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Cooperative parametric (quasi-Cherenkov) radiation produced by electron bunches in natural or photonic crystals

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ABSTRACT

We study the features of cooperative parametric (quasi-Cherenkov) radiation arising when initially unmodulated electron (positron) bunches pass through a crystal (natural or artificial) under the conditions of dynamical diffraction of electromagnetic waves in the presence of shot noise. A detailed numerical analysis is given for cooperative THz radiation in artificial crystals. The radiation intensity above 200 MW/cm^2 is obtained in simulations.

The peak intensity of cooperative radiation emitted at small and large angles to particle velocity is investigated as a function of the current density of an electron bunch. The peak radiation intensity appeared to increase monotonically until saturation is achieved. At saturation, the shot noise causes strong fluctuations in the intensity of cooperative parametric radiation.

It is shown that the duration of radiation pulses can be much longer than the particle flight time through the crystal. This enables a thorough experimental investigation of the time structure of cooperative parametric radiation generated by electron bunches available with modern accelerators.

The complicated time structure of cooperative parametric (quasi-Cherenkov) radiation can be observed in crystals (natural or artificial) in all spectral ranges (X-ray, optical, terahertz, and microwave).

1. Introduction

The generation of short pulses of electromagnetic radiation is a primary challenge of modern physics. They find applications in studying molecular dynamics in biological objects and charge transfer in nanoelectronic devices, diagnostics of dense plasma and radar detection of fast moving objects.

The advances in the generation of short pulses of electromagnetic radiation in infrared, visible, ultraviolet, and X-ray ranges of wavelengths are traditionally associated with the development of quantum electronic devices — lasers. Radiation in lasers is generated via induced emission of photons by bound electrons.

Electrovacuum devices, operating in a cooperative regime [1,2], have recently become considered as an alternative to short-pulse lasers, whose active medium is formed by electrons bound in atoms and molecules. These are free electron lasers, cyclotron-resonance masers, and Cherenkov radiators, whose active medium is formed by initially unmodulated electron bunches propagating in complex electrodynamical structures (undulators, corrugated waveguides and others) and being much greater than the radiation wavelength. The feature of the cooperative operation regime lies in the fact that the peak radiation power scales as the squared number of particles in the bunch. (This allows calling this regime "superradiance" by analogy with the phenomenon predicted by Dicke in quantum electronics [1]). To avoid misunderstanding, let us note that initially, the coherent part of electromagnetic radiation is highly suppressed, because the length of an electron bunch is much greater than the radiation wavelength. The electromagnetic wave emission starts as incoherent spontaneous process, becomes coherent through the nonlinear interaction of the electrons and the electromagnetic field.

In free electron lasers, the initial phases of charged particles in the electromagnetic wave are homogeneously distributed. As a result, bremsstrahlung produced by oscillating electrons starts from incoherent spontaneous emission. This is true even if the bunch length is much smaller than the radiation wave length. In contrast to bremsstrahlung, Cherenkov (quasi-Cherenkov) radiation starts from coherent spontaneous emission when such a short-length bunch is injected into a slow-wave structure, i. e. the radiation power is proportional to the squared number of particles.

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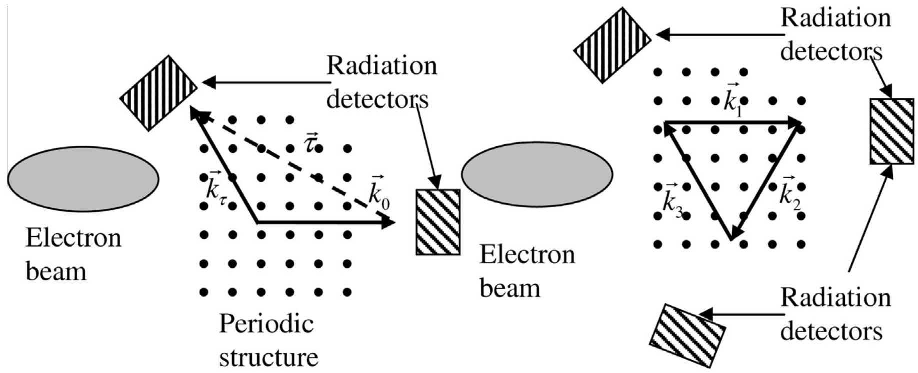

Fig. 1. The two-wave (left) and three-wave (right) diffraction geometries.

This paper considers cooperative quasi-Cherenkov radiation emitted by electron bunches when charged particles pass through crystals (natural or artificial) under the conditions of dynamical diffraction of electromagnetic waves. The concept of parametric (quasi-Cherenkov) radiation was originated in the works devoted to the interaction of charged particles with natural crystals (see, for example [3,5,6]). According to [3,5], the dynamical diffraction of photons emitted by a relativistic charged particle in a crystal leads to a change in the refractive index of X-ray quanta.

In accordance with [3,5], diffraction of virtual photons in a crystal possesses a set of refractive indices $n_\mu(\omega,\vec{k})$, some of which may appear to be greater than unity ($\vec{k}$ is the photon wave vector). Particularly, in the case of two–wave diffraction, the refractive indices are $n_1(\omega,\vec{k}) > 1$ and $n_2(\omega,\vec{k}) < 1$, and accordingly, two types of waves propagate in the crystal: a fast wave ($n_2 < 1$) and a slow one ($n_1 > 1$). The Cherenkov condition can be fulfilled for a slow wave, but not for a fast one. The former gives rise to spontaneous quasi-Cherenkov radiation, called the parametric X-ray radiation (PXR). The latter is emitted at the vacuum–crystal boundary. The considered phenomenon has a universal character and can be observed in different spectral ranges (microwave, terahertz, optical, etc.) for particles passing through varied two- and three-dimensional spatially periodic structures [9], often called the photonic crystals.

A detailed analysis of the features of incoherent spontaneous radiation of electrons passing through crystals in both frequency [3] and time [4] domains has been carried out. This radiation, emitted at both large and small angles with respect to the direction of electron motion. The problems of amplification of induced parametric X-ray radiation and microwave (optical) quasi-Cherenkov radiation have also been thoroughly studied in the literature [7], and the threshold current densities providing lasing in crystals have been calculated [8]. Coherent spontaneous radiation produced by modulated electron bunches in crystals has been analysed in [10–12].

The paper is arranged as follows: In the beginning, a nonlinear theory of interaction of relativistic charged particles and the electromagnetic field in crystals is set forth, followed by the results of numerical calculations of the parametric radiation pulse. The dependence of the radiation intensity on the current density of an electron bunch and the geometrical parameters of the system is considered.

2. Nonlinear theory of cooperative radiation

A theoretical analysis of radiation can be performed only by means of a self-consistent solution of a nonlinear set of the Newton–Maxwell equations:

$$\frac{d\vec{p}_\alpha}{dt} = q_e\left(\vec{E}(\vec{r}_\alpha,t) + \vec{v}_\alpha \times \vec{H}(\vec{r}_\alpha,t)/c\right), \tag{1}$$

$$\begin{aligned}
&\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{H}}{\partial t},\\
&\nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t} + \frac{4\pi}{c}\vec{j},\\
&\nabla \cdot \vec{D} = 4\pi\rho,\\
&\nabla \cdot \vec{H} = 0,
\end{aligned} \tag{2}$$

describing the electron motion in the electric $\vec{E}$ and magnetic $\vec{H}$ fields. Here $\vec{j} = q_e\sum_\alpha \vec{v}_\alpha \delta(\vec{r}-\vec{r}_\alpha)$ and $\rho = q_e\sum_\alpha \delta(\vec{r}-\vec{r}_\alpha)$ are the current and charge densities, respectively. Since the crystal is a periodic linear medium with frequency dispersion, the Fourier transform of the electric displacement field $\vec{D}(\vec{r},\omega)$ relates to the electric field $\vec{E}(\vec{r},\omega)$ as

$$\begin{aligned}
\vec{D}(\vec{r},\omega) &= \epsilon(\vec{r},\omega)\vec{E}(\vec{r},\omega)\\
&= \left(1 + \chi_0(\omega) + \sum_{\vec{\tau}} 2\chi_{\vec{\tau}}(\omega)\cos(\vec{\tau}\vec{r})\right)\vec{E}(\vec{r},\omega),
\end{aligned} \tag{3}$$

where the summation is made over all reciprocal lattice vectors. This permits to reduce Maxwell's Eqs. (2) to the equation of the form:

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\int_{-\infty}^{t}\epsilon(\vec{r},t-t_1)\vec{E}(\vec{r},t_1)dt_1 + \nabla(\nabla\cdot\vec{E}) - \Delta\vec{E} = -\frac{4\pi}{c^2}\frac{\partial\vec{j}}{\partial t}. \tag{4}$$

Let's simplify the Eq. (4) for the case when $|\chi_{0,\tau}| \ll 1$ and two strong waves are excited in the crystal: the forward wave and the diffracted wave (the so-called two-wave diffraction case). The forward wave (its wave vector is denoted by $\vec{k}_0$) is emitted at small angles with respect to the particle velocity, while the diffracted one, having the wave vector $\vec{k}_\tau = \vec{k}_0 + \vec{\tau}$, is emitted at large angles to it (Fig. 1). Under the conditions of dynamical Bragg diffraction, the following relation is fulfilled: $\vec{k}_\tau^2 \approx \vec{k}_0^2 \approx \omega^2/c^2$.

Let us perform the following simplifications: First, we shall neglect the longitudinal ($\nabla\cdot\vec{D} \to 0$) fields of the bunch. Second, we shall seek for the electric field $\vec{E}$ using the method of slowly varying amplitudes. Third, we shall assume that a transversally infinite bunch executes one-dimensional motion along the *OZ*-axis (this is achieved by inducing a strong axial magnetic field in the system).

Under the conditions of two-wave diffraction, the field $\vec{E}$ can be presented as a sum

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