Proton Accelerator Employed $V_{\mathrm{p}} \times B$ Mechanism and Wakefield by an Intense Electromagnetic Wave

Hiroaki ITO, Mohammad BAKHTIARI, Masashi IMAI, Noboru YUGAMI, and Yasushi NISHIDA
Energy and Environmental Science, Graduate School of Engineering, Utsunomiya University
7-1-2 Yoto Utsunomiya, Tochigi 321-8585, Japan

Abstract

A new proton accelerator utilizing the laser wakefield acceleration scheme and the $v_{\mathrm{p}} \times B$ mechanism is proposed. In the proton acceleration employing the $v_{\mathrm{p}} \times B$ mechanism, we have performed the simulation with the Runge Kutta method. The results shows 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. It will be possible to make the compact proton accelerator with these principles.

1 Introduction

The recent development of high intense laser with the chirped pulse amplification (CPA) technique leads us to investigate the laser-matter interaction phenomena. One of the interesting applications is to develop high energy particle accelerators based on plasmas with short pulse lasers. Recently it has been reported [1] that the maximum acceleration gradient via the laser driven wakefield acceleration is several thousand times larger than the conventional accelerators.

On the other hand, on directing our interest to other charged particle accelerators, new acceleration schemes which are more effective than the conventional rf acceleration hasn't ever been proposed so far, to our best knowledge. The $v_{\mathrm{p}} \times B$ scheme which can accelerate protons and heavy ions has attracted our attention. This acceleration scheme have been observed in the experiments on microwave-plasma interaction [3], which was predicted theoretically [4]. The presence of plasma is not essential, so the charged particles can be accelerated even in a vacuum [5]. The $v_{\mathrm{p}} \times B$ acceleration scheme with a transverse electromagnetic wave also has been demonstrated in proof-of-principle experiments [5]. In this paper, we propose a new proton acceleration method employing the $v_{\mathrm{p}} \times B$ scheme [6] and the radial wakefield excited via an intense ultra short pulse laser and describe the simulation results obtained with Runge Kutta method. A realistic accelerator concept is also described.

2 Theory

In general, it is difficult to utilize the electromagnetic (EM) wave as a driver wave in the charged particle accelerator, because EM wave is a transverse mode propagating at the speed of light in free space. In order to satisfy this demand, i.e. a driver wave should have a longitudinal electric field, a new acceleration scheme is proposed such as shown in Fig.1. When the EM wave traveling with the speed of light is obliquely incident at some angle (θ) with respect to the axis of the proton beam, the longitudinal electric field acting on the protons exists, thus we expect that the proton beam can be accelerated by this method. It, however, has the demerit that the trajectory of the proton beam is bent by the electromagnetic fields resulting from the obliquely incident EM wave. In order to correct this demerit, the $v_{\mathrm{p}} \times B$ scheme, in which the external static magnetic field B_0 is applied in the direction of the fluctuating magnetic field of EM wave, has been adapted to cancel the bending effect.

The relativistic momentum equation of proton may be written as

$$M\frac{d}{dt}(\gamma \boldsymbol{v}) = q[\boldsymbol{E} + \boldsymbol{v} \times (\boldsymbol{B} + \boldsymbol{B}_0)], \tag{1}$$

where γ is the relativistic factor, M and q is the rest mass and a unit charge of the ion, respectively. For simplification, suppose that a transverse EM wave is the plane wave, whish has the maximum electric field E_0 and the maximum magnetic field B_y and propagates with the speed of light in the direction with respect to an incident angle (see Fig.1). So, the electric field is given by $\boldsymbol{E} = \boldsymbol{E}_0 \exp \mathrm{i}(k_x x + k_z z - \omega t)$, where ω and k is the incident wave angular frequency and wavenumber. Substituting the above expression to Eq.(1), each component of the proton velocity is expressed in the form

$$v_x \left[1 - \frac{(\omega_{\mathrm{c}} + \Omega_{\mathrm{c}})^2}{\omega^2\gamma^6}\right] = \mathrm{i}\frac{q}{M\omega\gamma^3}E_x + \frac{q(\omega_{\mathrm{c}} + \Omega_{\mathrm{c}})}{M\omega^2\gamma^6}E_z,$$

$$v_z \left[1 - \frac{(\omega_{\mathrm{c}} + \Omega_{\mathrm{c}})^2}{\omega^2\gamma^6}\right] = \mathrm{i}\frac{q}{M\omega\gamma^3}E_z - \frac{q(\omega_{\mathrm{c}} + \Omega_{\mathrm{c}})}{M\omega^2\gamma^6}E_x,$$

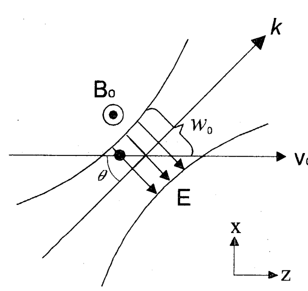

Fig.1 Diagram for acceleration model

where $\omega_c = qB_y/M$ and $\Omega_c = qB_0/M$.

Using Maxwell equation, the condition to remain the straight trajectory is given by

$$\left|\frac{E_x}{E_z}\right| = \frac{\omega_c + \Omega_c}{\omega\gamma^3} = \frac{1}{\tan\theta}. \qquad (2)$$

It may be possible to satisfy $v_x \approx 0$ by adjusting the external magnetic field, even though $\omega_c, \Omega_c < \omega,\ \gamma > 1$ in Eq.(2). It is apparent that as the incident angle $\theta = 90°$, $\Omega_c = -|\omega_c|$, that is, the external magnetic field is applied in the opposite direction of EM wave magnetic field B_y.

Multiplying Eq.(1) by $\boldsymbol{v}\cdot$, the energy gain for a unit time is given by

$$Mc^2\frac{d\gamma}{dt} = q\boldsymbol{v}\cdot\boldsymbol{E} \approx qv_zE_z. \qquad (3)$$

The energy gain is decided by the interaction length of the charged particles with the EM wave, which is the same scheme as the conventional accelerators.

Next, let us consider proton acceleration using the laser driven wakefield. The longitudinal and transverse components of a linear electron plasma wave(EPW) excited by the intense laser with Gaussian radial profile and a Gaussian time distribution, can be expressed [7] as $E_z = Ak_p\cos(\omega_p t - k_p z)\exp(-2r^2/w_o^2)$ and $E_r = A(4r/w_o^2)\sin(\omega_p t - k_p z)\exp(-2r^2/w_o^2)$, with

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

where I_{max} is the maximum laser intensity, τ is the pulse duration at FWHM, w_o is the spot size of EM wave at focus, ε_0 is the dielectric constant in vacuum and ω_p is the plasma frequency.

In general, the longitudinal component traveling with the incident laser is used for the electron acceleration. In the normal LWA, however, the transverse field is stronger than the longitudinal electric field. We propose the proton acceleration employing the transverse wakefield. The wakefield varies with time, so the most effective acceleration occurs when the proton always stays in the acceleration phase while it travels through the wakefield. The condition is given by $v_i T_p = w_o$, where v_i is the proton velocity across the area where the wakefield is excited and $T_p = 2\pi/\omega_p$. Because $\omega_p = (n_e|e|^2/\varepsilon_0 m_e)^{1/2}$, this condition can be satisfied by adjusting the plasma density. Thus, the energy gain is obtained as

$$\Delta\varepsilon = 2e\int_0^\infty E_r dr = 2A \ \ (\text{eV}). \qquad (4)$$

3 Calculation Results and Discussion

First, let us consider $v_p \times B$ acceleration scheme. In order to discuss in detail the proton energy gain, we have calculated the energy gain per an interaction of the protons with an intense laser with Runge Kutta method. The basic equation is the momentum equation (Eq.(1)). The parameters for the calculation are shown in Table 1.

Table 1 Calculation Parameter

Laser wavelength	800 nm
Laser intensity	6.4×10^{17} W/cm^2
Laser phase velocity	3×10^{10} cm/sec
Initial energy	10 MeV ($\beta = 0.145$)
Calculation time	240 (100 fsec)
Number of particle	100 particles

Figure 2 represents the energy gain $\Delta\varepsilon$ as a function of the incident angle, where the external static magnetic field is not applied. At the incident angle is 60°, the protons are accelerated with a maximum energy gain of 75 keV. The maximum acceleration gradient is estimated to be 2.5 GeV/m, which is much larger than the conventional rf accelerator. On the other hand, the intense laser cannot accelerate the protons at the incident angle 0°. We consider this result to be reasonable, since the laser does not have the longitudinal component. In the following calculations, the incident angle is fixed at 60°.

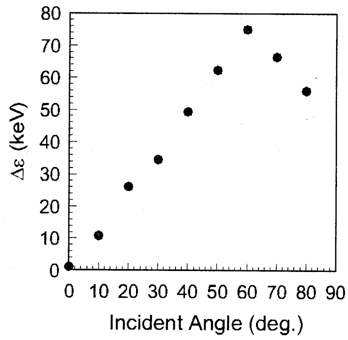

Fig.2 Energy gain as a function of the incident angle

The effect of the external static magnetic field B_0 is shown in Fig.3. It turns out from Fig.3 that the change of the energy gain due to the static magnetic field appears at around $B_0 = 10^3$ T and is remarkable at about 7×10^3 T, which is the same value as the magnetic field of the incident laser field. When the polarity of the static magnetic field is reversed, the strong acceleration does not occur and thus we have confirmed the effect of the static magnetic field. It is impossible to generate such a large magnetic field with the present technology. It is evident from the above results that the protons are accelerated without the external static field.

The proton acceleration due to obliquely incident laser has been presented. The energy gain, however, is not large enough, which is less than 1% of initial energy. Only a fraction of the laser energy can transfer to the proton, since the protons are not trapped in the wave trough because of the much difference between the proton beam velocity and the phase velocity of the laser. As a result, we consider that the effective acceleration does not occur. In an actual accelerator, the protons should be accelerated and speed up. The dependence of the energy gain on the initial proton energy is shown in Fig.4. As is expected, it is apparent that the energy gain becomes larger with the increase of the initial energy. We consider this result that the interaction length becomes longer, since the beam velocity approaches to the phase velocity of the laser.

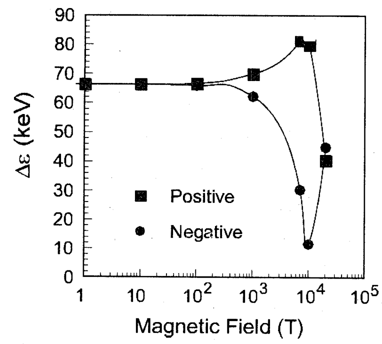

Fig.3 Energy gain as a function of the static magnetic field

Next, let us consider the proton acceleration due to the wakefield acceleration. Amplitude of EPW depends on the injection energy, since the mean plasma density need to be adjusted to satisfy the condition $v_i T_p = w_o$. The laser parameters for the excitation of EPW is the same as in Table.1. The dependence of the initial proton energy is shown in Fig.4. It turns out that the acceleration method by a radial wakefield excited by an intense laser has more advantage than the one mentioned above in lower injection energy (< 10 MeV). The wakefield amplitude is also a function of the product $\omega_p \tau$ and is maximum at $\omega_p \tau = \sqrt{2}$, that is, plasma density $n_e = 6.25 \times 10^{16}$ cm^{-3}. If the pulse duration becomes shorter, the boundary between the $v_p \times B$ method and the wakefield acceleration in Fig.4 can be moved to the higher energy side.

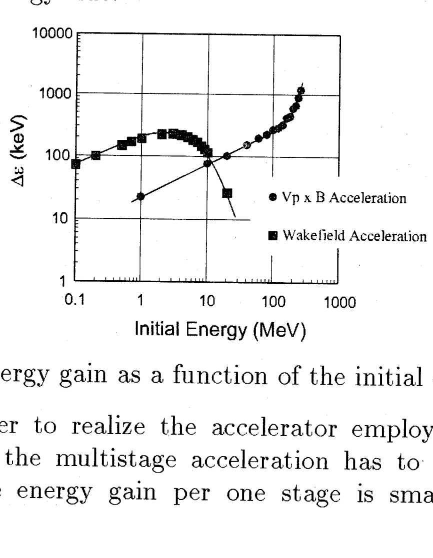

Fig.4 Energy gain as a function of the initial energy

In order to realize the accelerator employed these method, the multistage acceleration has to be used, since the energy gain per one stage is small. The schematic diagram for the multistage is shown in Fig.5. The protons are accelerated by the wakefield acceleration in lower energy and the $v_p \times B$ method in higher energy. We expect that this method is realized by arranging the position and the interval of mirrors.

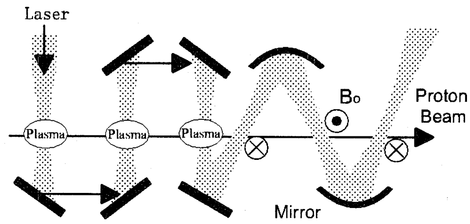

Fig.5 Schematic diagram for multistaging

4 Conclusion

We have been proposed the new proton acceleration method in this paper. The proton acceleration due to both the $v_p \times B$ and the wakefield has been confirmed from the calculations. The acceleration gradient is several hundred times larger than the conventional rf acceleration scheme. In the proton less than 1 GeV, the laser energy used for the interaction with the protons is a small amount, since the beam velocity is much smaller than phase velocity. We expect that the compact proton accelerator employed these schemes is realized by using the present apparatuses except for the external magnetic field. More detailed discussions are required for farther improvement of acceleration efficiency.

Acknowledgment

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] K. Nakajima, *et al.*, Phys. Rev. Lett. **74**, 4428 (1995), F. Amiranoff, *et al.*, Phys. Rev. Lett. **81**, 995 (1998).

[2] Y. Nishida, M. Yoshizumi, and R. Sugihara, Phys. Lett. **105A**, 300 (1984), Y. Nishida and T. Shinozaki, Phys. Rev. Lett. **65**, 2386 (1990).

[3] R. Sugihara, and Y. Midzuno, J. Phys. Soc. Jpn., **47** 1290 (1979).

[4] Y. Nishida, N.Yugami, H. Onihashi, T. Taura, and K. Otsuka, Phys. Rev. Lett. **66**, 1854 (1991).

[5] N. Yugami, K. Kikuta, and Y. Nishida, Phys. Rev. Lett. **76**, 1635 (1996).

[6] Y. Nishida, Yayoi-kennkyu Kai, March,1998, U. of Tokyo (in Japanese).

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