SECTION 1
PHYSICS OF RADIATION DAMAGES AND EFFECTS IN SOLIDS

INFLUENCE OF RELATIVISTIC ELECTRON BEAM DIVERGENCE ON ANGULAR CHARACTERISTICS OF PXR AND DTR GENERATED IN A SINGLE-CRYSTAL PLATE IN BRAGG SCATTERING GEOMETRY

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A dynamical theory of coherent X-ray radiation generated in a single-crystal target by the finite divergence beam of relativistic electrons has been developed in the scattering Bragg geometry. Coherent X-ray emission is considered in general case of asymmetric reflection for electron Coulomb field in the form of two emission mechanism contributions: parametric X-ray radiation (PXR) and diffracted transition radiation (DTR). The method of averaging radiation cross section over the angular electrons distribution is used. The influence of electron beam divergence on both spectral and angular characteristics of coherent radiation has been studied. The significant difference of the effects of electron beam divergence in PXR and DTR is shown. The possibilities of practical use of DTR from a single-crystal target for indication of beam divergence of ultrarelativistic electrons are investigated.

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INTRODUCTION

In the physics of interaction of relativistic electrons with matter, to know spatial and angular distributions of particles in the incident beam is important for the experimental data interpretation. That is why working out the express methods to get information about the characteristics of the beam used in the experiment is actual problem. One of the approaches is to use different types of radiation excited by relativistic charged particles in matter. The possibility of the use of parametric X-ray radiation (PXR) for the diagnostics of relativistic electron beams recently was experimentally studied in [1, 2]. In [3] it was suggested to use PXR generated in a thin crystal to get operative information on spatial position of relativistic electron beam. The applicability of transition radiation (TR) of vacuum ultraviolet range to measure the electron beam cross dimensions was demonstrated in [4]. The authors of [5] offer the use of X-ray Cherenkov radiation by ultrarelativistic charged particles in the photon energy range, which includes K-absorption edges for some of the materials, to reveal the beam cross-dimensions.

In all of the works above listed, the beam parameters estimation was carried out in the framework of kinematic PXR theory, therefore studying the influence of dynamic effects on the characteristics of coherent radiation by relativistic electron beams remains an important task.

As known PXR appears due to the scattering of a relativistic electron Coulomb field on a system of parallel crystal atomic planes [6, 7]. When a charged particle crosses the crystal plate surface, the transition radiation (TR) takes place [8]. TR appearing on the border diffracts then on a system of parallel atomic planes of the crystal that forms DTR in a narrow spectral range [9–11]. DTR photons move near the Bragg scattering direction.

The process of coherent X-ray radiation by a single relativistic electron in a crystal is described in the framework of the dynamical theory of x-rays diffraction in [12–15]. Under the influence of relativistic electron coulomb field the atomic electrons in solid body begin to oscillate and that leads to radiation of the X-ray waves, which for a certain frequency (Bragg frequency) interference constructively in a Bragg scattering direction creating the parametric X-ray radiation (PXR). The dynamic theory of X-ray diffraction takes into consideration the interaction of an atom in crystalline solid body with the wave field created under scattering on all atoms of solid medium, i.e. it describes the multiwave scattering. As the result of such a consideration the multiple reflection of the waves from atomic planes in crystal are taken into account in dynamic theory of PXR.

In these papers, the dynamic theory of coherent X-ray radiation generated by a relativistic electron in a crystal has been built for general case of asymmetric relative to the crystal (target) surface reflection of the electron Coulomb field. In this case, the system of the parallel reflecting atomic planes in the target can be located at arbitrarily given angle to the target surface. Under these conditions, coherent X-radiation in the direction of the Bragg scattering appears because of two coherent radiation mechanisms, namely PXR and DTR.

In the present work, a dynamical theory of coherent X-ray radiation generated in a single-crystal target by a divergent beam of relativistic electrons is developed in the scattering Bragg geometry. We have obtained the expressions describing spectral-angular distributions of PXR and DTR generated by a relativistic electron moving rectilinearly through the crystal plate at a predetermined angle relative to the axis of the electron beam. Further on the expression for the spectral-angular density of the radiation generated by an electron beam has been derived using the averaging of the radiation cross section over the angular distribution of electrons moving in straight lines in the beam. The influence of the electron beam divergence on angular characteristics of the coherent radiation has been investigated.

One of the goals of this paper is to demonstrate a significant effect of reduction of DTR contribution under increase of the electron beam divergence. This effect allows investigating PXR of a relativistic electron beam in a single crystal target without DTR background.

Another goal of this work is to define the possibilities of indication of electron beam divergence in accelerators with use of DTR. It is important to note that the effect of the beam divergence in the considered coherent radiation does not depend on cross sizes of the electron beam at the target-radiator.

RESULTS AND DISCUSSION

1. SPECTRAL-ANGULAR DENSITY OF PXR

Let us consider a beam of relativistic electrons crossing a monocrystalline plate (Fig. 1). Let us involve the angular variables $\boldsymbol{\psi}$, $\boldsymbol{\theta}$ and $\boldsymbol{\theta}_0$ in accordance with the definition of relativistic electron velocity $\mathbf{V}$ and unit vectors in direction of momentum of the photon radiated in the direction near electron velocity vector $\mathbf{n}$ and in the of Bragg scattering direction $\mathbf{n_g}$:

$$\mathbf{V}=\left(1-\frac{1}{2}\gamma^{-2}-\frac{1}{2}\psi^{2}\right)\mathbf{e}_1+\boldsymbol{\psi},\ \mathbf{e}_1\boldsymbol{\psi}=0,$$

$$\mathbf{n}=\left(1-\frac{1}{2}\theta_0^2\right)\mathbf{e}_1+\boldsymbol{\theta}_0,\ \mathbf{e}_1\boldsymbol{\theta}_0=0,\ \mathbf{e}_1\mathbf{e}_2=\cos 2\theta_B,$$

$$\mathbf{n_g}=\left(1-\frac{1}{2}\theta^2\right)\mathbf{e}_2+\boldsymbol{\theta},\ \mathbf{e}_2\boldsymbol{\theta}=0, \qquad (1)$$

where $\boldsymbol{\theta}$ is the radiation angle, counted from direction of axis of radiation detector $\mathbf{e}_2$, $\boldsymbol{\psi}$ is the incidence angle of an electron in the beam counted from the electron beam axis $\mathbf{e}_1$, $\boldsymbol{\theta}_0$ is the angle between the incident photon movement direction and axis $\mathbf{e}_1$, $\gamma=1/\sqrt{1-V^2}$ – Lorentz-factor of the particle. The angular variables are decomposed into the components parallel and perpendicular to the figure plane: $\boldsymbol{\theta}=\boldsymbol{\theta}_{||}+\boldsymbol{\theta}_{\perp}$, $\boldsymbol{\theta}_0=\boldsymbol{\theta}_{0||}+\boldsymbol{\theta}_{0\perp}$, $\boldsymbol{\psi}=\boldsymbol{\psi}_{||}+\boldsymbol{\psi}_{\perp}$.

Let us consider the task of measurement in real time of the electron beam divergence without taking to the account the electron multiple scattering in the target. For this case, we will consider a thin target, where the absorption of photons in the medium can be neglected too. If we perform the analytical procedures similar to those used in [13, 15] we will obtain the expressions for the spectral-angular density of PXR and DTR for the propagation direction of the emitted photon $\mathbf{k_g}=k_{\mathbf{g}}\mathbf{n_g}$ (see Fig. 1) taking into account the direction deviation of the electron velocity $\mathbf{V}$ relative to the electron beam axis $\mathbf{e}_1$.

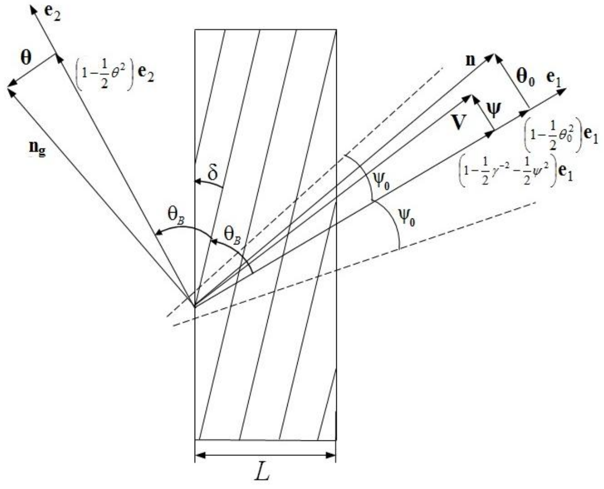

Fig. 1. The geometry of the emission process

$$\omega\frac{d^2N_{\mathrm{PXR}}^{(s)}}{d\omega d\Omega}=\frac{e^2}{\pi^2}\frac{\Omega^{(s)^2}}{\left(\gamma^{-2}+(\theta_\perp-\psi_\perp)^2+(\theta_{//}+\psi_{//})^2-\chi_0'\right)^2}R_{\mathrm{PXR}}^{(s)}; \qquad (2a)$$

$$R_{\mathrm{PXR}}^{(s)}=\frac{{\xi^{(s)}+\sqrt{\xi^{(s)2}-\varepsilon}}^{\;2}}{\xi^{(s)2}-\varepsilon+\varepsilon\sin^2\left(\frac{b^{(s)}\sqrt{\xi^{(s)2}-\varepsilon}}{\varepsilon}\right)}\frac{\sin^2\left(\frac{b^{(s)}}{2}\left(\frac{\xi^{(s)}+\sqrt{\xi^{(s)2}-\varepsilon}}{\varepsilon}-\sigma^{(s)}\right)\right)}{\left(\frac{\xi^{(s)}+\sqrt{\xi^{(s)2}-\varepsilon}}{\varepsilon}-\sigma^{(s)}\right)^2}; \qquad (2b)$$

$$\omega\frac{d^2N_{\mathrm{DTR}}^{(s)}}{d\omega d\Omega}=\frac{e^2}{4\pi^2}\Omega^{(s)2}\left(\frac{1}{\gamma^{-2}+(\theta_\perp-\psi_\perp)^2+(\theta_{//}+\psi_{//})^2}-\frac{1}{\gamma^{-2}+(\theta_\perp-\psi_\perp)^2+(\theta_{//}+\psi_{//})^2-\chi_0'}\right)^2R_{DTR}^{(s)}; \qquad (3a)$$

$$R_{DTR}^{(s)}=\frac{\varepsilon^2}{\xi^{(s)^2}-\left(\xi^{(s)^2}-\varepsilon\right)\coth^2\left(\frac{b^{(s)}\sqrt{\varepsilon-\xi^{(s)^2}}}{\varepsilon}\right)}, \qquad (3b)$$

where

$$\Omega^{(1)}=\theta_\perp-\psi_\perp;\ \Omega^{(2)}=\theta_{//}+\psi_{//};\ \sigma^{(s)}=\frac{1}{|\chi_{\mathbf{g}}'|C^{(s)}}\left(\gamma^{-2}+(\theta_\perp-\psi_\perp)^2+(\theta_{//}+\psi_{//})^2-\chi_0'\right);\ \xi^{(s)}(\omega)=\eta^{(s)}(\omega)+\frac{1+\varepsilon}{2\nu^{(s)}};$$

$$\eta^{(s)}(\omega)=\frac{2\sin^2\theta_B}{|\chi_{\mathbf{g}}'|C^{(s)}}\left(1-\frac{\omega(1-\theta_{//}\cot\theta_B)}{\omega_B}\right);\ \varepsilon=\frac{\sin(\theta_B-\delta)}{\sin(\theta_B+\delta)};\ b^{(s)}=\frac{1}{2\sin(\theta_B+\delta)}\frac{L}{L_{ext}^{(s)}}. \qquad (4)$$

The expressions (2) and (3) describe the spectral-angular density of PXR and DTR of the relativistic electron crossing a crystal plate at an angle $\boldsymbol{\psi}$ relative to the axis of the electron beam $\mathbf{e}_1$. The expressions are obtained in the framework of two-wave approximation of dynamic diffraction theory taking into account the angle between the reflecting system of parallel atomic planes of the crystal and the target surface (angle δ). The system (2) and (3) under $s = 1$ describes the fields σ-polarized, and under $s = 2$ the fields π-polarized.

An important parameter in (2)–(4) is the parameter ε that determines the degree of asymmetry of the reflection of the field in a crystal plate with respect to the target surface, δ is the angle between the target surface and the reflecting atomic planes. Parameter $b^{(s)}$ characterizing the thickness of the crystal plate is the ratio of half of the path of the electron in the target $L_e=L/\sin(\delta-\theta_B)$ to the extinction length

$$L_{ext}^{(s)} = \frac{1}{\omega\left|\chi'_{\mathbf{g}}\right|C^{(s)}}.$$

The spectral function $\eta^{(s)}(\omega)$ rapidly changes with the frequency of the radiation therefore this function is convenient for use as an argument in the diagrams demonstrating the spectra of PXR and DTR .

To find the angular density for PXR let us integrate the expression (2) over the frequency function $\xi^{(s)}(\omega)$ taking into account (2b) and using the relation $\frac{d\omega}{\omega} = -\frac{\left|\chi'_{\mathbf{g}}\right|C^{(s)}}{2\sin^2\theta_B}d\xi^{(s)}$, that follows from the expression (4). As the PXR spectral peak is very narrow, so under condition $b^{(s)}>>1$ integration can be performed with use a good known approximation. $\sin^2(ax)/x^2 \rightarrow \pi a\delta(x)$.

The result of the integration can be represented as

$$\frac{dN_{PXR}^{(s)}}{d\Omega} = \frac{e^2}{8\pi\sin^2\theta_B\left|\chi'_{\mathbf{g}}\right|C^{(s)}}\frac{\Omega^{(s)2}}{\sigma^{(s)2}}\frac{\varepsilon^2(\sigma^{(s)2}\varepsilon-1)}{\left(\frac{\sigma^{(s)2}\varepsilon-1}{2\sigma^{(s)}}\right)^2+\varepsilon\sin^2\left(\frac{\sigma^{(s)2}\varepsilon-1}{2\sigma^{(s)}\varepsilon}b^{(s)}\right)}b^{(s)}. \tag{5}$$

We find the angular density DTR integrating (3) over the frequency function $\xi^{(s)}(\omega)$:

$$\frac{dN_{DTR}^{(s)}}{d\Omega} = \frac{e^2\chi_0'^2}{2\pi^2\sin^2\theta_B\left|\chi'_{\mathbf{g}}\right|C^{(s)}}\frac{\Omega^{(s)2}}{\sigma^{(s)2}\left(\left|\chi'_{\mathbf{g}}\right|C^{(s)}\sigma^{(s)}+\chi'_0\right)^2}\varepsilon\sqrt{\varepsilon}\pi\cdot\tanh\left(\frac{b^{(s)}}{\sqrt{\varepsilon}}\right). \tag{6}$$

The curves showing the distribution of angular PXR density under different values of initial divergence ψ_0 of electron beam are presented in Fig. 2. These curves have been plotted for relativistic electron of 150 MeV energy (under such value of energy the dependence of angular PXR density on electron energy is saturated) and show the weak influence of initial divergence on distribution of PXR angular density, which is connected with the big width of angular distribution of PXR. Hence it follows that estimation of spatial characteristics of ultrarelativistic electron beams with use of PXR is impossible.

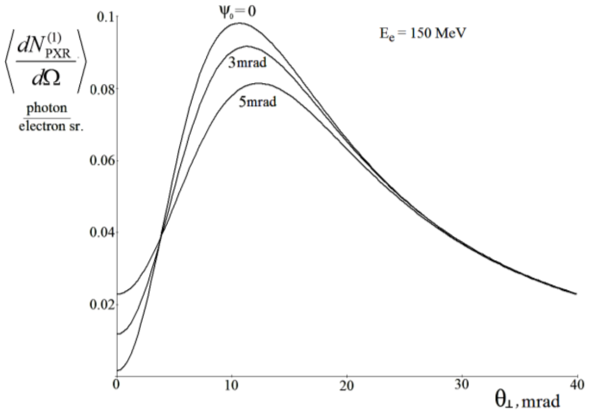

Fig. 2. The effect of the divergence of the electron beam on the PXR angular density: Energy of relativistic electron is E>150 MeV

In Fig. 3 the curves describing the angular density of DTR of relativistic electron of 500 MeV energy under different values of initial divergence ψ_0 are presented.

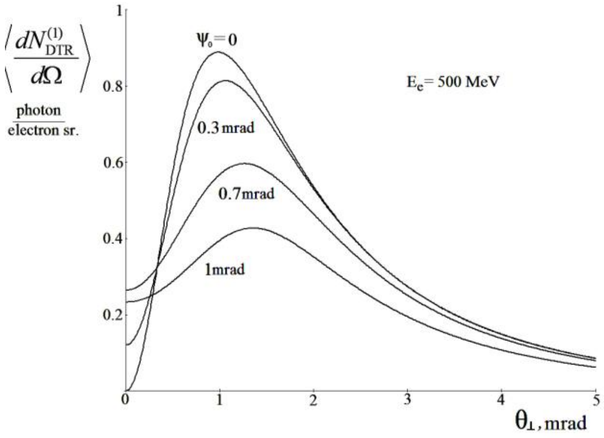

Fig. 3. Effect of divergence of the electron beam on the angular density DTR. The electron energy E=500 MeV

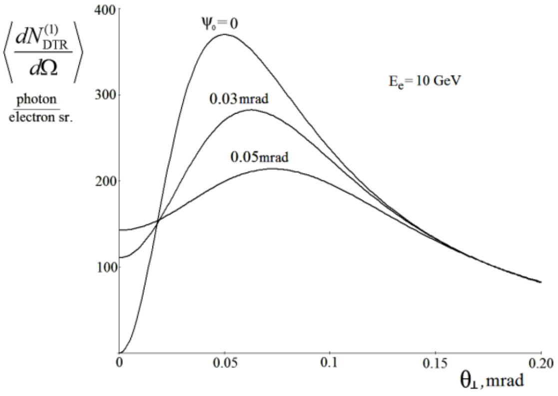

Fig. 4. The same as in Fig. 3, but for E=10 GeV

One can see that the DTR angular density is in a strong dependence on initial divergence of the electron beam. This fact can be explained by the very narrow angular distribution of DTR, which leads to strong influence of electron beam divergence on DTR angular density.

When the energy of radiating electrons in the beam increase the angular distribution of DTR photons became narrower and its dependence on initial divergence of the electron beam became stronger, that demonstrate the curves in Figs. 4 and 5.

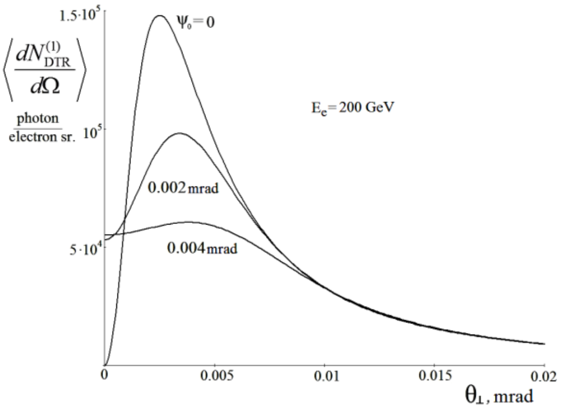

Fig. 5. The same as in Fig. 3, but for E=200 GeV

The curves in Fig. 4 are plotted for electron energy of 10 GeV, and in Fig. 5 for 200 GeV. Let us note that under superhigh electron energies when the measurements of angular characteristic of electron beam is a difficult task because of its sharp directivity one can easy calculate the dependence of number of radiated photons on the electron beam divergence.

2. THE AVERAGING OF COHERENT RADIATION GENERATED BY A RELATIVISTIC ELECTRON OF THE DIVERGENT BEAM IN A CRYSTAL OVER ANGLES OF ELECTRON INCIDENCE

Let us consider the effect of the electron beam divergence on the angular characteristics of the radiation. For that, let us average radiation of an electron over all of its possible straight trajectories in the beam. As an example, we will carry out the averaging of the spectral-angular density of PXR and DTR for the electron beam with the Gauss angular distribution:

$$f(\psi) = \frac{1}{\pi\psi_0^2} \cdot \exp\left\{-\frac{\psi^2}{\psi_0^2}\right\}, \tag{7}$$

where ψ_0 is the divergence of the beam of radiating electrons (see Fig. 1). By averaging the expressions (5) and (6) we obtain

$$\left\langle \frac{dN^{(s)}_{\mathrm{PXR,DTR}}}{d\Omega} \right\rangle = \frac{1}{\pi{\psi_0}^2} \int\int d\psi_\perp d\psi_{//} \exp\left\{-\frac{{\psi_\perp}^2 + {\psi_{//}}^2}{{\psi_0}^2}\right\} \frac{dN^{(s)}_{\mathrm{PXR,DTR}}}{d\Omega}. \tag{8}$$

On the base of expression (5) and (6) describing the angular densities of PXR and DTR and expression (8) we carried out numerical calculations for the radiation of relativistic electron crossing the W (110) single-crystal plate for the case of symmetric reflection of pseudo photons of relativistic electron coulomb field (δ = -10°, $\varepsilon \approx 2.7$) under following values of parameters: $\theta_B \approx 20.5°$, $\omega_B \approx 8$ keV, $L = 2$ μm. The calculations are made for σ-polarized X-ray waves under condition $\theta_{//}=0$.

In Fig. 2, the curves constructed according to (5), describe the angular density of PXR, and in Fig. 3 and Fig. 4, the curves constructed according to the formula (6) describe the angular density of DTR. One can see that the angular density of PXR (see in Fig. 2) depends on the divergence of relativistic electron beam considerably weaker than the angular density of DTR (see in Fig. 3), which can be explained by the fact that the distribution of angular density of DTR is sharper than that of PXR. This effect can be used for reduction of DTR contribution to angular density of the radiation without significant change of PXR contribution that gives the possibility of investigation of the contributions of these mechanisms to total yield of the radiation.

With the increase of the energy of the radiating electrons of the beam, the angular distribution of the DTR becomes narrower and its dependence on the electron beam divergence becomes stronger, which is shown by the curves in Figs. 4, 5. Thereby, DTR can be used for divergence indication of ultra-high energy electron beams, for example, on international accelerator ILC.

CONCLUSIONS

In the present work, the dynamic theory of coherent X-ray radiation of divergent beam of the relativistic electrons crossing a single crystal plate is considered. We have obtained the expressions for spectral-angular density parametric X-ray radiation and diffracted transition radiation of relativistic electron taking into account the deviation of electron velocity direction relative to the electron beam axis. In the framework of two-wave approximation of diffraction theory the expression for PXR and DTR are obtained for general case of asymmetric reflection of pseudo photons of the electron coulomb field. Based on the obtained expression for spectral-angular and angular density of the radiation of an electron in the beam using averaging over the distribution of the electron incidence angles the expressions for radiation of the electron beam as a whole have been obtained. The effect of the electron beam divergence on the angular characteristics of PXR and DTR was investigated. As an example, in the present work we carried out the averaging of the angular density of PXR and DTR for the electron beam with Gauss angular distribution function.

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ВЛИЯНИЕ РАСХОДИМОСТИ ПУЧКА РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ НА УГЛОВУЮ ПЛОТНОСТЬ ПРИ И ДПИ, ГЕНЕРИРУЕМЫХ В МОНОКРИСТАЛЛИЧЕСКОЙ ПЛАСТИНКЕ В ГЕОМЕТРИИ РАССЕЯНИЯ БРЭГГА

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Развита динамическая теория когерентного рентгеновского излучения, генерированного в геометрии рассеяния Брэгга в монокристаллической мишени пучком релятивистских электронов конечной расходимости. Когерентное рентгеновское излучение рассматривается в общем случае асимметричного отражения кулоновского поля электрона в виде вкладов двух механизмов излучения: параметрического (ПРИ) и дифрагированного переходного (ДПИ). Используется усреднение поперечного сечения излучения по угловому распределению электронов. Изучено влияние расходимости электронного пучка на спектральные и угловые характеристики когерентного излучения. Показано значительное отличие влияния расходимости электронного пучка на ПРИ и ДПИ. Исследована возможность практического использования ДПИ из монокристаллической мишени для индикации расходимости пучка ультрарелятивистских электронов.

ВПЛИВ РОЗБІЖНОСТІ ПУЧКА РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ НА КУТОВУ ЩІЛЬНІСТЬ ПРВ І ДПВ, ЩО ГЕНЕРУЮТЬСЯ В МОНОКРИСТАЛІЧНІЙ ПЛАСТИНЦІ В ГЕОМЕТРІЇ РОЗСІЯННЯ БРЕГГА

С.В. Блажевич, Ю.О. Болтенко, Т.В. Коськова, О.О. Мазілов, А.В. Носков

Розвинено динамічну теорію когерентного рентгенівського випромінювання, генерованого в геометрії розсіяння Брегга в монокристалічній мішені пучком релятивістських електронів кінцевої розбіжності. Когерентне рентгенівське випромінювання розглядається в загальному випадку асиметричного відбиття кулонівського поля електрона у вигляді внесків двох механізмів випромінювання: параметричного (ПРВ) і дифрагованого перехідного (ДПВ). Використовується усереднення поперечного перерізу випромінювання за кутовим розподілом електронів. Вивчено вплив розбіжності електронного пучка на спектральні і кутові характеристики когерентного випромінювання. Показано значну відмінність впливу розбіжності електронного пучка на ПРВ і ДПВ. Досліджено можливість практичного використання ДПВ з монокристалічної мішені для індикації розбіжності пучка ультрарелятивістських електронів.