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Beam deflection by planar–curved laser channels

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ABSTRACT

In this work based on channeling phenomenon the problem of electron beam deflection by plane averaged potential formed by two crossed lasers is described. The effective potential formed at grazing reflection of laser field from curved conducting surface is derived. The critical radius for electron steering in such a system as well as the conditions for effective beam reflection are introduced.

1. Introduction

Nowadays the design of future accelerators demands new techniques for beam extraction, deflection, collimation, shaping and steering. As known, both crystal channeling and volume reflection of particle beams in crystals provide approved methods for these tasks and have been considered as promising techniques for future extraction systems at large accelerator facilities [1]. These modern methods, however, have some drawbacks, and additional improvements are needed to overcome those limitations. One of these candidates is based on interaction of charged particles with intense laser beams that could open next generation tools for the particle beam manipulation.

As previously shown, the advance of laser technology has made possible forming optical lattice (OL) strong enough to handle charged particle beams [2,3]. The averaged effective potential in the region of two laser beams overlapping is capable of trapping charged particles in the channeling regime. We have already reported on the evident parallels of optical lattice channeling (OLC) and crystal channeling [4,5]. OL was formed by two independent laser beams crossed at a particular angle. However, OL could be also formed near the surface when a laser beam is reflected by it. And having the surface curved (e.g. a spherical mirror), the interference laser field formed due to multiple radiation reflection follows the surface profile creating the planar channels of the same curvature (in the case of grazing incidence). The theory of electrons deflection by OL based on "*planar–curved laser channels*" is presented in this work.

2. Optical lattice of crossed laser beams

The region of two electromagnetic waves overlapping was first considered by Kapitza and Dirak [6] as a periodic structure for electrons crossing it. Since their work the research in this field remains of growing interest and strongly correlates with the laser technique development. Later on in several works [7–11] electron beam channeling as well as steering in presence of an inhomogeneous laser wave were described. The phenomenon is based on the use of periodic effective potential shaped by interfering laser beams. Similar system is extensively analyzed by other groups [12–14] in terms of ponderomotive force. The peculiarities of electrons dynamics in OL have been also considered from different possible applications point of view in a number of papers [2–5,15–20].

In general, in the overlapping region for two electromagnetic waves of equal frequencies and amplitudes the periodic potential channels are formed. Hence, charged particles could be trapped by such long enough channels providing the projectile undulation in a channeling regime. If the channels are bent within optimized bending conditions, which support the projectile channeling, the

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beam should follow the bent channel that defines the steering phenomenon. Besides steering, charged particles beams reflection from OL is of great interest as it may provide novel manipulation technique for future accelerator facilities.

3. Electron deflection from optical lattice

In this article we analyze two systems, in which electron both reflection and deflection are possible. The first case considered is the electron reflection from two crossed laser beams (see Fig. 1). Indeed, the channeled electron motion is limited by the potential borders within a channel, while the electron approaching the OL region from outside can be reflected by those potential barriers.

In that sense to consider electron both steering and deflection by "curved laser channels" formed near curved reflecting surface becomes interesting. Electromagnetic field (EM) expressions in such a system are below derived and then followed by the analysis for the effective potential and steering conditions.

3.1. Planar laser channels

The analysis of electron reflection from planar potential channels is based on the effective potential expression reported in [19] for an electron in two crossed p-polarized laser beams (see Fig. 1). The potential is presented in the form

$$U_{eff}(x,\theta,\beta_\parallel) = U_0 \cos\left(2\frac{\omega_0}{c}x\sin\theta\right), \tag{1}$$

$$U_0 = \frac{4\pi e^2 I\left[(1+\sin^2\theta)\beta_\parallel^2 + \cos 2\theta - 2\beta_\parallel\cos\theta\right]}{\gamma m c\omega_0^2(1-\beta_\parallel\cos\theta)^2}, \tag{2}$$

where I and ω_0 are, respectively, the laser intensity and its frequency, 2θ is the angle, at which two lasers are crossed, $\beta_\parallel$ is the electron longitudinal velocity component parallel to the channels axes and, hence, parallel to Oz for the considered geometry, m, e and γ are the electron mass, charge and the Lorentz factor, correspondingly, c is the speed of light. For simplicity the laser beams cross section intensity distribution here and later on is considered to be uniform. The case of Gaussian laser intensity distribution could be easily described with additional laser beam shape form-factor. The main results derived in the article will remain valid. Indeed, the results presented in our previous works coincide with those calculated for Gaussian laser beams reported in [13].

Let a relativistic electron with $\gamma \gg 1$ approaches a region of two lasers overlapping. Let the electron momentum lies in xOz-plane and is aligned so that $p_\parallel \gg p_x$, where $p_\parallel$ is the momentum component parallel to the effective potential channels and p_x is transverse to them (see Fig. 1). It was shown earlier [5,19] that the longitudinal momentum component in OL is constant, and, since $\beta_\parallel \to 1$, the longitudinal speed may be expressed as

$$\beta_\parallel \approx \frac{cp_\parallel}{E_\parallel}\left(1-\frac{c^2p_x^2}{2E_\parallel^2}\right), \tag{3}$$

where $E_\parallel = c\sqrt{m^2c^2+p_\parallel^2}$ is the electron longitudinal energy. The threshold initial transverse momentum value, at which electrons still can be reflected by the planar effective potential channels, can be calculated from the energy conservation law

$$cp_x^{max} = \sqrt{2E_\parallel U_0\left(p_\parallel\right)} \tag{4}$$

Once p_x^{max} is introduced, one can estimate the portion of divergent electron beam reflected by the planar channels. The beam enters the region with the planar potential channels that are parallel to the Oz-axis (see Fig. 1). The electron momentum distribution is described by

$$f(p_n,p_l) = \frac{1}{2\pi\sigma_n\sigma_l}\exp\left(-\frac{p_n^2}{2\sigma_n^2}-\frac{(p_l-p_0)^2}{2\sigma_l^2}\right), \tag{5}$$

where p_l is the electron momentum parallel to the averaged beam motion direction, p_n is the transverse momentum and p_0 is the averaged electron momentum. Then the electrons with $|p_n|\cos\delta + |p_l|\sin\delta < p_x^{max}$ will be reflected from the channels. And in the case of a small positive δ this condition can be simplified to $|p_n| + |p_l|\delta < p_x^{max}$.

Assuming that the reflection does not change the electron longitudinal and total energy, the longitudinal momentum distribution function becomes

$$f(p_l) = \frac{1}{2\sqrt{2\pi}\sigma_l}\left[1+\mathrm{erf}\left(\frac{p_x^{max}-p_l\delta}{\sqrt{2}\sigma_n}\right)\right] \exp\left(-\frac{(p_l-p_0)^2}{2\sigma_l^2}\right), \tag{6}$$

where $\mathrm{erf}(\mu)$ is the error function. The function of longitudinal momentum distribution for reflected electrons is presented in Fig. 2 for various δ values. Integrating Eq. (6) at fixed $\delta_3 = 3.2$ mrad, one can see that only 18.5% of the initial beam electrons are reflected by the channel border. Indeed, the above presented condition is satisfied only for this part of the beam. The minimum intensity needed for OL to trap (or reflect) an electron of a certain energy can be easily derived from the expressions (2) and (4)

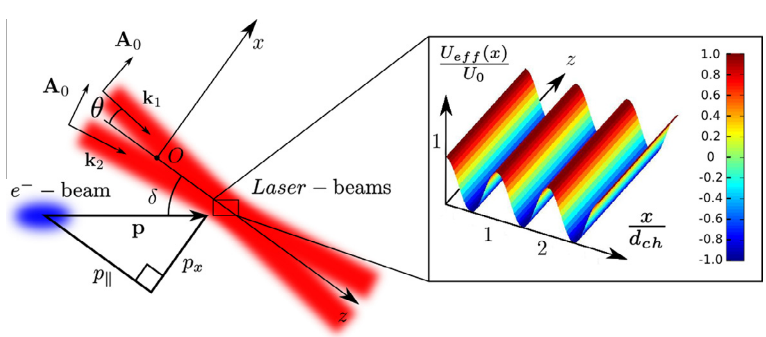

Fig. 1. General scheme of the considered system and normalized effective potential in the region of laser beams overlapping. Here $\mathbf{k}_{1,2}$ are the lasers wave vectors ($|\mathbf{k}_{1,2}| \equiv \omega_0/c$), A_0 is the lasers vector potential amplitude, lasers and Oz-axes are crossed at angle θ, electron beam averaged momentum $\mathbf{p}$ is presented as $|\mathbf{p}|^2 = p_0^2 = p_\parallel^2 + p_x^2$ and $p_\parallel = p_0\cos\delta$. The angle δ is small and positive.