Vacuum Channeling Radiation by Relativistic Electrons in a Transverse Field of a Laser-Based Bessel Beam

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Relativistic electrons counterpropagating through the center of a radially polarized $J_1$ optical Bessel beam in vacuum will emit radiation in a manner analogous to the channeling radiation that occurs when charged particles traverse through a crystal lattice. However, since this interaction occurs in vacuum, problems with scattering of the electrons by the lattice atoms are eliminated. Contrary to inverse Compton scattering, the emitted frequency is also determined by the amplitude of the laser field, rather than only by its frequency. Adjusting the value of the laser field permits the tuning of the emitted frequency over orders of magnitude, from terahertz to soft X rays. High flux intensities are predicted ($\sim 100$ MW/cm$^2$). Extended interaction lengths are feasible due to the diffraction-free properties of the Bessel beam and its radial field, which confines the electron trajectory within the center of the Bessel beam.

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Channeling radiation was predicted by Kumachov [1] to occur when a beam of relativistic positrons is launched almost parallel to the symmetry planes of a solid-state crystal. Classically, this phenomenon can be understood in terms of the charged particle bouncing back and forth between the atomic planes. This transverse oscillation causes the particle to emit radiation. During the early 1980s, Andersen [2] and Klein [3] investigated this process experimentally. A thorough review of activity during these early years was compiled by Bazylev and Zhevago [4].

Quantum mechanically, in the transverse direction, the particle may be conceived to move in an harmonic oscillator [5]. A positron impinging parallel to the symmetry plane of the crystal populates only the lowest eigenstate and, as such, will not radiate. However, when its trajectory is tilted, it also populates the upper states. Spontaneous radiation is emitted as it drops from an upper to a lower energy state.

Throughout the years it has been suggested to replace the crystalline lattice with a macroscopic transverse static field [6] or a superposition of two intersecting laser beams [7]. In the former case, the coupling of the electrons with the radiation is relatively weak for typically available fields, whereas in the latter case, the interaction length is limited due to the small diameters of the crossing laser beams, the need for tight focusing, and diffraction effects (see [8]).

In this Letter we present a new channeling radiation paradigm in which a counterpropagating radially polarized $J_1$ Bessel beam (BB), see the top frame in Fig. 1, plays a role analogous to that of the lattice. Contrary to the aforementioned alternative schemes for replacing the crystal lattice with an optical lattice, usage of a Bessel beam permits long interaction lengths, which are not limited by the usual diffraction of focused laser beams, and which do not require high laser intensities. Moreover, as will be shown, the electrons bounce back and forth (see inset in Fig. 1) due to the radial force associated with the BB profile, and emit radiation with a frequency proportional to the amplitude of the BB field. The same mechanism responsible for the generation of radiation also facilitates the confinement of the $e$-beam over the entire length of the BB. It should be mentioned that coherent channeling radiation in vacuum is also possible, but this is beyond the scope of this Letter.

Consider a “hollow” $J_1$ BB (see the main frame in Fig. 1) where the peak of the first lobe is at radius $R_{\text{las}}$ and the $e$-beam radius $R_b$ is such that $R_b < R_{\text{las}}$; this is in order to ensure that the electrons are propagating within the BB where the radial force exerted by the potential is linear in $r$. This region is between the vertical dashed lines depicted in Fig. 1. The laser field components may be derived from the longitudinal component of the electric field $E_z = E_0 \cos(\omega_b(t + z/v_{\text{ph}}))$, where $E_0$ is the amplitude of the laser field, $\omega_b$ is the laser frequency, and $v_{\text{ph}}$ is the phase velocity of the light wave.

The BB propagates in the opposite direction to the electrons moving along $z \sim vt$ and, according to Maxwell’s stress tensor, the time-averaged radial force density it exerts is

$$\langle f_r \rangle_T = -\frac{\epsilon_0}{2} \left( \frac{\omega_0}{c} E_0 \sin \theta_0 \right)^2 r,$$

where $\epsilon_0$ is permittivity and $\theta_0$ is the angle of the light ray relative to the $z$ axis, such that $v_{\text{ph}} = c/\cos \theta_0$. Denoting by $n_{\text{el}}$ the electron density that is exposed to this BB, the transverse components of the equation of motion read...