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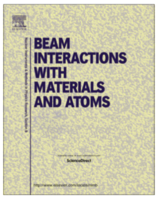

Radical increase of the parametric X-ray intensity under condition of extremely asymmetric diffraction

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ABSTRACT

Parametric X-ray radiation (PXR) from relativistic electrons moving in a crystal along the crystal-vacuum interface is considered. In this geometry the emission of photons is happening in the regime of extremely asymmetric diffraction (EAD). In the EAD case the whole crystal length contributes to the formation of X-ray radiation opposed to Laue and Bragg geometries, where the emission intensity is defined by the X-ray absorption length. We demonstrate that this phenomenon should be described within the dynamical theory of diffraction and predict a radical increase of the PXR intensity. In particular, under realistic electron-beam parameters, an increase of two orders of magnitude in PXR-EAD intensity can be obtained in comparison with conventional experimental geometries of PXR. In addition we discuss in details the experimental feasibility of the detection of PXR-EAD.

1. Introduction

Parametric X-ray radiation (PXR) occurs when a charged particle moves uniformly in a periodic medium [1,2] and possesses unique features such as high brightness, narrow spectral width and the possibility of tuning the X-ray frequency simply by rotating a crystal target. Moreover, PXR is emitted under a large angle with respect to the particle velocity and its brilliance is competitive with other X-ray sources, as already demonstrated experimentally [3]. Consequently, all these properties make it a suitable candidate for the development of novel-laboratory-compact X-ray sources with high brightness and tunable, quasi-monochromatic frequency.

There has been a lot of experimental research in this field [1,4–16] and at present an effort is made toward increasing the intensity of the PXR source. For example, the choice of the materials of the target was analyzed in Ref. [17]. In Ref. [18] it was demonstrated that under condition of anomalous absorption (the Borrmann effect) the PXR intensity is slightly increasing.

At the same time, in the majority of conventional experiments with PXR an electron beam is incident on a crystal under a large angle to its surface, i.e., transition geometry. In this situation according to kinematic model of diffraction [2] the PXR intensity is proportional to the smallest of either crystal L or X-ray absorption L_{abs} lengths. In the X-ray frequency range $L_{\mathrm{abs}} \sim 10^{-2}$ cm and therefore in most cases $L_{\mathrm{abs}} \ll L$. For this reason, only a small part of the electron trajectory contributes to the formation of PXR.

As was mentioned above, PXR is emitted under a large angle with respect to the electron velocity, which makes it feasible to change the geometry of an experiment in a way such that the entire crystal length will contribute to the formation of PXR. Accordingly, this will lead to the increase of the total number of quanta in the PXR peak.

In the first experiment of the detection of PXR [19] the grazing geometry was used, when an electron beam was moving in a short crystal in a thin layer parallel to the crystal-vacuum interface and the emission occurred under a large angle with respect to the crystal surface. The first theoretical estimations were performed within the framework of the dynamical theory of diffraction under the condition of extremely asymmetric diffraction (EAD) [20] and it was demonstrated that the whole crystal length may contribute to the formation of PXR, despite the condition $L_{\mathrm{abs}} < L$. Later, an analogous PXR geometry was discussed in Ref. [21,22] and the increase of the PXR intensity was observed [23].

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However, in [20,21,23] the detailed analysis of the optimal conditions under which the PXR-intensity increase takes place has not been performed. In this work we fill this gap and provide a comprehensive theoretical analysis and show the experimental feasibility of the observation of PXR-EAD. Moreover, as will be shown below, we predict the PXR-EAD intensity being two orders of magnitude larger than the one observed by conventional transition geometries. Quantitative estimations will be provided for the parameters of the electron beam of Mainz Microtron MAMI, where one of the most detailed analysis of the PXR spectrum was performed [5].

2. Qualitative consideration

In order to discuss the qualitative characteristics of PXR-EAD we assume that a monocrystal plate of a thickness d and a length L is used as a target. In addition we consider that two realistic conditions $L \gg d$ and $L_{\mathrm{abs}} < d$ are also fulfilled. In Fig. 1 the electron trajectories and tracks of emitted photons are plotted for two possible geometries of an experiment, namely the transition geometry (Laue case Fig. 1 Right pane) and the grazing geometry of PXR-EAD (Fig. 1 Left pane).

As was demonstrated in many works [1,24] the formation of PXR is caused by the vanishing coherence length [25], as it takes place in the case of Cherenkov radiation. This means that all photons emitted along the electron trajectory have equal phase and are coherent. However, only photons, which are not absorbed in a crystal contribute to the detectable PXR peak. As follows from Fig. 1 in the case of transition geometry the photons are emitted only on the part of an electron trajectory, which has the length $L_{\mathrm{abs}} \cos 2\theta_{\mathrm{B}}$. Here θ_{B} is the angle between the electron velocity $\vec{v}$ and the crystallographic planes, due to which the PXR peak is formed. This PXR peak is located under the angle $2\theta_{\mathrm{B}}$ with respect to $\vec{v}$ [1]. As a result, the total number of quanta emitted in the case of transition geometry can be estimated as

$$N_{\mathrm{PXR}} = Q_{\mathrm{PXR}} L_{\mathrm{abs}} \cos 2\theta_{\mathrm{B}}, \tag{1}$$

where Q_{PXR} defines the number of photons emitted from the unit length of the electron trajectory. Its value can be estimated within the kinematic theory of diffraction [2]. For our qualitative analysis it is sufficient to know that Q_{PXR} is independent of the crystal length under the condition $L_{\mathrm{abs}} < d$.

Returning to the grazing geometry of PXR-EAD we observe that the absorption does not occur (Fig. 1). Let an electron beam with a transverse size Δa, an angular spread $\Delta\theta_{\mathrm{e}}$ and a natural emittance (not normalized) $\varepsilon = \Delta a \Delta\theta_{\mathrm{e}}$ propagates in a crystal parallel to the crystal-vacuum interface. We denote as $\vec{N}$ the normal to the crystal surface. We also assume that the central part of the beam has a coordinate $z_0 = -a_0,\ a_0 < L_{\mathrm{abs}}$ and its velocity $\vec{v}_0$ is perpendicular to $\vec{N}$, viz. $\vec{N} \cdot \vec{v}_0 = 0$. Finally, we consider that the PXR-EAD photons are emitted along $\vec{N}$. This geometry coincides with the experimental conditions of Ref. [19]. In this situation, all photons emitted from the whole electron trajectory L are not absorbed, contribute to the formation of PXR-EAD and as will be shown below the Cherenkov condition is fulfilled. Consequently, we can write analogously to Eq. (1) for the total number of emitted quanta of PXR-EAD

$$N_{\mathrm{PXR-EAD}} = Q_{\mathrm{PXR-EAD}} L. \tag{2}$$

The exact value $Q_{\mathrm{PXR-EAD}}$ will be determined below. Here we only notice that its magnitude is comparable with Q_{PXR}, i.e., $Q_{\mathrm{PXR}} \approx Q_{\mathrm{PXR-EAD}}$. Consequently, we can define a parameter ξ, which characterizes the increase of the intensity of PXR-EAD with respect to the intensity of PXR in the ideal case $\Delta a = \Delta\theta_{\mathrm{e}} = 0$

$$\xi = \frac{N_{\mathrm{PXR-EAD}}}{N_{\mathrm{PXR}}} \approx \frac{L}{L_{\mathrm{abs}} \cos 2\theta_{\mathrm{B}}}. \tag{3}$$

However, the experimentally available electron beams impose constraints on the upper value of the parameter ξ. Indeed, in order the condition $a_0 < L_{\mathrm{abs}}$ to be fulfilled the transverse width and the angular spread should satisfy inequalities (see Fig. 2)

$$\begin{aligned} &\Delta a < L_{\mathrm{abs}}, \\ &L \leqslant \tfrac{\Delta a}{\Delta\theta_{\mathrm{e}}} \leqslant \tfrac{L_{\mathrm{abs}}^2}{\varepsilon}, \end{aligned} \tag{4}$$

which limit the actual value of the parameter ξ

$$\xi \leqslant \frac{L_{\mathrm{abs}}}{\varepsilon \cos 2\theta_{\mathrm{B}}}. \tag{5}$$

Let us investigate the maximal value of the parameter ξ from the inequality (5) within the experimental conditions of Ref. [5]. For PXR from the crystalline planes (220) of a silicone crystal the following values of parameters were employed [5]

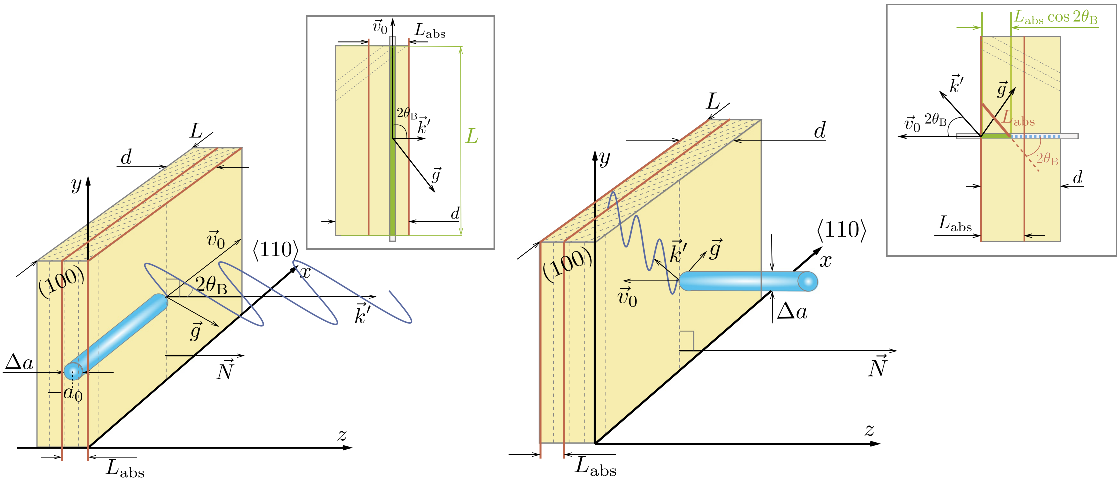

Fig. 1. Left pane: Grazing geometry of PXR-EAD. An electron beam propagates with velocity $\vec{v}_0$ along the ⟨110⟩ axis in a crystal parallel to the crystal-vacuum interface in a layer, whose thickness is smaller than L_{abs}. The emitted radiation exits from a crystal in the direction $\vec{k}' = \omega \vec{v}_0 / v_0^2 + \vec{g}$ and is not absorbed. Right pane: Conventional transition geometry of PXR. An electron beam is incident on a crystal surface under a large angle. The propagation length of the emitted X-ray radiation is larger than the absorption length L_{abs}. Consequently, only a small part of the electron trajectory $L_{\mathrm{abs}} \cos 2\theta_{\mathrm{B}}$ contributes to the formation of the X-ray radiation, which leads to the decrease of the PXR intensity.