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First observation of parametric X-ray radiation enhancement for grazing incident electrons

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Absract. The results of first observation of PXR enhancement realizing in the scheme of grazing incidence of emitting electrons onto the surface of crystalline target in conditions of asymmetric diffraction of electron Coulomb field are presented. The measured enhancement for 7MeV electrons and Si crystal was found to be nearly 2.7. The experimental result is in agreement with theoretical predictions.

1. Introduction.

Parametric X-ray radiation (PXR) appears due to the Bragg diffraction of a fast charged particle Coulomb field on a system of atomic planes in a crystal [1-5]. The spectrum of PXR comprises a set of narrow reflexes. The emission mechanism being discussed is of interest for creating of effective source of quasimonochromatic tunable X-rays, but photoabsorption bounds the yield of PXR and the brightness of such sources is not enough for many applications. Because of this, the search of possibilities to suppress an influence of a photoabsorption on PXR generation is one of the main directions of explorations in the field of creating of sources alternative to classical synchrotron.

The main idea of the suppression of photoabsorption consists in increase of the effective generation path L_{el} of emitting electrons in a target (photons generated on L_{el} are free to escape from an absorbing target). Two approaches to the problem of L_{el} increasing have been proposed [4,6]. The first of them has been realized in the experiment [4] wherein PXR was observed for the first time. An electron beam directed at butt-end of the target moved inside the target parallel to its surface. As this took place, generated photons escaped from the target traveling through above surface and hence the path of emitted photons in the target did not depend on the electron path L_{el} which was bounded by multiple scattering only. An essential disadvantage of the method being discussed consists in the limitation on the effective transverse size of an electron beam, which must be less than a photoabsorption length L_{ab} . It should be noted that the position of reflecting plane in the experiment [4] was not parallel to a crystal surface, so that the geometry of asymmetric scattering was realized in this experiment (such geometry provided a take-off of PXR photons perpendicularly to a crystal surface).

Another way is based on the grazing incidence of an electron beam onto the crystal surface in conditions of asymmetric scattering geometry [6]. In line with [6] the grazing geometry allows to increase PXR yield tens times. The aim of this paper consists in the experimental verification of the effect [6]. The paper is organized as following. The results of calculations of optimal conditions for verification of the effect of PXR enhancement in grazing incidence geometry are presented in the next Section. The Section 3 is devoted to the description of both experimental setup and the obtained data. Our conclusions are presented in Section 4.

2. PXR enhancement in conditions of grazing incidence of emitting electrons onto the crystal surface.

PXR has been searched in many theoretical and experimental works. Traditionally PXR is considered in symmetrical geometry of diffraction, when the crystallographic plane coincides with the surface of the target and radiation propagates near to mirror direction relative to surface of the target. The used geometry of PXR process is presented in Fig.1. The electron beam propagates along the direction $\mathbf{e}_1$, its orientation relative to the surface of the target is controlled by angle a . The angle between reflecting crystallographic plane R and the crystal surface is designated as b . The direction of $\mathbf{e}_1$ coincides with the mirror direction for incident electron beam relative to the reflecting crystallographic plane R, specified by the reciprocal lattice vector $\mathbf{g}$. The angular distribution of PXR is concentrated near to $\mathbf{e}_2$ and the variable $\Theta_{\|}$ describes the distribution of emitted photons in incidence plane, specified by the axis of an electron beam $\mathbf{e}_1$ and the vector $\mathbf{g}$. The traditional geometry is realized when $b = 0$. The yield of PXR is limited by photoabsorption. In the traditional case PXR yield is collected from the length of trajectory of emitting particle L_{el} approximately equal to the photoabsorption length L_{ab} for generated PXR signal.

The possibility to increase PXR yield, described in [6], is based on PXR propagation under large angle relative to the velocity of emitting electron. The relation between L_{el} and L_{ab} may be changed substantially in asymmetrical geometry of diffraction. This relation may be presented in simple form

$$\frac{L_{el}}{L_{ab}} = \frac{\sin(2b + a)}{\sin(a)} \quad (1)$$

Presented formula shows the ratio between PXR yield for asymmetrical and symmetrical geometries. Two conditions should be fulfilled for bright manifestation of the effect of PXR enhancement. The first of them is grazing incidence of emitting electrons on the surface of the target ($a \to 0$). This condition is difficult to fulfill for real electron beam that has a finite transverse size (the linear size of the target increases when the incidence angle tends to zero). In conditions under consideration the incidence angle is limited by the value asin(d / L) (d – diameter of the beam, L – the linear size of the target in incidence plane), otherwise a part of the beam does not interact with the target.

The second condition consists in PXR propagation normally to the surface of the target. An influence of the photoabsorption is minimal in conditions under consideration.

PXR spectral-angular characteristics in asymmetric geometry may be calculated on the basis of kinematical diffraction theory. A simple formula obtained in [6]

$$N(a,b)=\frac{2e^2w_g^4}{g^4}\left(\ln\left(1+g^2\Theta_d^2\right)-\frac{g^2\Theta_d^2}{1+g^2\Theta_d^2}\right)\times\frac{\sin(2b+a)\sin^2(b+a)\left(1+\cos^2(2b+2a)\right)}{\sin(a)\,c_0''\left(\dfrac{g}{2\sin(b+a)}\right)}, \quad (2)$$

$$w_g^2=w_0^2F(g)S(\mathbf{g})e^{-\frac{1}{2}g^2u_T^2},$$

differs from traditional one by coefficient (1) only. Here w is the energy of emitted photon, w_0 is the plasma frequency, $F(g)$ is the formfactor of an atom, $S(\mathbf{g})$ is the structure factor of an elementary cell, u_T is the mean-square amplitude of thermal vibrations of atoms of the target, γ is Lorentz factor of the emitting electron, Θ_d is collimator angular size, $c_0''(w)$ is the imaginary part of dielectric susceptibility of the target.

In real experiment PXR enhancement is limited by the transverse size of the beam. In order for all beam electrons to interact with the target, grazing angle must exceed the relation d/L ($d<<L$). As a result the maximum possible enhancement is determined by d/L. Assuming the beam size d to be of the order of 0.1 cm and the length of the target L to be of about 1cm one can calculate PXR enhancement as a function of b. Such dependence calculated on the base of (1) is presented in Fig.2.

3. Experimental setup and results of measuring.

For the experimental verification of the discussed effect of PXR enhancement in grazing incidence geometry it is necessary to measure both the yield of PXR in conditions of normal incidence and that in conditions of grazing incidence. The comparison of PXR yields in traditional and grazing cases should be performed with minimal difference in experimental parameters for both cases. It is very convenient to compare the yields when the difference between the measured PXR yields lies in replacement of the target only. In conditions under consirderation the energy of PXR photons and the collimator size are the same in both cases.

The experimental setup was created on base of 7MeV microtron of P.N. Lebedev Physical Institute RAS. The scheme of the experiment is presented in Fig.3. The electron beam 2, generated by microtron 1, is formed by carbon collimators 3. The magnets 4 clean the beam from background photons appearing in the microtron and collimators (collimators decrease intensity of the original beam 10^3 -10^4 times). The magnetic lenses 5 and corrector 6 shape the beam and direct it onto the target 7. The target was placed into a goniometer with three degrees of freedom of rotation and the possibility of taking it out of the electron beam. The target was controlled in horizontal plane with the step of rotation $7.1\cdot10^{-5}$Rad and in vertical plane with the step of rotation $4\cdot10^{-5}$Rad. The beam intensity, location and angular divergence were controlled by proportional chamber 11 and Faraday cup 12. The photon signal from the target 7 was collimated by collimator 8 and detected by energy-dispersive X-ray p.i.n. detector 9 with resolution 152eV (Amptek XR-100CR: 6mm^2 x 500μm, Be window 0.3mil). The above intensive background from the microtron and collimators 3, was reduced by lead protection 13 and noise shielding. The vacuum of the system was better then 10^{-4}torr.

The calculation of PXR in grazing incidence geometry shows a possibility to obtain the enhancement of PXR yield using two perfect silicon crystals with different orientation of the crystallographic plane towards the surface of the crystal. For traditional case the target with surface coinciding with crystallographic plane (111) ($b = 0$) was chosen. For the grazing case the plane of the surface of the target coincided with (100) crystallographic plane ($b = 0.955$ Rad.). The thickness of targets was 450mk for traditional case and 200mk for grazing case. One of the most important problems was choosing the observation angle determining the energy of detected PXR. The energy of PXR should be in area where the background has a smooth spectral distribution. The measurement of spectral distribution of the background without the target showed the smooth distribution with peaks of characteristic X-ray lines of the elements of target's vacuum chamber (Al, Ti, Cr, Fe and Ni). The background of the target became apparent as characteristic radiation of K-lines. The influence of multiple scattering of electrons in the target on PXR properties increases in grazing geometry, it may distort the PXR spectrum. Thus, we chose the energy range of PXR behind of Si K-edge where the influence of the multiple scattering is minimal because the photoabsorption is maximal and the background has no peaks. In conditions undr consideration the observation angle was 40 degrees (angle between axes of electron beam and X-ray detector). The orientation dependences for traditional and grazing cases, calculated on base of (2) with account of test conditions are presented in Fig.4.

The radiating area of target's surface increases when incidence angle is decreased. It changes the observation angle of the detector and hence the detected spectrum becomes wider than for a point source. In our case the diameter of the beam was 5mm and the long size of the beam trace on the target in grazing geometry was about 19mm ($a = 0.267$ Rad). The relation of the long size of the beam trace on the target to the distance between the detector and the target should be much more, than the characteristic size of PXR angular distribution $\sqrt{g^{-2} + w_0^2 / w^2} = 68$ mRad. In this case the line spreading is negligible. The detector was placed on a distance 320cm from the target (the above relation 0.006). The size and position of collimator 8 were so chosen that the target was fully available for the detector in traditional and grazing cases. The collimating angle was $5.86 \cdot 10^{-7}$ster.

For the correct comparison of PXR yields in traditional and grazing cases, the background should be subtracted from the total detected signal (the background increases in grazing case) and the measuring of each point should be normalized on the beam current. The background was smooth. Its level did not exceed 20% of the signal in area of PXR manifestation. The normalizing and comparison were performed on the base of characteristic K-line yield of Si, measured in traditional and grazing cases for identical current. The results of PXR measurement in traditional and grazing geometry are presented in Fig.5. The fitting of the experimental points by the theoretical curve, calculated in kinematical approach for PXR, is presented by solid line. The position of maximum of orientation distribution is 41mRad. It well coincides with the theoretical prediction 34mRad. The difference may be explained by the influence of multiple scattering and initial angular spread of electron beam.

4. Conclusions

Presented experimental results show the possibility to increase PXR yield on the base of grazing incidence of emitting electrons onto the surface of crystalline target in conditions of asymmetric diffraction of the electron Coulomb field. The enhancement has been measured for 7MeV electrons interacting with Si crystal. The comparison of the yields for traditional and grazing cases shows enhancement near 3 times. The obtained data is in agreement with theoretical predictions.

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Figures captions

Fig.1. Geometry of PXR process.
Fig.2. PXR enhancement in condition of grazing incidence and asymmetric diffraction geometry.
Fig.3. The experimental setup.
Fig.4. The orientation dependences of PXR. 1 - traditional case; 2 - grazing geometry.
Fig.5. Orientation dependences of PXR yield for Si crystal. ○ – traditional case; □ – grazing case.