J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 335–339

Ion Acceleration in Laser Wakefield

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(Received: 5 December 2000 / Accepted: 16 August 2001)

Abstract

A proton and/or heavy ion accelerator utilizing the transverse electric field of the laser wakefield is proposed. We have performed the simulation in the proton acceleration employing the transverse laser wakefield. The results show that the energy gain per one stage is not large enough but the acceleration gradient is several hundred times larger than the conventional proton acceleration scheme. The proton acceleration by the transverse wakefield is more effective in lower proton energy. It will be possible to make the compact proton accelerator with this method.

Keywords:

compact proton/ion accelerator, plasma based accelerator, high power laser, laser driven wakefield, plasma wave

1. Introduction

There has been currently great interest in the application of the highly energetic electrons generated from the interaction of an intense ultra-short laser pulse with a plasma. Acceleration of electrons by an electron plasma wave has been of considerable attention because it has potentiality to exceed the acceleration gradient much larger than that of a conventional radio frequency (rf) linear accelerator. Several methods have been proposed for high energy particle accelerators with ultrahigh acceleration gradients with the help of the plasma wave generated by an intense microwave or laser, such as the plasma beat wave accelerator, laser wakefield accelerator (LWA) [1] in 1979, $V_p \times B$ accelerator [2] and self-modulated laser wakefield accelerator [3]. Present day high power laser systems with the chirped pulse amplification technique can produce an ultra short pulse with an intensity well above 10^{18} W/cm^2 and enable us to perform proof-of-principle experiments of laser driven plasma accelerators. Recently it has been reported that electrons accelerated up to the energy of 300 MeV by the laser wakefield and the plasma wave have been observed [4-6], but plasma based electron accelerators are too premature to be used as a real linear collider.

On the other hand, the study of acceleration of protons and/or ions has a longer history than that of electron acceleration. More recently the "electron ring accelerator" had been studied until early 1970's in USSR, USA, Germany and Japan [7]. The studies have terminated without remarkable successes. The investigation on the proton/ion accelerators has not been so active for several decades in spite of a high demand for ion accelerators. Such developments of laser systems, however, have promoted an interest in compact ion accelerators with various applications for high energy physics and medical field. The above mentioned plasma based acceleration schemes which have successfully accelerated electrons, cannot be employed for the acceleration of protons and ions with energy less than 1 GeV, since the phase velocity of the plasma wave is much faster than the particle's velocity because of their heavier mass than electrons. Several ideas for

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accelerating proton/ion based on the plasma wave have got an attention including the backward Ramman scattering [8] and Alfvén wave [9] which slow waves are to trap the accelerated particles.

An acceleration method for accelerating proton beam using lasers and plasmas is an acceleration method using a transverse components of the laser wakefield excited by the interaction of the high intense ultra short laser pulse with the plasma. This acceleration method has been already proposed and reported in the simulations that protons are accelerated by transverse laser wakefield [10]. The simulations in Ref. [10] have been performed for the one-dimensional motion of protons, i.e. the transverse direction. In this paper, we perform the simulations extended to two-dimensions and discuss in detail the behavior of protons in the laser driven wakefield and the phase matching between the proton beam and the transverse wakefield.

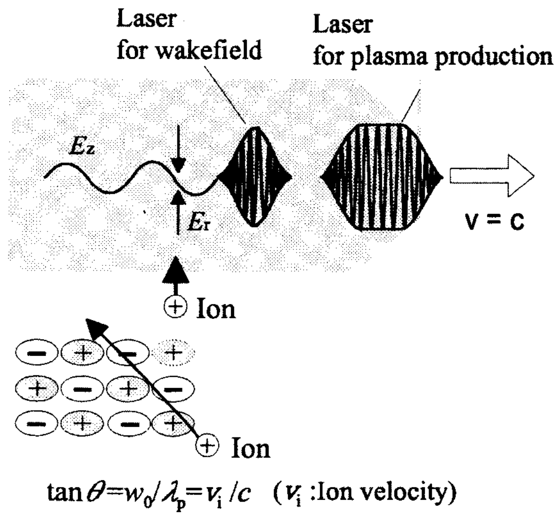

Fig. 1 Schematic diagram for the proton acceleration by the laser driven wakefield.

2. Theory

An electron plasma wave (EPW) is excited by the ponderomotive force of the EM wave exciting a density oscillation with the plasma frequency in an underdense plasma. The EPW with large amplitude driven by the laser pulse has both transverse and longitudinal components. The transverse component is induced both by the temporal and radial profiles of the laser pulse and the longitudinal component corresponds to the longitudinal motion induced by the temporal profile of the pulse. The plasma electrons are described by cold fluid equations with the ponderomotive potential term induced by the spatial and temporal profiles of the laser pulse. Assuming the linear approximation, in which the electron density perturbation is small compared with the equilibrium electron density and that ions are fixed, the equations can be solved. The longitudinal component of the density perturbation δn_z corresponds to longitudinal electron oscillations. The electric field E_z deduced by the Poisson equation is also longitudinal. The transverse contribution δn_r corresponds to cylindrical electron oscillations associated with the radial electric field E_r. Each component of a linear EPW excited by the intense laser with Gaussian radial profile and a Gaussian temporal distribution, can be expressed [11,12] as

$$E_z = Ak_p \cos\left(\omega_p t - k_p z\right) \exp\left(-\frac{2r^2}{w_0^2}\right), \qquad (1)$$

$$E_r = A\frac{4r}{w_0^2} \sin\left(\omega_p t - k_p z\right) \exp\left(-\frac{2r^2}{w_0^2}\right), \qquad (2)$$

with

$$A = \sqrt{\pi}\, \omega_p \tau \exp\left(-\frac{\omega_p^2 \tau^2}{4}\right) \frac{I_{max}\, e}{2\varepsilon_0 m_e c\, \omega^2},$$

where I_{max} is the maximum laser intensity, τ is the pulse duration at FWHM, w_0 is the spot radius of the EM wave at focus, ω_p is the plasma frequency, m_e is the rest mass of the electron, and ε_0 is the dielectric constant in vacuum.

The ratio of the two components of the density perturbation on the laser axis is given by $\delta n_r/\delta n_z = (\lambda_p/\pi w_0)^2$, where $\lambda_p = 2\pi c/\omega_p$ is the wavelength of the excited plasma wave. Thus, the electron density perturbation can be treated as longitudinal when \$\pi $\pi w_0 \gg \lambda_p$ and radial when $\pi w_0 \ll \lambda_p$ [13,14]. In the conventional LWA, the transverse field is stronger than the longitudinal electric field, since EPW excitation takes place mainly in the radial region. We proposed the ion acceleration by employing the transverse wakefield, i.e. the ion beam is injected into the wakefield from the radial direction. Depending on its relative phase $\varphi \equiv \omega_p t - k_p z$ with respect to the wakefield, an injected ion is accelerated or decelerated by E_r and focussed or defocused by E_z. Thus, as shown in Fig. 1 which represents the ion motion in the frame of the wakefield, the most effective acceleration occurs when the ion always stays in the acceleration phase during the wakefield. The laser driven wakefield useful for the charged particle acceleration is limited within the spot size, since it decreases exponentially in the radial direction as seen in Eqs. (1) and (2). The condition for the most effective acceleration, which require phase matching between the transverse wakefield and the ion beam, is given by $v_i T_p = 2w_0$, where v_i is the ion velocity across the area where the wakefield is excited and $T_p = 2\pi/\omega_p$ is the period of wakefield. This condition can be satisfied by adjusting the plasma density, since ω_p depends on the plasma density, $\omega_p = (n_e |e|^2/\varepsilon_0 m)^{1/2}$. The plasma density required for the appropriate ion acceleration is rewritten as

$$n_e\left[\mathrm{cm}^{-3}\right] \approx 6\times 10^{17}\,\frac{\varepsilon_i\,[\mathrm{MeV}]}{M w_0^2\,[\mu\mathrm{m}]}, \qquad (3)$$

where ε_i is the initial ion energy and M is the ratio of the ion mass to the proton mass. In the ideal case in which the above condition is satisfied and the effect of longitudinal wakefield is negligibly small, the maximum energy gain is obtained as

$$\Delta\varepsilon = 2e\int_0^{w_0} E_r\,dr = 2A\,(1-\mathrm{e}^{-2})\,(\mathrm{eV}). \qquad (4)$$

The coefficient A is a function of the product $\omega_p \tau$ and is maximum when $\omega_p \tau = \sqrt{2}$. For the proton energy $\varepsilon_i = 1$ MeV, for examples, the maximum energy gain is expected when the plasma density is $n_e = 10^{16}$ cm^{-3} and the laser pulse duration is $\tau = 250$ fsec.

3. Simulation Results

The acceleration mechanism of heavy ion is the same as that of proton in principle in spite of the difference between the proton and heavy ion, i.e. mass and charge state. For the simplest discussion, let us consider the energy gain for the proton acceleration utilizing the laser-driven transverse wakefield. We have performed two-dimensional time dependent simulations based on the momentum equation in order to study the behavior of protons in the laser wakefield in detail. Each small displacement of proton for the time step is calculated by the Time center Leap Frog method [15]. The final proton energy is obtained by repeating the procedure until the proton passes through the wakefield.

The simulation has been performed in the case where the laser for the excitation of EPW has the parameters of wavelength $\lambda = 800$ nm, and maximum power $P = 1$ TW focused into the spot size $2w_0 = 10$ μm, corresponding to a Ti-Sapphire laser system. Assuming that the proton is injected in the $+r$ direction, we need to take into account the dependence of the electric field E_r on the relative phase φ for obtaining more efficient acceleration of the proton by the laser wakefield. Thus, in the simulations the proton is injected into the wakefield when its phase is $\varphi = \pi$. Figure 2 represents the typical simulation result for the proton with an initial energy $\varepsilon_i = 1$ MeV, where the plasma density is $n_e = 10^{16}$ cm^{-3} satisfing $v_i T_p = 3w_0$. In this simulation, the laser pulse duration is assumed to be $\tau = 250$ fsec, since the wakefield amplitude is maximum at $\omega_p \tau = \sqrt{2}$ as above-mentioned. The solid and dashed lines represent respectively the proton energy and the electric field of the wakefield acting on the proton while the proton travels through the wakefield. It is evident from Fig. 2 that the proton continuously feels the

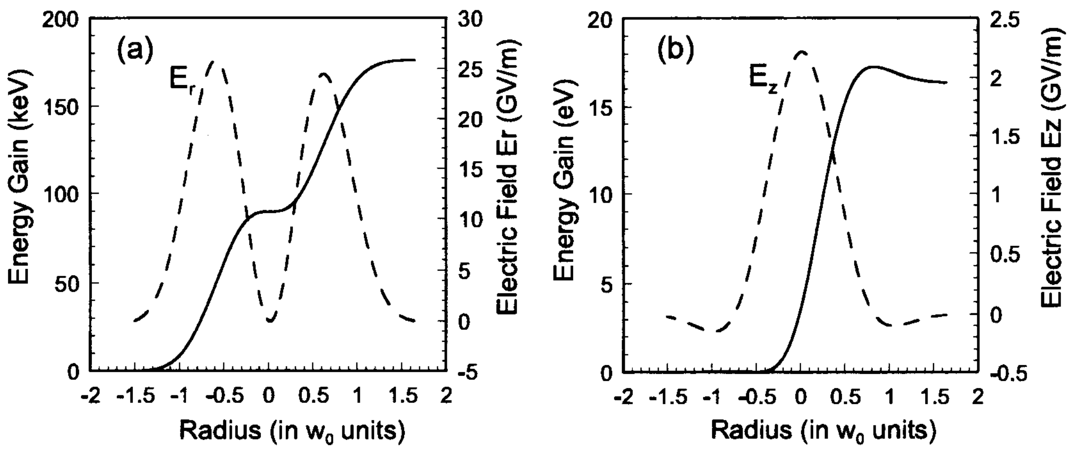

Fig. 2 Variation of the proton energy and the electric field of wakefield accelerating proton as the proton travels. (a) and (b) represent the radial and axial component of the proton's motion. Solid and dashed lines are the proton energy gain and the electric field of the wakefield, respectively.

acceleration force in the wakefield and is accelerated with the energy gain of about 175 keV. Considering that the acceleration length is $3w_0$ =15 μm, the acceleration gradient is estimated to be 12 GeV/m, which is much larger than the conventional rf accelerator. On the other hand, it is obvious from Fig. 2 that the longitudinal electric field is ten times smaller than the transverse one and that the proton is accelerated little in the axial direction.

Neglecting the nonlinear effect, we can expect that the proton is accelerated to high energy in proportion to the laser power, because E_r is directly proportional to the amplitude of the laser wakefield and so the incident laser power. If the laser with power 10 TW is used for the excitation of the wakefield, the proton with the same injection energy can be accelerated with the energy gain of about 1.7 MeV.

The amplitude of the wakefield depends on the initial proton energy, since the mean plasma density need to be adjusted to satisfy the phase matching condition between the laser wakefield and the proton. It is important to perform the simulation of the dependence of the energy gain on the initial injection energy. The simulation result is shown in Fig. 3, where the laser pulse duration is 100 fsec and other parameters are the same as the above simulation. It is seen that this acceleration method employing the transverse wakefield is not suitable for the high energy proton acceleration. It is readily shown from Eq. (2) that the wakefield amplitude decreases exponentially beyond the maximum point $\omega_p\tau = \sqrt{2}$. Thus, the wakefield acceleration for protons is not adequate for the high energy particles. It is not also easy to excite the wakefield with large amplitude in high density region. Figure 4 shows the energy gain as a function of the plasma density. The most effective acceleration occurs at the plasma density which satisfies the matching condition Eq. (3). The proton traverses the deceleration phase of wakefield, since the oscillation period of plasma wave becomes large with increase of the plasma density. It turns out from Fig. 4 that the matching condition can be satisfied by adjusting the plasma density.

Finally, we propose the compact proton accelerator

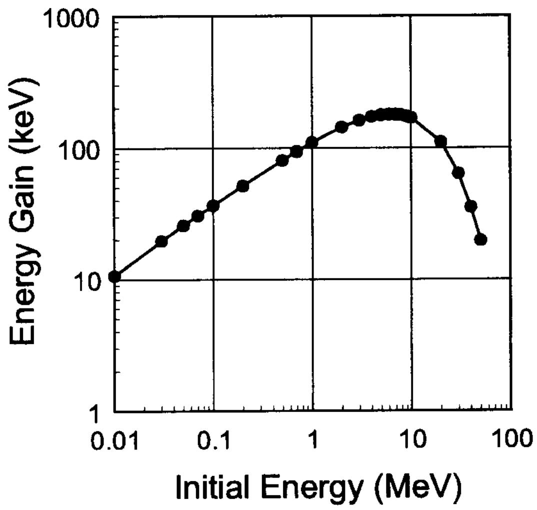

Fig. 3 Proton energy gain as a function of the initial energy. The laser parameters are λ = 800 nm, P = 1 TW, and τ = 100 fsec.

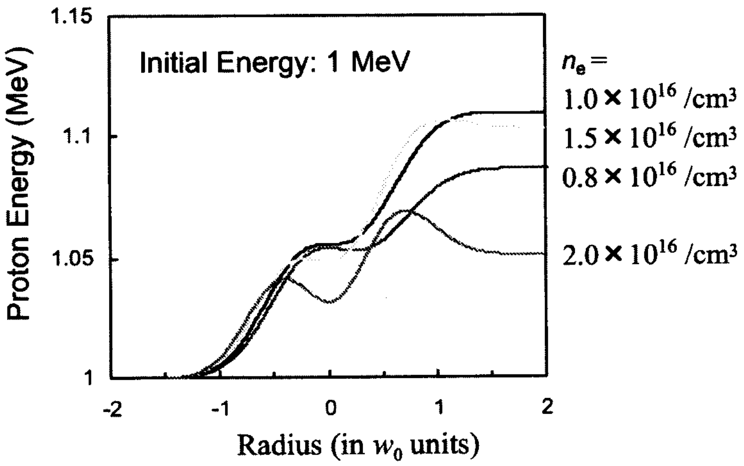

Fig. 4 Dependence of proton energy on plasma density.

employing the above-mentioned acceleration method. In order to realize this accelerator, the multistage acceleration has to be used, since the energy gain per one stage is small. We expect that this method can be realized by precisely arranging the position and the interval of mirrors.

4. Summary

We have proposed a proton acceleration method and the design of the accelerator employed this method mentioned in this paper. Possibility of the proton acceleration due to the laser driven wakefield has been confirmed from the simulations. Thus, it has been demonstrated that this acceleration method can be used for the heavy ion. The energy gain per one stage is not large, the acceleration gradient, however, is several hundred times larger than a conventional rf acceleration scheme. We expect that the compact proton accelerator employing this scheme can be realized by using the present apparatuses. The increase of laser power can lead to increased gain in proton energy per stage at the cost of the accelerator's compactness. Such a proton accelerator using a huge laser system cannot be regarded as a compact accelerator. Similar to the electron accelerator which the longitudinal component of wakefield traveling with the incident laser is used, there are some limitations in the accelerator with this acceleration scheme. 1) The radius of accelerated beam cannot be larger than the laser spot size. 2) The length of the beam will be smaller than the pulse of laser. However, we consider that these problems may be solved by using some parallel lasers. There seems to be some room for making improvements including new acceleration schemes. More detailed discussions are required for further improvement of the acceleration efficiency.

Acknowledgement

This work is supported in part by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture, Japan.

References

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

[2] Y. Nishida, M. Yoshizumi and R. Sugihara, Phys. Lett. **105A**, 300 (1984), Y. Nishida, M. Yoshizumi and R. Sugihara, Phys. Fluids. **28**, 1574 (1985).

[3] N.E. Andreev, L.M. Gorbunov *et al.*, JETP Lett. **55**, 571 (1992).

[4] H. Dewa *et al.*, Nucl. Inst. and Meth. **A410**, 357 (1998).

[5] D. Bernard *et al.*, Nucl. Inst. and Meth. **A432**, 227 (1999).

[6] J.R. Marqués *et al.*, Phys. Rev. Lett. **76**, 3566 (1996), C.W. Siders *et al.*, Phys. Rev. Lett. **76**, 3570 (1996).

[7] M. Reiser, Seminar on New Trends in Particle Acceleration Techniques, Capri (1982).

[8] A. Ogata and T. Katsouleas, *Proc. 1998 Workshop on Advanced Accelerator Concepts*, AIP Conf. **472**, 551 (1999).

[9] B. Rau and T. Tajima, Phys. Plasmas **5**, 3575 (1998).

[10] M. Bakhtiari, H. Ito *et al.*, Jpn. J. Appl. Phys. **39**, L1097 (2000).

[11] E. Esarey, P. Sprangle *et al.*, IEEE Trans. Plasma Sci. **24**, 252 (1996).

[12] F. Amiranoff *et al.*, Phys. Rev. Lett. **81**, 995 (1998).

[13] J.R. Marqués *et al.*, Phys. Plasmas **5**, 1162 (1998).

[14] F. Dorchies, F. Amiranoff *et al.*, Phys. Plasmas **6**, 2903 (1999).

[15] C.K. Birdsall and A.B. Langdon, *Plasma Physics via Computer Simulation* (McGraw-Hill, NY 1985).