HIGH-ENERGY LASER PONDEROMOTIVE ACCELERATION.

I. V. Smetanin, P. N. Lebedev Physics Inst., Moscow, Russia,
C. Barnes, SLAC, USA
K. Nakajima, KEK, Tsukuba, Japan

Abstract

A new concept of TeV-range laser ponderomotive acceleration in a plasma is proposed. Particles are accelerated in the point-like scattering by the leading front of the laser pulse, propagating at the group velocity less than the vacuum speed of light. In this scheme, the gain in particle energy is determined by the group velocity and does not depend on laser intensity, which determines the quantum probability of acceleration. The quantum and classical analysis of the scheme proposed is presented. Estimates show that the concept proposed is a promising technique for compact laser acceleration of TeV energy range.

1. INTRODUCTION

Ponderomotive motion of charged particles in the field of non-uniform electromagnetic wave is under investigation for a long time, being initiated by P. L. Kapitza and P. A. M. Dirac [1]. Recent advances in high-intensity laser systems [2] has renewed now an interest in the development of the next generation accelerators technology [3,4].

In the conventional theory of laser ponderomotive acceleration (LPA) [5,6], the laser-particle interaction is assumed to proceed in vacuum, i.e., where the laser pulse group velocity is equal to the vacuum speed of light, $\beta^* = v_{gr} / c = 1$. The acceleration is originated by the transverse gradient of the ponderomotive potential. As a result, the accelerated particle is expelled from the focal region at a definite non-zero scattering angle, and the gain in energy increases with an increase in peak intensity. In a plasma, however, it is more realistic to suggest that the laser pulse group velocity is less than *c*, $\beta^* < 1$. In this case, a natural limit for conventional vacuum LPA mechanism [5,6] arises: with an increase in laser peak intensity, particle velocity will inevitably exceed the value of pulse group velocity.

We propose here a new concept of laser ponderomotive acceleration of particles in a plasma.We intend to show that the new acceleration regime occurs when the group velocity of high-power laser pulse is less then the vacuum speed of light. The physical mechanism of acceleration is the elastic scattering of particle by the ponderomotive potential in the reference frame moving together with the laser pulse. A simple analytical quantum and classical consideration is presented. We show that the energy gain is determined for this regime by the initial energy of particle and pulse group velocity only, and does not depend on peak intensity. Laser intensity determines the probability for the particle to be reflected from the leading edge of the pulse, and, thus, the number of particles captured in the acceleration regime. To estimate this probability, we use quantum Klein-Gordon equation. In fact, acceleration in this new concept is a point-like process, and thus is insensitive to the phase of injection. Estimates show that acceleration of electrons up to TeV -range of energy is attainable in a single point-like interaction using current laser technologies, that makes this novel concept prospective for the next generation of particle accelerators.

2. CLASSICAL ANALYSIS

Let us assume the high-power ultrashort laser pulse propagating in a medium (a gas or plasma, for example) with a definite group velocity, $\beta^* < 1$. In this new reference frame, the laser pulse ponderomotive potential becomes static, so the interaction can be considered now as just the elastic potential scattering. Let the initial energy and velocity of the particle are γ_0 and β_0, respectively, and the initial angle of collision, α_0, and $\alpha_0 = 0$ corresponds to the laser pulse co-propagating with the accelerated particle. Using Lorentz transformation, it is easy to find the energy of the particle in the moving frame

$$\gamma' = (1 - \beta^* \beta_0 \cos\alpha_0)\gamma_0 \gamma^* \qquad (1)$$

where $\gamma^* = (1 - \beta^{*2})^{-1/2}$ is the characteristic γ -factor of the laser pulse. According to the classical scattering theory, if this energy is less than the field peak ponderomotive potential,

$$\gamma' \le \left(1 + a_0^{\ 2} / 2\right)^{1/2} \qquad (2)$$

the particle has to be reflected. Here, a_0 is the normalized peak value of the laser field vector potential amplitude. As an effective Hamiltonian is time-independent in the moving frame, the final energy γ of the particle does not change after scattering (in the infinity), and, after the Lorentz transform, we have in the laboratory frame

$$\gamma(1 - \beta^* \beta \cos\alpha) = \gamma' / \gamma^* \qquad (3)$$

In this implicit relation, β is the particle absolute velocity, and α is the final scattering angle, $\alpha=0$ corresponds to the co-propagation case.

Contributed to 18th International Conference on High-Energy Accelerators (HEACC 2001), 26-30 March 2001, Tsukuba, Japan

Work supported in part by Department of Energy contract DE-AC02-76SF00515

It is easy to conclude from comparison of Eqs. (1) and (3) that there is the following conservation law for the acceleration mechanism under discussion,

$$\gamma(1-\beta_z\beta^*) = const\,. \qquad (4)$$

The results of the above simple kinematics approach coincide with that of electrodynamics consideration. The integral of motion (4) appears in the form of energy conservation law in the 1D theory of ultrashort pulse propagation in the cold underdense plasma [4].

For the particle initially at rest, the maximum energy gain is at $\alpha = 0$, i.e., $\gamma_{\max} = \left(1+\beta^{*2}\right)\gamma^{*2} \approx 2\gamma^{*2}$, and the particle velocity exceeds the laser pulse group velocity $\beta_{\max} = 2\beta^*/(1+\beta^{*2}) > \beta^*$. Thus, the particle accelerated is in front of the laser pulse during all the interaction process, and its gain in energy does not depend on the value of the laser peak intensity, but on the dielectric properties of the medium only, which is qualitatively different than that for conventional vacuum LPA [5,6].

The integral of motion (4) coincides in the limit of vacuum LPA $\beta^* = 1$ with that derived by Harteman et al. [5], $\gamma(1-\beta_z) = const$. This integral, however, results in a completely different feature in the laser-particle interaction. Scattering at zero angle $\alpha = 0$ is condemned. Expelled particle inevitably has a transverse velocity. At sufficiently high intensities, the quiver amplitude of motion in laser wave becomes comparable to the beam waist, and electron is effectively expelled out from the focal region due to the transverse gradient of the laser field. The laser-particle interaction is thus terminated within a wavelength, which leads to the strong dependence on injection conditions [5].

In the new non-vacuum LPA concept which we propose, there is no strong dependence on the injection phase. Really, in the moving reference frame, the laser field vector potential is stationary, and the acceleration mechanism in this case is more akin to the well-known potential scattering.

The origin of the difference between conventional LPA and the regime proposed is that conventional mechanism utilize the *transverse* intensity gradient, whereas in the case of our interest the scattering of particle by the *leading front* of the laser pulse occurs.

For the case of injection at definite initial energy, the maximum final energy of particle is for scattering at zero angle $\alpha = 0$ and from Eqs. (1) and (3) we get,

$$\gamma_{\pm} = [(\beta^* \pm \beta_0)^2 + \gamma_0^{-2}]\gamma_0\gamma^{*2} \qquad (5)$$

where the signs correspond to the initially counter- ("+") or copropagating ("-") laser pulse and accelerated particle. Although the energy gain is maximal for counter-propagating injection, this interaction geometry is efficient for sufficiently low energies due to the threshold condition (2). At high injection energies and energy gains, the co-propagating injection is preferable.

3. QUANTUM ANALYSIS.

As it has been shown above, the most specific feature of the LPA regime under consideration is that the energy gain for particle accelerated does not depend on the laser pulse intensity, but on the group velocity only, i.e. on the dielectric properties of the medium. The value of the laser peak intensity determines only the threshold of this acceleration regime, i.e. possibility of the acceleration according to the classical scattering condition (2). In a more correct quantum feature, the value of ponderomotive potential determines the probability of scattering, which determines the number of accelerated particles. To estimate its value, one can start with Klein - Gordon equation, as the spin effects are evidently not important for LPA.

It is convenient to consider the problem in the moving reference frame, in which the effective potential is time-independent. As the most interesting case is the scattering at the angle $\alpha = 0$, one can use for estimates the 1D approximation. As the averaged ponderomotive potential is time-independent, the energy of the particle is conserved, and one can seek solution in the asymptotical form $\varphi(z,t) \propto \exp(-i\varepsilon t/\hbar)\exp(\pm i k_0 z)$ where ε is the particle energy in the moving frame, and $k_0 = \sqrt{\varepsilon^2 - m^2c^4}\,/\hbar c$ is the asymptotic wavenumber of electrons in the field-free regions. In fact, we assume the stationary flow of particles collides with the potential, and seek the parts of this flow which will be reflected and transmitted. Using the standard methods of quantum mechanical calculations [], one can easily write estimates for the reflection R and transmission T=1-R coefficients in the two following limiting cases .

First, in the case, when the energy of particle is less than the ponderomotive potential, i. e., $k_0 < eA_0/\hbar c\sqrt{2}$, where A_0 is the peak amplitude of the laser vector potential, the approximate solution can be given in the WKB-approximation : $T \approx \exp(-2\Gamma)$,

$$\Gamma = \int_{z_1}^{z_2} \left(\frac{e^2 A^2(z)}{\hbar^2 c^2} - k_0^2 \right)^{1/2} dz \qquad (6)$$

Here, the integration is over classically prohibited zone, between the turning points z_1 and z_2, where the integrand becomes zero. In this case, most of the particles, except an exponentially small fraction, are reflected, and consequently, accelerated.

In the opposite case, when the energy is well above the ponderomotive barrier, $k_0 >> eA_0/\hbar c\sqrt{2}$, the result of the perturbation theory is

$$R \approx \left| \frac{1}{k_0} \int_{-\infty}^{+\infty} \frac{e^2 A^2(z)}{2\hbar^2 c^2} \exp(2ik_0 z) dz \right|^2 \sim \left(\frac{eA_0}{\hbar k_0 c} \right)^4 << 1 \qquad (7)$$

which is, in fact the ratio of the quiver momentum to the initial electron momentum in the moving frame.

It is interesting to make some estimates for laser ponderomotive acceleration of electrons in plasma. We will assume the electron beam with the initial energy 150 MeV ($\gamma_0 = 300$) is injected into the interaction region in the direction of laser pulse propagation. The maximum energy gain is in the forward direction and given by Eq. (9). At given output energy of electrons, the required group velocity and corresponding Lorentz factor are

$$\gamma^* = \frac{1}{\sqrt{2}} \frac{\gamma + \gamma_0}{\left[1 + \gamma\gamma_0 (1 - \beta\beta_0)\right]^{1/2}} \qquad (8)$$

The group velocity determines the required plasma density, $n_e[cm^{-3}] \approx 1.115 \times 10^{21} \gamma^{*-2} \ \lambda^{-2}[\mu m]$, and threshold peak intensity and normalized laser field amplitude are given by relations (1),(2)

$$a_{0th} = \sqrt{2} (\gamma^{*2} \ \gamma_0^2 (1 - \beta^* \beta_0)^2 - 1)^{1/2} \qquad (9)$$

The corresponding peak intensity is $I[W/cm^2] = 1.37 \times 10^{18} a_0^2 \lambda^{-2}[\mu m]$. In the Fig. 1, the dependencies of the normalized amplitude and laser peak intensity on the final energy of electrons are shown. The required plasma density and Lorentz factor, corresponding to the pulse group velocity, are shown in the Fig.2.

The regime proposed makes it possible acceleration of electrons up to TeV energy range using modern laser technology. For the injection energy 275 MeV ($\gamma_0 \sim 550$)

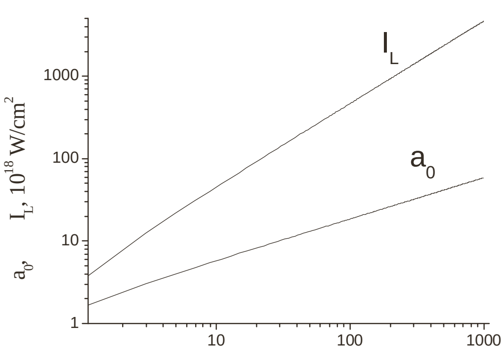

Fig.1. Threshold laser peak intensity and normalized amplitude corresponding to the GeV -domain energy gain of electrons. Injection energy – 150 MeV.

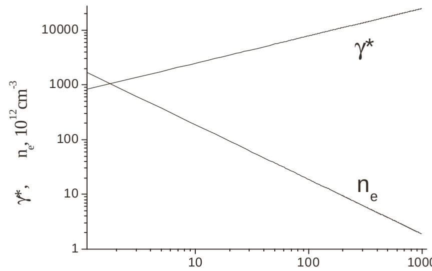

Fig. 2. Plasma density and Lorenz -factor of corresponding laser pulse group velocity for acceleration to GeV energies. Injection energy 150 MeV.

and plasma density $n_e \sim 1.115 \times 10^{12} cm^{-3}$ ($\gamma^* \sim 3.2 \times 10^4$) the energy gain is ~1TeV ($\gamma \sim 2 \times 10^6$). The threshold normalized laser field amplitude required is then $a_0 \sim 45$ which corresponds to laser peak intensity ~$2.74 \times 10^{21} W/cm^2$.

It is interesting to estimate the parameters required for acceleration of electrons up to PeV -range of energies ($\gamma \sim 2 \times 10^9$). At 700 MeV the injection energy and $10^{24} W/cm^2$ the peak intensity, we have an estimate for group velocity Lorentz-factor $\gamma^* \approx 1.6 \times 10^6$, which corresponds to the plasma density $n_e \approx 4 \times 10^8 cm^{-3}$.

In conclusion, we have proposed in this paper a new relativistic ponderomotive acceleration concept, which is based on the scattering of particles by the leading front of the laser pulse moving in a plasma at the group velocity which is less than the speed of light. The gain in particle energy is determined by the injection energy and pulse group velocity and does not depend on peak intensity, which determines the quantum probability of acceleration. The quantum and classical analysis of the proposed concept is presented. Estimates show that the scheme proposed is prospective for the next generation accelerator technology.

REFERENCES

[1] P. L. Kapitza and P. A. M. Dirac, Proc. Cambridge Philos. Soc. **29**, 297 (1933)

[2] M. D. Perry and G. Mourou, Science **264**, 917 (1994)

[3] T. Tajima and J.. Dawson, Phys. Rev. Lett. **43**, 267 (1979)

[4] E. Esarey, P. Sprangle, J. Krall, A. Ting, IEEE Trans. Plasma Sci. **24**, 252 (1996)

[5] F. V. Hartemann *et al.*, Phys. Rev. E, **51**, 4833 (1995).

[6] B. Quesnel, P. Mora, Phys. Rev. E, **58,** 3719 (1998)

[7] A. B. Migdal, *Qualitative Methods in Quantum Theory*, W.A. Benjamin, Inc., Reading, 1977.