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Influence of multiple scattering of relativistic electrons on the linewidth of Parametric X-ray Radiation produced in the extremely Bragg geometry in the absence of photoabsorption

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HIGHLIGHTS

- Multiple scattering of electrons destructively influences on the linewidth of Parametric X-ray Radiation.
- There are conditions when photoabsorption effect on the linewidth of Parametric X-ray radiation can be neglected.
- Natural linewidth of Parametric X-ray radiation is much smaller than of that affected by scattering process.

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ABSTRACT

The multiple scattering effect on the linewidth of backward Parametric X-ray Radiation (PXR) produced in the *extremely* Bragg geometry by *low energy* relativistic electrons traversing a single crystal is discussed. It is shown that there are conditions when the influence of photoabsorption on the linewidth can be neglected, and only the multiple scattering process of relativistic electrons in crystals leads to the PXR lines broadening. Based on obtained theoretical and numerical results for the linewidth broadening caused by multiple scattering of 30 and 50 MeV relativistic electrons in a Si crystal of various thicknesses, an experiment could be performed to help in revealing the scattering effect on the PXR lines in the absence of photoabsorption. This leads to more accurate understanding of the influence of scattering process on the linewidth of backward PXR and helps to better construct a table-top narrow bandwidth X-ray source for both scientific and industrial applications.

1. Introduction

Parametric X-ray Radiation (PXR) is produced when relativistic charged particles, such as electrons, move through a crystalline material (Ter-Mikaelyan, 1972; Rullhusen et al., 1998; Baryshevsky et al., 2005). In particular, production of PXR by relativistic protons was observed in straight and bent crystals (Afanasenko et al., 1992; Adishchev et al., 2005; Scandale et al., 2011). PXR is mainly concentrated in directions close to the Bragg angles of particle field reflection from crystallographic atomic planes. The case of backward PXR in the extremely Bragg geometry ($\varphi \ll 1$ in Fig. 1) is of special interest when relativistic electrons fall on the surface of a crystal at a small angle $\psi \ll 1$ ($\psi > \psi_c$) with respect to one of the crystallographic axes (z-axis in Fig. 1), since contributions of bremsstrahlung and channeling radiation are then in this case considerably suppressed. Here $\psi_c = \sqrt{4Ze^2/Ed}$ is the critical angle of axial channeling (Lindhard, 1965), d is the inter atomic distance along the z-axis, E is the particle energy, e is the charge of particle, and $Z|e|$ is the charge of nucleus of the atom.

As far as we know, backward PXR in the extremely Bragg geometry was produced by low energy relativistic electrons in Darmstadt (Freudenberger et al., 2000) and by high energy electron beam at the Mainz Microtron MAMI (Lauth et al., 2006), but the linewidth was measured at MAMI. Measurements of the linewidth show that PXR in the extremely Bragg geometry has a very narrow linewidth of a few meV (milli-electron-Volt) that points to the fact that such a quasi-monochromatic and narrow bandwidth X-ray radiation has a number of important applications (Sones et al., 2006; Takahashi et al., 2012; Takabayashi and Sumitani, 2013). These narrow lines appear in the spectral angular radiation density as a result of the interference of reflected waves from crystallographic atomic planes oriented perpendicular to the z-axis (see Fig. 2). The natural width of these lines is determined

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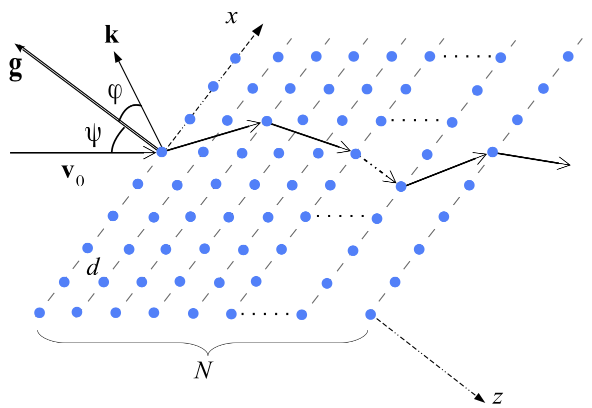

Fig. 1. 2D schematic (view from the y-axis) of multiple scattering of relativistic electrons in a crystal producing backward PXR in the extremely Bragg geometry ($\phi \ll 1$), where $\mathbf{v}_0$ is the velocity vector of incoming electron, ψ is the incidence angle of electrons with respect to the z-axis ($\psi > \psi_c$), $\mathbf{g}$ is the reciprocal lattice vector, $\mathbf{k}$ is the wave vector of emitted photons, ϕ is the angle between $\mathbf{k}$ and $\mathbf{g}$ ($\varphi \ll 1$), N is the number of crystal planes and d is the distance between lattice planes.

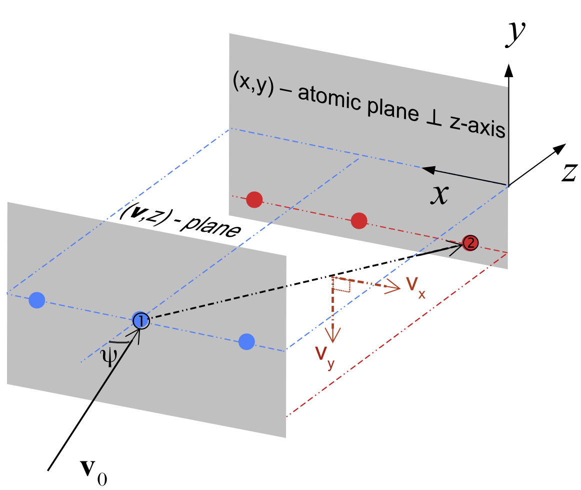

Fig. 2. 3D schematic of single scattering of an electron on the atom 1 of top plane going to the atom 2 of other plane along the x- and y-axes.

by the number of crystallographic planes, which the relativistic electrons interact with (Shul'ga and Tabrizi, 2002, 2003). However, results of measurements at MAMI (Lauth et al., 2006) show that the linewidth of backward PXR produced by high energy relativistic electrons in the extremely Bragg geometry in a crystal is much larger than its natural line.

There are two kinds of effects which destructively influence on the PXR lines. The *instrumental* effects such as finite detector opening (Freudenberger et al., 1997), angular spread of electron beam (Brenzinger et al., 1997) and finiteness of the collimator (Gogolev and Potylitsyn, 2008) are connected with the instruments to measure PXR lines. The *non-instrumental* effects on the PXR lines caused by such processes as absorption of emitted photons and multiple scattering of relativistic electrons in a crystal are connected with the physical phenomena during PXR production. In the subsequent discussion, the two aforementioned non-instrumental effects on the linewidth of backward PXR in the extremely Bragg geometry will be considered .

For a thick crystal with a thickness L larger than the absorption length of emitted photons L_a, the influence of absorption on the linewidth of PXR becomes most important (Nitta, 1996; Lauth et al., 2006). For very thick crystals ($L \gg L_a$), the PXR intensity ultimately no longer increases with L (Baryshevsky et al., 1988). Multiple scattering process of relativistic electrons in crystals (see Fig. 1) is another physical phenomenon which destructively contributes to the linewidth of PXR (Freudenberger et al., 1997; Brenzinger et al., 1997; Lauth et al., 2006). Although influence of photoabsorption together with multiple scattering of high energy relativistic electrons on the linewidth of backward PXR in the extremely Bragg geometry were investigated at MAMI (Lauth et al., 2006), it is still an open question whether scattering process of *low energy* relativistic electrons has the significant effect on the PXR lines in the extremely Bragg geometry in the absence of photoabsorption.

Here we summarize motivation of our interest to backward PXR produced by *low energy* relativistic electrons in the *extremely* Bragg geometry:

1. Although backward PXR was produced by *low energy* relativistic electrons under extremely Bragg condition with a boost of intensity by a factor of two (Freudenberger et al., 2000), but the linewidth was not measured and the influence of multiple scattering of *low energy* relativistic electrons on the PXR lines in the extremely Bragg case in the absence of photoabsorption is of special interest.
2. Contribution of channeling radiation and bremsstrahlung in the case of PXR produced in extremely Bragg geometry are suppressed.
3. Compared with the production of PXR by high energy relativistic electron beam in expensive accelerators such as MAMI (Lauth et al., 2006), PXR in the extremely Bragg geometry can be produced by *low energy* relativistic electrons in an relatively inexpensive accelerator (Freudenberger et al., 2000).

Following our motivation, we investigate in this paper the influence of small angle multiple scattering of low energy relativistic electrons on the linewidth of backward PXR produced in the extremely Bragg geometry in a single crystal of various thicknesses L less than the absorption length L_a of emitted photons. We find conditions when the influence of photoabsorption on the PXR lines is negligible.[1]

The paper is organized as follows. In Section 2 we discuss scattering process of relativistic electrons in a crystal in small angle approximation, then consider the spectral angular radiation density of backward PXR produced in the extremely Bragg geometry taking into account multiple scattering of relativistic electrons. In Section 3 we find necessary conditions on which to neglect the influence of photoabsorption on the linewidth of backward PXR. Section 4 presents numerical results for linewidth broadening caused by multiple scattering of low energy relativistic electrons in a Si crystal of various thicknesses. The paper is concluded with a summary in Section 5.

2. Spectral angular radiation density of backward PXR in the extremely Bragg geometry taking into account small angle multiple scattering process

2.1. Scattering in small angle approximation

Analysis of experimental data on backward PXR produced by high energy relativistic electrons in the extremely Bragg geometry (Lauth et al., 2006) shows that, apart from the absorption of emitted photons in crystals, deflection of relativistic electrons from initial straight forward direction in crystals makes important contribution to the linewidth of PXR. In other words, assumption

[1] Hereafter, we will use system of units, in which $c = \hbar = 1$.