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Characteristic, parametric, and diffracted transition X-ray radiation for observation of accelerated particle beam profile

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ABSTRACT

The applicability of X-ray radiation for the observation of accelerated particle beam profiles is studied. Three types of quasi-monochromatic X-ray radiation excited by the particles in crystals are considered: characteristic X-ray radiation, parametric X-ray radiation, diffracted transition X-ray radiation. Radiation is collected at the right angle to the particle beam direction. It is show that the most intensive differential yield of X-ray radiation from Si crystal can be provided by characteristic radiation at incident electron energies up to tens MeV, by parametric radiation at incident electron energies from tens to hundreds MeV, by diffracted transition X-ray radiation at GeV and multi-GeV electron energies. Therefore these kinds of radiation are proposed for application to beam profile observation in the corresponding energy ranges of incident electrons. Some elements of X-ray optics for observation of the beam profile are discussed. The application of the DTR as a source of powerful tunable monochromatic linearly polarized X-ray beam excited by a multi-GeV electron beam on the crystal surface is proposed.

1. Introduction

The possibilities of optical diagnostics of intense relativistic beams with small transverse size are limited by diffraction (for beam sizes about or less than 1 μm) and coherent emission from dense beams (beam bunches). More detailed discussion about these two restrictions can be found in [1,2]. In order to overcome them one can use radiations emitted by the beam particles in the X-ray range. For example, the application of parametric X-rays (PXR) for beam diagnostics has been proposed in Refs. [3,4]. Recently, the observation of the electron beam profile with use of PXR emitted by an electron beam in silicon crystal has been successfully demonstrated in experiment [1]. The X-ray image of the beam profile was obtained with use of a pinhole *obscura camera* [1].

In the present paper we consider different sources of monochromatic X-ray radiation excited by relativistic particles in a crystal and other targets, namely characteristic X-ray radiation (CXR), parametric X-ray radiation and diffracted transition X-ray radiation (DTR) for application in diagnostics. We propose to apply a specific kind of radiation for each range of electron energy, in particular DTR for diagnostics of multi-GeV beams. Besides, we propose to use an array of pinholes or an array of Fresnel zone plates or an array of refractive converging X-ray lenses or an array of small crystals to reduce the measurement time.

2. Sources of X-rays excited by relativistic particles in a crystalline target

At present, the most intense sources of quasi-monochromatic X-rays excited by relativistic particles in solid targets that can be used for observation of the beam profile are:

1. Characteristic X-ray radiation, that arises due to excitation of atoms in a target by incident particles. CXR is monochromatic, unpolarized and isotropic. The energy of the CXR is determined by the atoms of the target.
2. Parametric X-ray radiation, which comes from Bragg diffraction of the co-moving electromagnetic field of the particle by crystallographic planes inside a crystalline target. PXR is monochromatic, linearly polarized, and directed in the specular direction with an angular divergence of about γ_{eff}^{-1}, where

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$\gamma_{eff}^{-1} = \sqrt{\gamma^{-2} + 1 - n^2}$, γ is the Lorenz factor and n is the X-ray index of refraction. In the X-ray band $n = \sqrt{1 - |\chi_0|}$, where χ_0 is the average dielectric susceptibility. The PXR frequency is close to the Bragg frequency in the direction of observation.

3. Diffracted transition X-ray radiation, which is similar to PXR but comes from Bragg diffraction of the *transient* part (transition radiation) of the electromagnetic field of the particle when it enters the target [5,6]. At high Lorentz factor γ of the particle, the transient field is essentially made of the virtual photons which accompanied the particle in vacuum before entering the target. The diffraction occurs on crystallographic planes near the crystal surface. Like PXR, DTR is monochromatic, linearly polarized, and directed in the specular direction, but with a smaller angular divergence of about γ^{-1} and a frequency equal to the Bragg frequency in the direction of observation.

The energy of these radiations can be in the range from a few to tens of keV, which is convenient for an observation with standard methods of X-ray physics. In principle, any of these radiations can be used for the observation of beam profiles, but their yields depend differently on the energies of the incident particles. In order to clear up the possibilities of applications of these kinds of radiation for beam diagnostics, in the present paper we will perform calculations of the differential yields of the CXR, PXR and DTR as functions of the incident electron energy.

3. Generation of X-ray radiation

There are many possible experimental geometries for the generation of the above mentioned radiations by relativistic electrons in crystals. To understand the respective properties of CXR, PXR and DTR at different incident electron energies, we calculate here and compare yields of these radiations from the most popular Si single crystal in the symmetrical Bragg geometry at an observation angle of 90 degrees. The arrangement of Si single crystal plate and angular distributions of radiation are shown in Fig. 1. We consider PXR and DTR from crystallographic planes (220) aligned parallel to the Si crystal surface and CXR from atoms of the same Si crystal. The thickness of the plate should exceed the attenuation lengths for CXR and PXR and extinction depth for DTR. In our case the thickness should be about or more then 20 μm.

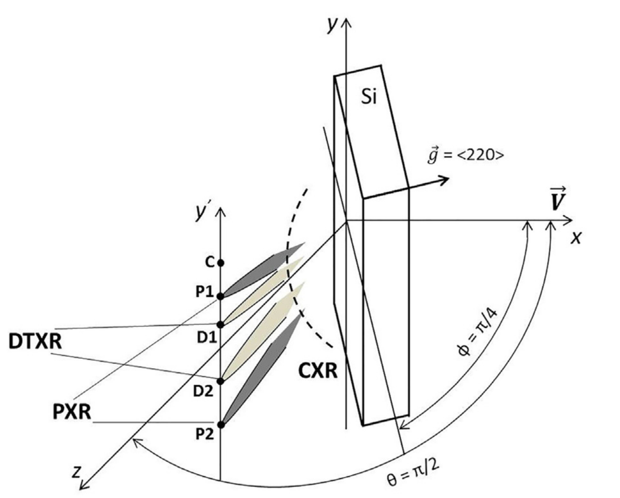

Fig. 1. The layout for generation of the CXR, PXR and DTR. The Si single-crystal slab is installed at angle $\phi = 45°$ with respect to the electron beam. The crystallographic planes (220) that provide PXR and DTR reflections are parallel to the target surface and represented by the reciprocal lattice vector $\vec{g} = 220$. Angular distributions of PXR and DTR are schematically shown by lobe-like curves in the y,z plane. CXR is isotropic, its angular distribution is represented by the dashed curve. PXR and DTR are distributed about the specular direction corresponding to an incidence on the z axis. CXR, PXR and DTR can be observed by X-ray detector(s) installed in the y,z plane, at 90° from the electrons velocity vector. In order to optimize the PXR or DTR yield, one puts the detector at angle $\pm\gamma_{eff}$ or $\pm\gamma$ respectively with respect to the z axis in the y,z plane. The maxima of PXR are at P1 and P2. For DTR they are at D1 and D2. CXR can be observed in any point in the vicinity the z axis, e.g. in point C.

4. Yield and energy of characteristic X-ray radiation

We calculate the CXR yield Y_{CXR} excited by relativistic electrons using the formula obtained from Eq. (1) in Ref. [7]

$$Y_{CXR} = \frac{dN_{CXR}}{d\Omega} = \frac{\omega_K T_e n_0 \sigma_K}{4\pi}\left[1 - \exp\left(-\frac{T}{T_e \cos\frac{\theta}{2}}\right)\right], \quad (1)$$

where dN_{CXR} is the number of CXR quanta emitted per unit solid angle $d\Omega$, ω_K is the fluorescent yield, n_0 is the atomic density of the target, T is the target slab thickness, T_e is the path length at which radiation intensity attenuates by a factor of e, $T_e = \frac{1}{\mu}$, μ is the linear attenuation coefficient for the radiation in the target material, θ is the observation angle, σ_K is the K-shell ionization cross section by relativistic electrons. The formula for Si K-shell ionization cross section by relativistic electrons σ_K^{Si} was found in [8] by approximation of experimental data available in literature:

$$\sigma_K^{Si}(barn) = 134 \ln\gamma + 1025. \quad (2)$$

Results of calculations of the CXR yield as a function of incident electron energy is shown in Fig. 2. The CXR is unpolarized. The energy of CXR quanta 1.74 keV is determined by properties of Si atoms, $T_e = 13.3$ μm for Si CXR in Si crystal.

5. Yield and energy of parametric X-ray radiation

Calculations of the PXR differential yield have been performed with the small-angle approximation of the kinematical PXR theory of Ter-Mikaelian [9] at $\gamma >> 1$

$$Y_{PXR} = \frac{dN_{PXR}}{d\Omega} = \frac{\alpha \cdot Z^2 \cdot M \cdot \left|\chi_{\vec{g}}(\omega_{PXR})\right|^2}{\left(\frac{c}{V\sqrt{\varepsilon}} - \cos\theta\right)^2} \cdot \frac{\delta_\perp^2 + \delta_{||}^2 \cdot \cos^2 2\phi}{\left(\gamma_{eff}^{-2} + \delta_\perp^2 + \delta_{||}^2\right)^2}, \quad (3)$$

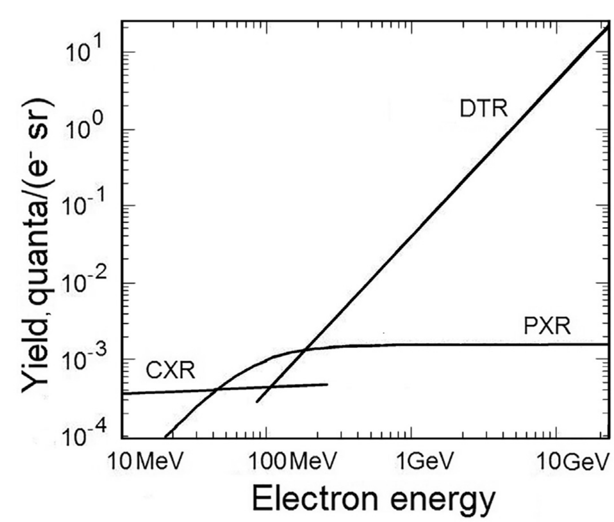

Fig. 2. Calculated differential yields of CXR and PXR, DTR at their maxima as functions of incident electron energy. The CXR, PXR, DTR are emitted from Si crystal of thickness exceeding 20 μm in the geometry shown in Fig. 1.

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