Monochromatization of charged-particle beams by a laser pulse in a wiggler

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A charged-particle beam can be monochromatized by a stimulated interaction with a laser beam in a wiggler. The energy spread of the beam decreases by several orders of magnitude for real parameters.

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The first experimental laser based on free electrons used the stimulated wiggler radiation of a relativistic electron beam.[1] This proved that a magnetic wiggler can be used as a coherent converter of energy between an electron and a laser beam. An energy exchange of this type (acceleration of particles or enhancement of radiation) depends on the particle velocity and on the threshold value of the field.[2] Suppose that a beam of charged particles with an energy spread Δ_0 and angular divergence δ_0 passes through a magnetic wiggler, $H_z(x) = H_0 \cos(2\pi/l)x$, at an angle θ_0 with respect to the laser beam that propagates along the wiggler. The angle θ_0 is determined from the coherence condition (stimulated wiggler radiation or absorption threshold),

$$v_0 \cos\theta_0 = \frac{c}{1 + \frac{\lambda}{l}}, \tag{1}$$

where v_0 is the average particle velocity in the beam, and λ is the wavelength of the laser beam. The average energy of the beam remains constant after the interaction, and for the particles whose velocities do not satisfy Eq. (1) because of their spread, there is a threshold field[2]

$$\xi_{\text{thresh}} \equiv \frac{e}{2\pi mc^2}(\lambda E + lH_0)_{\text{thresh}} = \frac{\sqrt{2\frac{l}{\lambda}}}{\sqrt{2+\frac{\lambda}{l}}}\frac{\mathcal{E}}{mc^2}\left|1 - \left(1+\frac{\lambda}{l}\right)\frac{v}{c}\cos\theta\right| \tag{2}$$

(E is the amplitude of the electric field of the laser) above which the energy varies

$$\mathcal{E}' = \mathcal{E}\left[1 + 2\frac{l}{\lambda}\,\frac{1 - \left(1+\frac{\lambda}{l}\right)\frac{v}{c}\cos\theta}{2 + \frac{\lambda}{l}}\right]. \tag{3}$$

It can be seen from Eq. (3) that half of the beam particles for which $v\cos\theta < \dfrac{c}{1+\frac{\lambda}{l}}$

are accelerated (they absorb only laser quanta) and the other half for which $v \cos\theta > \dfrac{c}{1+\dfrac{\lambda}{l}}$ lose energy (they only radiate energy). Consequently, as a result of a coherent energy exchange, the particle beam acquires an arbitrary energy width Γ after the interaction, which depends on its initial parameters and on λ/l. By choosing an appropriate parameter λ/l, however, we can change the energy in such a way that the particles with $\mathscr{E} < \mathscr{E}_0$ would have an energy $\mathscr{E}' = \mathscr{E}_0$ after the interaction. The other half of the particles with $\mathscr{E} > \mathscr{E}_0$ in this case will have the energy $\mathscr{E}' < \mathscr{E}_0$ (the energy variation is $\mathscr{E}' - \mathscr{E} > \Gamma_0/2$). This determines the finite energy width Γ of the beam. It follows from Eq. (3) that $\Gamma \ll \Gamma_0$, i.e., the beam is monochromatized. A second type of monochromatization, in which the beam particles with an initial energy $\mathscr{E} > \mathscr{E}_0$ lose energy equal to $\Gamma_0/2$ as a result of radiation (so that $\mathscr{E}' = \mathscr{E}_0$), can occur. The other half of the particles with $\mathscr{E} < \mathscr{E}_0$ will have an energy $\mathscr{E}' < \mathscr{E}_0$ in this case, as in the first case, but with a different value of Γ [although their finite widths will differ negligibly, as can be seen from Eq. (3)]. We note that since the real beams have a symmetric velocity distribution of particles (with respect to the average value), and the variation of particle energy as a result of interaction, as can be seen from (3), is proportional to the initial energy, the final energy distribution of particles will be asymmetric. The finite energy width of the beam is given by (for the two cases, respectively)

$$\Gamma = \Gamma_0 \frac{\Delta_0}{1 \pm \Delta_0} . \tag{4}$$

Since $\Delta_0 \ll 1$ even for beams with a large spread, the parameters λ/l_0, θ_0, and ξ_{thresh} (which are necessary for monochromatization), as well as Γ corresponding to the two cases nearly coincide with each other, and $\Gamma = \Gamma_0 \Delta_0$. The required value of the parameter λ/l is given by

$$\frac{\lambda}{l} = \sqrt{1+\sigma} - 1, \tag{5}$$

where

$$\sigma = 2\frac{c^2}{v_0^2}\left(\frac{mc^2}{\mathscr{E}_0}\right)^2 + 2\frac{v_0^2}{c^2}\left(\frac{\delta_0}{\Delta_0}\right)^2\left[1 + \sqrt{1 + \frac{c^4}{v_0^4}\left(\frac{mc^2}{\mathscr{E}_0}\right)^2\left(\frac{\Delta_0}{\delta_0}\right)^2}\right].$$

Equations (1) and (2), after incorporating (5), determine the angles between the particle beams and the laser, which are essential for monochromatization, as well as the field intensities.

Since only the longitudinal particle momenta directed along the laser beam vary as a result of interaction, the angular structure of the beam must also vary. The finite divergence of a beam is $\delta = \dfrac{1}{2}(\theta_2 - \theta_1)$, where the angles of the maximum particle deviations $\theta_{1,2}$ are given by

$$\theta_{1,2} = \arctan\left\{(\tan\theta_0 \pm \delta_0)\left[1 \pm \delta_0 \tan\theta_0 \pm \frac{\Gamma}{\Gamma_0}\left(1+\frac{\lambda}{l}\right)^2\right]^{-1}\right\}.$$

To monochromatize the beam in an electric wiggler $E(t) = E_0 \cos \Omega t$, the beam axis must be oriented at an angle ϕ_0 with respect to the laser beam, which satisfies the coherence condition

$$v_0 \cos\phi_0 = c\left(1 - \frac{\Omega}{\omega}\right) \tag{6}$$

(ω is the laser frequency). The required value of the parameter Ω/ω is given by

$$\frac{\Omega}{\omega} = 1 \mp \sqrt{\frac{1}{1+\sigma}} \tag{7}$$

where the minus sign in front of the root corresponds to the case $\Omega < \omega$, the plus sign corresponds to the case $\Omega > \omega$, and σ is given by expression (5). The threshold value of the field, above which the monochromatization occurs in an electric wiggler, is

$$\xi'_{\text{thresh}} \equiv \frac{e}{mc}\left(\frac{E}{\omega} + \frac{E_0}{\Omega}\right)_{\text{thresh}} = \frac{\mathcal{E}}{mc^2}\,\frac{\sqrt{2}\left(\frac{\omega}{\Omega} - 1\right)}{\sqrt{2\frac{\omega}{\Omega} - 1}}\left|1 - \frac{\frac{v}{c}\cos\phi}{1 - \frac{\Omega}{\omega}}\right|.$$

The finite energy width Γ of the beam is given by Eq. (4), and the angular divergence is determined from Eqs. (6) and (7) in the same way as that in a magnetic wiggler.

We shall give some numerical estimates. The finite energy width of an electron beam with an energy $\mathscr{E}_0 \approx 50$ MeV, $\Gamma_0 \approx 0.5$ MeV, and $\delta_0 \sim 10^{-3}$ rad is $\Gamma \approx 2.5$ KeV after its interaction with a CO_2 laser ($\lambda = 10.6\,\mu$m) in a magnetic wiggler. The angle of the beam axis with respect to the laser beam is $\theta_0 \approx 2.5 \times 10^{-2}$ rad, and the required wiggler spacing is $l \approx 3$ cm. The essential intensities of the laser and of the wiggler are $E \approx 3 \times 10^5$ V/cm and $H_0 \approx 0.3$ G. For a proton beam with an energy $\mathscr{E}_0 \approx 70$ GeV, $\Gamma_0 \approx 0.7$ GeV, and $\delta_0 \sim 10^{-3}$ rad we have $l \approx 2.5$ cm and $\theta_0 \approx 2.8 \times 10^{-2}$ rad. The finite energy width of a beam is $\Gamma \approx 3.5$ MeV for the same values of the field. To obtain the same degree of monochromatization of these beams in an electric wiggler, the frequency of the electric field must be $\Omega \sim 10^{10}$ Hz and the field intensity must be $E_0 \sim 50$ V/cm.

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