the well-known Landau distribution. The measured value of the most probable ionization energy loss practically coincides with the calculated one for ultra-relativistic particles.

This experiment is a basis for forthcoming studies of properties of the focused PXR emitted by protons in a bent crystal as well as properties of the PXR emitted by heavy ions and other kinds of particles like positrons in crystals.

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НАБЛЮДЕНИЕ ПАРАМЕТРИЧЕСКОГО РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ, ВОЗБУЖДАЕМОГО ПРОТОНАМИ С ЭНЕРГИЕЙ 50 ГэВ, И ИДЕНТИФИКАЦИЯ ПРОИСХОЖДЕНИЯ СПЕКТРАЛЬНОГО ФОНА

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Описана экспериментальная установка на выведенном пучке ускорителя У70, которая предназначена для исследований сфокусированного параметрического рентгеновского излучения (ПРИ) и ПРИ, возбуждаемого релятивистскими ионами и др. частицами. Приведены предварительные результаты измерений спектров ПРИ и характеристического рентгеновского излучения. Идентифицировано происхождение спектрального фона, препятствующего исследованиям ПРИ на ускорителе протонов. Измерено и обсуждается распределение ионизационных потерь релятивистских заряженных частиц в рентгеновском детекторе, подобное распределению Ландау.

СПОСТЕРЕЖЕННЯ ПАРАМЕТРИЧНОГО РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ, ЩО ЗБУДЖУЄТЬСЯ ПРОТОНАМИ З ЕНЕРГІЄЮ 50 ГеВ, І ІДЕНТИФІКАЦІЯ ПОХОДЖЕННЯ СПЕКТРАЛЬНОГО ФОНУ

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Описана експериментальна установка на виведеному пучку прискорювача У70, яка призначена для досліджень сфокусованого параметричного рентгенівського випромінювання (ПРВ) і ПРВ, збуджуваного релятивістськими іонами та ін. частинками. Наведено попередні результати вимірювань спектрів ПРВ і характеристичного рентгенівського випромінювань. Ідентифіковано походження спектрального фону, що перешкоджає дослідженням ПРВ на прискорювачі протонів. Виміряно і обговорюється розподіл іонізаційних втрат релятивістських заряджених частинок у рентгенівському детекторі, подібний розподілу Ландау.