POLARIZATION OF RADIATION OF A FAST ELECTRON BEAM IN A STRONG MAGNETIC FIELD

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In this contribution we examine the polarization of synchrotron radiation emitted by a beam of relativistic electrons moving in a strong magnetic field. To this end, we solve the balance equation taking into account both significant energy losses and changes in electron spin orientation of electrons of a relativistic beam due to photon emission. It can be concluded that in the case of a positively polarized electron beam the overall degree of radiation polarization decreases due to broadening of the emission spectrum if both the electron energy and the magnetic field strength are high.

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Spin-polarization effects are a fundamental characteristic of the synchrotron radiation (SR) process. In particular, SR polarization depends on the electron spin projection with respect to the magnetic field direction. Photon emission can cause a change in spin orientation, with a higher probability of transition to a state with a negative spin projection. As a result, the spins gradually align opposite to the field direction, a phenomenon known as the radiative self-polarization effect. This effect was experimentally observed in storage rings and has important applications in particle accelerator physics [1].

Radiative self-polarization in a strong magnetic field has attracted significant attention in recent years, as the polarization time is predicted to be within the femtosecond range in this case. In laboratory conditions, strong magnetic fields can be plausibly generated only within a small spatial region. In contrast to conditions in storage rings, an electron beam would traverse this region without energy replenishment. Under such conditions, calculating SR polarization requires considering both changes in electron spin projections and significant energy losses due to radiation.

For example, in [2, 3], a mechanism for generating a strong magnetic field is proposed based on the interaction of a dense electron beam with a target positioned at a grazing angle. The authors estimate a field strength of $4 \cdot 10^9\ G$ for an electron energy of 10 GeV and a beam density of 10^{21} cm^{-3}, which are similar to the parameters of the FACET-II facility [4].

In this work, we consider the polarization of synchrotron radiation, taking into account the evolution of the distribution function of the beam's spin components due to self-polarization and energy losses. To this end, we numerically solve the balance equation for the electron distribution function, which has the form

$$\frac{\partial n_\mu(\tau,\varepsilon)}{\partial\tau} = \int_\varepsilon^\infty \left(n_\mu(\tau,\epsilon) w^{\mu\mu}(\varepsilon,\epsilon) + n_{-\mu}(\tau,\epsilon) w^{\mu,-\mu}(\varepsilon,\epsilon)\right) d\epsilon - n_\mu(\tau,\varepsilon) \int_0^\varepsilon \left(w^{\mu\mu}(\epsilon,\varepsilon) + w^{-\mu,\mu}(\epsilon,\varepsilon)\right) d\epsilon,$$

where $\mu = 2s_z$ is the electron polarization, $n_\mu(\tau,\varepsilon)$ is the energy distribution of the beam spin components, and $w^{\mu'\mu}(\varepsilon,\varepsilon')$ is the differential rate of radiation-induced transitions from the state (μ,ε) to the energy interval $d\varepsilon'$ near the state (μ',ε'). The SR rates entering this equation are expressed in terms of the dimensionless parameter

$$\varepsilon = \frac{E}{mc^2}\frac{H}{H_c},$$

where E is the electron energy, H is the magnetic field, and $H_c \approx 4.41 \cdot 10^{13}\ G$ is the critical Schwinger field. The dimensionless time τ is defined as $\tau = t/t_0$, where $t_0 = (\alpha\omega_H)^{-1}$, ω_H is the cyclotron frequency and α is the fine-structure constant. For magnetic field strength of $4 \cdot 10^9\ G$ and electron energy of 10 GeV [3], we obtain an estimate of $t_0 \approx 1.7$ fs and $\varepsilon \approx 2$.

The expressions for synchrotron radiation rates are well known [5] and can be written as

$$dw^{\mu'\mu}(\varepsilon',\varepsilon) = \frac{1}{16\pi\sqrt{3}} \frac{(\varepsilon+\varepsilon')^2}{\varepsilon^3\varepsilon'} G^{\mu'\mu} d\varepsilon',$$

$$G^{\mu\mu} = \left(K_{\frac{2}{3}}(a) - Y(a)\right)(1+\xi) + \left(3K_{\frac{2}{3}}(a) + (2\rho^2-1)Y(a) - 4\mu\rho K_{\frac{1}{3}}(a)\right)(1-\xi),$$

$$G^{-\mu\mu} = \rho^2\left[\left(K_{\frac{2}{3}}(a) - Y(a)\right)(1-\xi) + \left(3K_{\frac{2}{3}}(a) + Y(a) + 4\mu K_{\frac{1}{3}}(a)\right)(1+\xi)\right],$$

where $K_\nu(x)$ is the modified Bessel function and $Y(a)$ is the integral Bessel function of the order 1/3,

$$Y(a) = \int_a^\infty K_{\frac{1}{3}}(x)dx,$$

and the quantities a and ρ are defined as

$$a = \frac{2}{3}\frac{\varepsilon-\varepsilon\prime}{\varepsilon\prime\varepsilon}, \qquad \rho = \frac{\varepsilon-\varepsilon\prime}{\varepsilon+\varepsilon\prime}.$$

Having obtained the electron density $n_\mu(\tau,\varepsilon)$, one can calculate the radiation intensity of the electron beam at a fixed dimensionless frequency $\Omega = \varepsilon - \varepsilon'$ as

$$I(\tau,\Omega,\xi) = \Omega \sum_{\mu'\mu} \int_\Omega^\infty n_\mu(\tau,\varepsilon) w^{\mu'\mu}(\varepsilon,\varepsilon,\xi) d\varepsilon.$$

In the above expressions the quantity ξ is the Stokes parameter describing the linear horizontal and vertical polarization. It is important to note that the parameter ξ entering the rates is related to the analyzer setup. The corresponding Stokes parameter Ξ describing the polarization of the radiation itself is defined as

$$\Xi = \frac{I(\xi=+1) - I(\xi=-1)}{I(\xi=+1) + I(\xi=-1)}$$

In this work, the polarization of synchrotron radiation from a beam with a mean electron energy of $\varepsilon_0 = 10^{-2}$ and $\varepsilon_0 = 10^4$ was calculated. The energy dispersion was set to $0.1\varepsilon_0$. Figure 1 shows the evolution of the density distribution for the spin component $\mu = -1$ for an initially unpolarized beam. As can be seen from fig.1(a), the distribution function gradually shifts toward the low-energy region if the initial dimensionless beam energy ε_0 is small. In contrast, for high initial energy, the behavior of the distribution function is different (fig.1(b)). A sudden energy loss occurs at the initial stage of beam propagation, leading to the formation and growth of a new local maximum in the density.

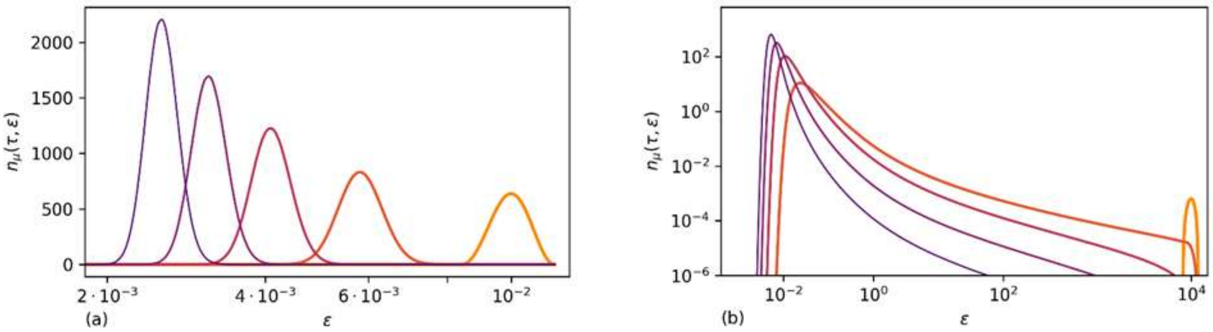

Fig. 1. Evolution of $\mu = -1$ component of the electron density of an initially unpolarized beam.
Dimensionless time is equal to τ = 0, 100, 200, 300, 400.
The initial mean electron energy is $\varepsilon_0 = 10^{-2}$ (a) and $\varepsilon_0 = 10^4$ (b) . The initial energy dispersion is $0.1\varepsilon_0$

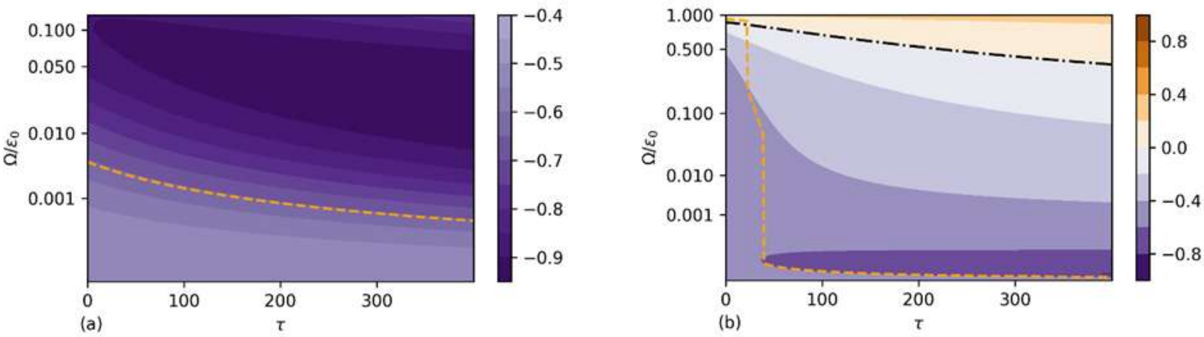

Fig. 2. The Stokes parameter of synchrotron radiation as a function of propagation time and the dimensionless radiation frequency Ω. The initial mean energy is $\varepsilon_0 = 10^{-2}$ (a) and $\varepsilon_0 = 10^4$ (b) .
The beam is initially polarized along the magnetic field, $\mu = +1$.
The dashed line shows the location of the spectral maximum. The dot-dashed line shows the frequency for which the condition $\Xi = 0$ holds true

Fig. 2 depicts the Stokes parameter of the synchrotron radiation emitted by a beam initially polarized along the magnetic field as a function of propagation time and the dimensionless radiation frequency. For the beam polarization of $\mu = +1$, the Stokes parameter is negative at small frequency and changes its sign when frequency is comparable with the beam energy ε_0. However, when $\varepsilon_0 \ll 1$, the spectral maximum is located at low frequency and the radiation is practically absent for $\Omega \sim \varepsilon_0$. In contrast, if the beam energy is high and $\varepsilon_0 \gg 1$, the radiation spectrum broadens and its maximum lays near the frequency where $\Xi = 0$, which leads to a decrease in the overall degree of radiation polarization. The respective calculation of the Stokes parameter using total intensity integrated over frequency gives a value of about $\Xi \approx -0.7$ for $\varepsilon_0 = 10^{-2}$ and a value of $\Xi \approx -0.2$ for $\varepsilon_0 = 10^4$.

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