DIFFRACTION ON A POLYCRYSTAL FOR INVESTIGATIONS AND DIAGNOSTICS OF X-RAY RADIATION OF RELATIVISTIC PARTICLES IN A FORWARD DIRECTION

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It is shown that the diffraction on a polycrystal can be used for investigation and diagnostics of X-ray radiation emitted in a forward direction by relativistic charged particles moving in crystalline or other targets or fields. Methods for measuring radiation spectral density, divergence, and linear polarization at any requisite energy from a few units to tens of keV are proposed. The explanation for the origination of experimentally observed and earlier unidentified spectral peaks as a result of Bragg diffraction on a polycrystal is proposed. The experiment for verification of the explanation is suggested.

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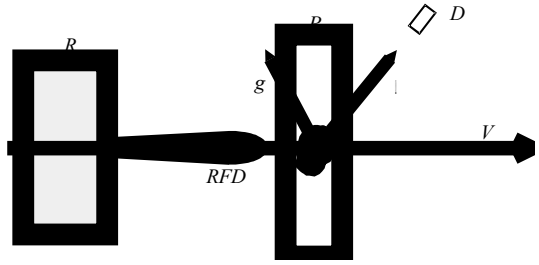
1. INTRODUCTION

There exist several kinds of X-ray radiation of relativistic charged particles moving through a radiator, i.e., amorphous or crystalline targets or fields. These are ordinary bremsstrahlung, transition radiation (TR), resonance transition radiation, coherent bremsstrahlung, channelling radiation, parametric X-ray radiation (PXR), undulator radiation, Thomson or Compton scattering, etc. Most of them are going from the radiator in a forward direction mainly within the angle of about γ^{-1} relative to the incident particle velocity vector V, where γ is the relativistic factor of incident particles. Several of the above-mentioned kinds of radiation can be generated in the radiator (e.g., in a crystal) simultaneously, and the total radiation in a forward direction (RFD) is going along the vector V. To investigate the composition of the total radiation and the role of its components, experimental measurements of the RFD spectral properties are needed. However, it is generally difficult to measure the spectral properties of the RFD from relativistic particle beams on account of its high intensity, wide spectrum and a restricted counting rate of spectrometers. In the gamma-ray band, it is the Compton scattering that is successfully used for investigations of the RFD. In the X-ray band, the use of Bragg diffraction seems to be more natural. In this paper we suggest that the Bragg diffraction in a polycrystal placed behind the radiator should be used for measurements of the RFD spectral density, divergence and linear polarization at any wanted X-ray energy. Besides, we shall discuss the experiment, where, in our opinion, the Bragg diffraction of X-ray RFD by the polycrystal was observed.

2. HOW TO MEASURE X-RAY RADIATION IN A FORWARD DIRECTION WITH THE USE OF A POLYCRYSTAL

The scheme of the setup for measurements of the X-ray RFD properties is shown in Fig. The beam of incident relativistic particles from the accelerator passes through the radiator R and generates RFD going along the particle beam within the angle of about γ^{-1}. Then the RFD crosses the polycrystalline foil P. The particle beam can be either deflected by the bending magnet or can pass through the foil, too, if its radiation in the foil does not prevent the observation of radiation under study. The spectrometric X-ray detector D is installed at an observation angle θ.



The relativistic particle beam passes through the radiator R and generates radiation in a forward direction (RFD). The RFD is going along the particle velocity vector V and passes through the polycrystalline foil P. One of randomly aligned grains of the polycrystal with the crystallographic planes and corresponding reciprocal vector g is shown in the foil. The spectrometric X-ray detector D is installed at observation angle θ relative to particle velocity vector. The observation direction is shown by the unit vector Ω. The detector can register RFD diffracted by polycrystal at Bragg energies

The polycrystalline foil consists of a number of randomly aligned crystalline grains. Some of them can appear oriented relative to the vector V and the observation direction Ω to satisfy the Bragg condition. One of these grains with the crystallographic planes denoted by the reciprocal lattice vector g is shown in the foil in Fig. The X-ray RFD of Bragg energy E_B will be reflected by these planes into the detector. Thus, the spectrometric detector will be able to register several spectral peaks of energies E_B corresponding to several main crystallographic planes of the polycrystal. These energies can be found by the formula from Ref. [1]

$$E_B = \frac{c\hbar g^2}{2|g \cdot \Omega|}, \qquad (1)$$

where Ω is the unit vector in the observation direction at the observation angle θ relative to the particle velocity vector V and the RFD axis,

$$|\vec{g}\cdot\vec{\Omega}| = |g|\cos\frac{\pi-\theta}{2} = g\sin\frac{\theta}{2},$$

$g = |\vec{g}| = \frac{2\pi\sqrt{l^2+m^2+n^2}}{a}$, α is the lattice constant; l, m, n are the Miller indices for the crystallographic planes with a nonzero structure factor. The scheme in Fig. is similar to the one used in the well-known Debye-Scherrer method for investigations of polycrystalline samples by a monochromatic X-ray beam. Here, we propose that this scheme with the known polycrystal should be used for investigation and diagnostics of intense RFD X-ray beams that may have wide and complicated spectra.

2.1. MEASUREMENT OF THE RFD SPECTRAL DENSITY

The number of counts registered by the detector in the spectral peak of energy E_B is proportional to the RFD spectral density at this energy. For absolute measurements of RFD spectral density, one should calibrate the foil+detector system using the radiator with the known spectral density of X-ray radiation and provide a reliable monitoring of the number of incident electrons. For measurement of RFD spectral density in arbitrary units, one can change radiators or their properties at a fixed geometry of both the foil and the detector and register number of counts in the spectral peaks at energy E_B generated by constant number of incident particles. For example, in this way one can measure the spectral density of channelling radiation as a function of crystal-radiator alignment. Note that only a small part of RFD can be diffracted by a thin polycrystalline foil into the detector. This is favourable for preventing the spectrometer from overloading at measurements of intense X-ray RFD beams. The wanted energy E_B can be provided by a proper choice of the polycrystal and the observation angle in accordance with the formula (1).

2.2. MEASUREMENT OF THE RFD DIVERGENCE

The width ΔE of the measured spectral peak at energy E_B is a function of the experimental polar angular resolution $\Delta\theta$ and the incident X-ray RFD beam divergence α in the observation plane, and also the energy resolution of the detector ΔE_d. The experimental angular resolution is determined by the angular size of both the detector and the RFD beam spot on the foil in the observation plane. Using the Eq.(1), one can find

$$\Delta E^2 = \Delta E_d^2 + \left(\frac{E_B}{2\tan\frac{\theta}{2}}\right)(\Delta\theta^2+\alpha^2). \qquad (2)$$

In practice, the divergence can be measured provided that the spectral peak broadening due to the RFD divergence exceeds or is comparable to the broadening due to the experimental angular resolution and energy resolution of the detector. In this case, the divergence α in the observation plane can be found from Eq. (2).

2.3. MEASUREMENT OF THE RFD LINEAR POLARIZATION

The Bragg diffraction intensity has its maximum for X-rays polarized in the plane perpendicular to the diffraction plane, and its minimum for the X-rays polarized in the plane of diffraction. These maximum and minimum are particularly pronounced at θ close to $\pi/2$. Due to these well-known peculiarities of Bragg diffraction, the setup shown in Fig. should possess the polarization analyzing power. The setup can be used for measurements of the RFD linear polarization at energy E_B. To this end, one should perform measurements of polycrystal-diffracted radiation at a fixed observation angle θ as a function of the azimuthal angle of the detector rotation around the vector V.

3. DISCUSSION OF SOME EXPERIMENTAL RESULTS FROM REF. [2]

In our opinion, the diffraction of RFD by the polycrystal could be observed in Ref. [2]. The experimental setup in Ref. [2] was partially similar to the one shown in Fig. The authors of Ref. [2] studied the PXR and the diffracted TR in the Bragg direction, the radiations being generated by the 150 MeV electron beam in silicon single-crystal radiators of various configurations. Diffraction of TR realized in the same single-crystal radiators. Behind the radiator, a $10\,\mu m$ thick molybdenum foil was installed. The characteristic X-ray radiation, excited in the foil, was used for monitoring the number of beam electrons that have passed through the radiators. Those authors have measured a series of nice spectra having a low spectral background by a Si(Li) detector at $\theta = 25.8^\circ$. In the spectra they observed clearly marked spectral peaks of PXR and diffracted TR from the radiator, and also the peaks of characteristic X-ray radiation from the molybdenum foil at reference energies $E_{K\alpha}$ =17.45 keV and $E_{K\beta}$ =19.6 keV. Besides, they observed spectral peaks with energies ≈ 12.5 keV and ≈ 25.0 keV, the origin of which was not identified in Ref. [2]. Here, we shall discuss the data concerned with these unidentified spectral peaks (USPs).

In Ref. [2] the authors have noted that the molybdenum foil was amorphous. To understand the origin of the USPs, let us suppose that the molybdenum foil is polycrystalline. This polycrystal can diffract the radiation of Bragg energies from the RFD, generated in the radiator, into the cone and, in particular, in the detector direction. The Bragg energies calculated by formula (1) for the crystallographic planes with nonzero structure factors (110), (220), (200) of molybdenum lattice [3] at the reference lattice constant $a = 3.15$ A and $\theta = 25.8^o$ are $E_B^{(110)}$=12.5 keV, $E_B^{(220)}$=25.0 keV, $E_B^{(200)}$

=17.6 keV, respectively. The calculated energies $E_B^{(110)}$ and $E_B^{(220)}$ are practically coincident with the ones of both USPs observed in Ref. [2]. The energy $E_B^{(200)}$ is close to $E_{K\alpha}$ of the characteristic peak, and these peaks are not seen resolved in the experimental spectra in Ref. [2].

Consider some other experimental data concerned with USPs described in Ref. [2]:

i. The USPs disappear if the radiator is removed. This is because the RFD from the radiator disappears. Therefore, only characteristic peaks excited by the electron beam in the foil are seen in Fig.11,b of Ref. [2]. Note that the spectral peaks of PXR with the energies practically equal to the energies of USPs can be generated by the beam electrons in molybdenum grains. Their absence in Fig. 11,b of Ref. [2] means that the PXR from the polycrystal is weak and is no obstacle for correct measurements of RFD (see item 3 in next section).

ii. The USPs disappear if the molybdenum foil is removed. This is because the Bragg diffraction without the polycrystal is absent.

iii. The energies of USPs do not vary with significant variations of the crystal-radiator alignments. This is because the RFD is going along the fixed vector V independently of the crystal-radiator alignment.

iv. The energies of USPs are the same at arbitrary alignment of the molybdenum foil. This is because the RFD is diffracted by the molybdenum grains which appears at appropriate for Bragg diffraction alignment independently of the alignment of the whole foil.

v. The 12.5 keV USP seems to vanish with the alignment of the Si crystal-radiator <100> axis close to the incident particle beam axis (see Fig.12,c in Ref. [2]). This may be due to a significant broadening of the USP as a result of an appreciably increased RFD divergence. The increased RFD divergence may be a result of increased electron beam scattering in the crystal-radiator at this alignment because of the crystal-radiator configuration [2]. Besides, the increasing of the electron beam scattering is possible at motion of electrons along the <100> strings of the crystal.

Thus, the above-considered experimental data from Ref. [2] seems are in agreement with our explanation of the USPs origin as a result of the RFD Bragg diffraction by the molybdenum polycrystal.

4. RESULTS AND DISCUSSION

1. In this paper we have suggested the methods for diagnostics and measurements of intense X-ray RFD. They permit measurements of spectral density, divergence and linear polarization of the RFD with the use of Bragg diffraction on a polycrystal. The methods seem relatively simple and inexpensive, as only a single polycrystalline foil with an arbitrary alignment should be installed, and ordinary spectrometric detector(s) can be used for measurements at any energy chosen in the range from several keV to tens of keV.

2. Here, we have suggested the explanation of spectral peak origination at energies of about 12.5 and 25.0 keV, observed and unidentified in Ref. [2]. The peaks are due to the Bragg diffraction of RFD from the radiator by a polycrystalline molybdenum foil installed behind the radiator. This explanation can be additionally verified with the experimental setup described in Ref. [2]. For this purpose, one can vary the registration angle of the detector θ and observe variations of the spectral peak energies. For the molybdenum polycrystal, they should obey the following formulae obtained from (1):

$$E_B^{(110)} = \frac{1.969 \cdot \sqrt{2}}{\sin\frac{\theta}{2}} \text{ keV} \qquad (3)$$

for the spectral peak from the (110) plane of molybdenum ($\approx$ 12.5 keV in Ref. [2] at $\theta = 25.8^o$) and

$$E_B^{(220)} = \frac{1.969 \cdot \sqrt{8}}{\sin\frac{\theta}{2}} \text{ keV}, \qquad (4)$$

for the spectral peak from the (220) plane of molybdenum ($\approx$ 25.0 keV in Ref. [2] at $\theta = 25.8^o$). Besides, a new peak at energy

$$E_B^{(200)} = \frac{1.969 \cdot 2}{\sin\frac{\theta}{2}} \text{ keV}, \qquad (5)$$

from the (200) plane of molybdenum may appear. In the experimental conditions [2] at $\theta = 25.8^o$, the energy of this spectral peak $E_B^{(200)}$=17.64 keV is close to the one for the characteristic $K\alpha$ peak at $E_{K\alpha}$ =17.45 keV. These peaks could not be resolved by the detector with an energy resolution of 450 eV used in [2].

Besides, our explanation can be verified by using another kind of polycrystal at the same observation angle. For example, the copper polycrystal can diffract the RFD with energies 13.3, 15.4, 21.8 keV from crystallographic planes (111), (200), (220) respectively at $\theta = 25.8^o$.

3. As we mentioned above, the electron beam can generate the PXR in the randomly aligned crystal grains of a polycrystal. However, only a small part of these grains has a proper alignment and produces the PXR reflection in the observation direction. One can estimate relative number of such grains. As the angular size of PXR reflection is about γ_{eff}^{-1} [6], only grains with reciprocal lattice vectors g within the solid angle $\sim\gamma_{eff}^{-2}$ can take part in generation of the reflection in fixed observation direction. The relative number of such grains is $\frac{\gamma_{eff}^{-2}}{2\pi}$. The effective thickness T_{eff} for generation of PXR reflection in fixed observation direction of the polycrystal with thickness T may be estimated as

$$T_{eff} \sim \frac{\gamma_{eff}^{-2}}{2\pi} T, \qquad (6)$$

where $\gamma_{eff} = (\gamma^{-2} + |\chi_0|)^{-\frac{1}{2}}$ is the effective relativistic factor [6], γ is the relativistic factor of incident particles, χ_0 is the dielectric susceptibility. Thus, the

PXR from ordinary polycrystal should be weak and therefore is not seen in Fig. 11,b of Ref. [2].

4. To investigate radiation in a forward direction in the wanted X-ray energy range, one can use a polycrystal and position-sensitive X-ray detector(s) installed at corresponding observation angles.

The diffraction on a polycrystal provides good possibility for studying the PXR and/or other kinds of radiation diffracted in a crystal-radiator with simultaneous measurements of radiation in a forward direction. For example, the search for PXR in a forward direction may be continued and/or channelling or transition radiation may be studied with the use of a polycrystal.

5. FINAL NOTES AND ACKNOWLEDGMENTS

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The author is thankful to N.N. Nasonov for discussion of the misprint in Eq. (6) [4]. Value γ_{eff} [6] is used in Eq. (6) of the present paper to eliminate this misprint. Note, that PXR from common polycrystal was studied theoretically in Ref [7] and experimentally in Ref. [8].

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ИСПОЛЬЗОВАНИЕ ДИФРАКЦИИ НА ПОЛИКРИСТАЛЛЕ ДЛЯ ИССЛЕДОВАНИЙ И ДИАГНОСТИКИ РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ РЕЛЯТИВИСТСКИХ ЧАСТИЦ В НАПРАВЛЕНИИ ВПЕРЕД

А.В. Шагин

В работе показано, что дифракция на поликристалле может быть использована для исследования и диагностики рентгеновского излучения, которое испускают в направлении вперед релятивистские заряженные частицы, движущиеся в кристаллических или других мишенях и полях. Предложены методы для измерения спектральной плотности, расходимости и линейной поляризации излучения при любой желаемой энергии от нескольких единиц до десятков килоэлектронвольт. Предложено объяснение происхождения наблюдавшихся в эксперименте и ранее не идентифицированных спектральных пиков как результата дифракции Брэгга на поликристалле. Предлагается эксперимент для проверки этого объяснения.

ВИКОРИСТАННЯ ДИФРАКЦІЇ НА ПОЛІКРИСТАЛІ ДЛЯ ДОСЛІДЖЕНЬ І ДІАГНОСТИКИ РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ РЕЛЯТИВІСТСЬКИХ ЧАСТОК У НАПРЯМКУ ВПЕРЕД

О.В. Шагін

У роботі показано, що дифракція на полікристалі може бути використана для дослідження і діагностики рентгенівського випромінювання, що випускають у напрямку вперед релятивістські заряджені частки, що рухаються в кристалічних або інших мішенях і полях. Запропоновано методи для виміру спектральної густини, розбіжності і лінійної поляризації випромінювання при будь-якій бажаній енергії від декількох одиниць до десятків кілоелектронвольт. Запропоновано пояснення походження спектральних піків, що спостерігалися у експерименті і раніше не ідентифікованих, як результату дифракції Брегга на полікристалі. Пропонується експеримент для перевірки цього пояснення.