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PIC simulation of the Proton Acceleration in Plasma Waves Produced by Backward Raman Scattering

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ABSTRACT

Plasma waves which have phase velocity same with that of the incident beam can accelerate the beam. The phase velocity must be far smaller than the speed of light if the incident beam is of protons. Moreover, the phase velocity of the wave has to increase gradually as the proton test beam is accelerated. Plasma waves produced by laser backward Raman scattering can meet these requirement, because their wave phase velocity can be controled by changing the plasma density distribution. In order to verify this acceleration scheme, a one-and-two-halves PIC simulation code was developed. In the simulations, we can give the plasma density distribution, the laser power and frequency, can initial velocity of the test beam, etc..

1. Introduction

A longitudinal electrostatic wave (plasma wave) can accelerate charged particles, if the phase velocity of the wave is synchronized with the particle. Numerous experiments of the laser- or electron-beam-driven plasma accelerators based on this principle have been demonstrated the accelerations of the relativistic electron beams [1]. However, no experimental studies of proton/ion acceleration using plasmas have been made for the last twenty years.

Study of proton/ion acceleration using plasmas has longer history than that of electron acceleration. The "electron ring accelerator" had been studied extensively until early 1970's in USSR, USA, Germany and Japan, in which a small amount of ions in an electron ring should have been forced to acquire the speed of the electrons. However, the studies have terminated without remarkable success [2]. Recently, similar ideas have been rekindled by Russian scientists [3]. Some other ideas of plasma-based ion accelerators are found in references [4-6].

The same technique as electron acceleration using the relativistic plasma waves cannot be applied to the acceleration of protons with energy below ~1GeV, because velocity of protons is not constant in this energy region. To trap the protons in the plasma wave, the phase velocity of the plasma wave has to match with that of the injected protons, firstly. Secondly, this phase velocity has to increase in accordance with the proton acceleration.

An idea to solve the above problem is proposed in this paper [8], which uses backward Raman scattering stimulated by laser produces a slow plasma wave via parametric instability. It excites plasma waves whose phase velocity is controlled by plasma density variation along the laser axis.

In the next section, this new proton acceleration scheme is explained. Section 3, 4, and 5 describes a particle-in-cell (PIC) simulation code which was developed to study the scheme. Section 6 contains summary and discussion.

2. Proton acceleration in Plasma wave Produced by Backward Raman Scattering

Dispersion relations of waves in a plasma are

$$\varpi^2 = \varpi_p^2 + c^2k^2 \qquad (1)$$

$$\varpi^2 = \varpi_p^2 \qquad (2)$$

for the electromagnetic and electrostatic waves, respectively, where ϖ and k are frequency and wave number of eigen mode, ϖ_p is a plasma frequency and c is the speed of light. Eq.(2) tells us that the electrostatic mode is fixed at ϖ_p but can have any wave number. The plasma wave with larger *k* propagates with smaller phase velocity.

The backward Raman scattering is a three-wave parametric instability [9-11]. An incident electromagnetic wave (pump laser) decays into an electromagnetic wave (Raman-scattered wave) and a longitudinal electrostatic wave (plasma wave). The phase matching conditions in three-wave interaction:

$$k_L = k_R + k_p,$$

$$\varpi_L = \varpi_R + \varpi_p, \qquad (3)$$

must be satisfied, where suffixes L and R mean the pump laser and the scattered radiation, respectively. Eqs.(1) and (3) give the wave number of the scattered radiation as a function of ϖ_L and ϖ_p,

$$k_R = \pm\frac{\varpi_L}{c}\sqrt{1-2\frac{\varpi_p}{\varpi_L}}, \qquad (4)$$

where, and henceforward, + and - signs correspond to forward and backward scattering, respectively. Substituting Eq.(4) in Eq.(3), the wave number of the excited plasma wave is obtained as

$$k_p = k_L \mp \frac{\varpi_L}{c}\sqrt{1-2\frac{\varpi_p}{\varpi_L}}$$

$$= \frac{\varpi_L}{c}\left(\sqrt{1-\frac{\varpi_p^2}{\varpi_L^2}} \mp \sqrt{1-2\frac{\varpi_p}{\varpi_L}}\right). \qquad (5)$$

Finally, the phase velocity of the plasma wave is calculated as

$$\beta_p = \frac{\varpi_p}{ck_p} = \frac{\varpi_p}{\varpi_L}\frac{1}{\sqrt{1-\varpi_p^2/\varpi_L^2} \mp \sqrt{1-2\varpi_p/\varpi_L}}. \qquad (6)$$

This equation shows that the plasma wave produced by backward Raman scattering has slow phase velocity which increases with the plasma density.

There still remain two differences between the proton and electron accelerations. First, the acceleration gradient is much smaller in the proton acceleration. The acceleration gradient at the wave breaking limit of the electron acceleration is given by $m_e\varpi_p c$, while it is $m_e\varpi_p v_p$ in the proton acceleration.

Second, the Landau damping suppresses the Raman scattering. It is not serious in a low-temperature plasma as long as the pump laser exists. However, once the pump laser vanishes, the plasma wave also fades out because of this damping mechanism. Though a short laser pulse leaves the wake behind in the laser wakefield acceleration of electrons, this scheme does not work in the proton acceleration, because the wake cannot survive until a slow proton test beam arrives. In other words, the plasma wave has to be excited continuously by a dc-like laser.

Calculation given in Ref.[7] shows that a proton beam can be accelerated from ~2 to 50MeV in ~12 ps in a plasma, in which the density is changed from ~$3\text{x}10^{19}\text{cm}^{-3}$ to ~$3\text{x}10^{20}\text{cm}^{-3}$ in ~0.5mm. The required laser energy for this acceleration is less than 500 mJ, if we use a laser with wavelength of 800 nm.

3.PIC Simulation of Backward Raman Scattering

We have developed a one-and-two-halves PIC simulation code to study the proton acceleration. As in Fig.1, we distribute the uniform plasma from x=0 to x=100/k_p, and test protons from x=–130/k_p to –80/k_p with velocity 0.3c (energy 98.5 MeV). Fig.2 shows spectrum of the electric field at $t = 400/\varpi_p$. A laser is injected into a uniform plasma at x=0, whose frequency is $2.47\varpi_p$, and amplitude grows linearly from t=0 to $1/\varpi_p$ and then becomes constant. Its normalized vector potential is 0.1. Fig.2 shows that a slow plasma wave by the backward Raman scattering is produced at $k_x \approx 1.08\varpi_p/c$, whose phase velocity is approximately 0.3c. Fig.3 shows that the electric field of the plasma wave is $\sim 0.14 m_e\varpi_p c/e = 0.47 m_e\varpi_p v_p/e$.

4. Trapping of Protons by a Plasma Wave

The protons in the slow plasma wave is simulated as shown in Fig.3 and 4. The protons with velocity 0.3c are injected, as a test beam into a uniform plasma under the same conditions with those in Fig.1. Depending on the phase of the plasma wave at the injection, each proton becomes accelerated or decelerated. The proton distribution is highly distorted to form a sinusoidal velocity distribution (Fig4.(a)), and it becomes wider as the test particles propagate with the plasma wave (Fig. 3 and 4.(b)).

Inserting the initial proton velocity 0.3c, into Eq. (6), we get $\varpi_p/\varpi_L \cong 0.405$. If the laser wavelength is 1 μm, the electric field at the wave breaking limt, $G_{full} = m_e\varpi_p c\beta_p$, becomes 390GeV/m.

Fig.4(a) shows that some test particles are accelerated from 0.3c to 0.306c ~ $98.7(GeV)$ in the distance ~60/k_p or 23.61μm. The acceleration gradient of this simulation, G_{sim}, becomes 83.7GeV/m. As the result, the ratio G_{sim}/G_{full} becomes 0.214.

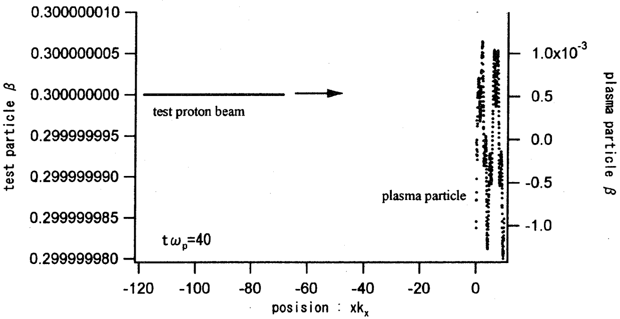

Fig.1. Distribution of the plasma particles and the injected protons.

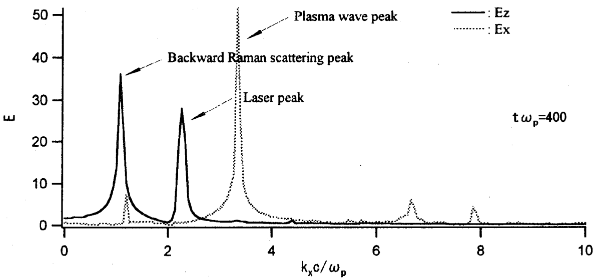

Fig.2. Spectra of the plasma wave and the laser.

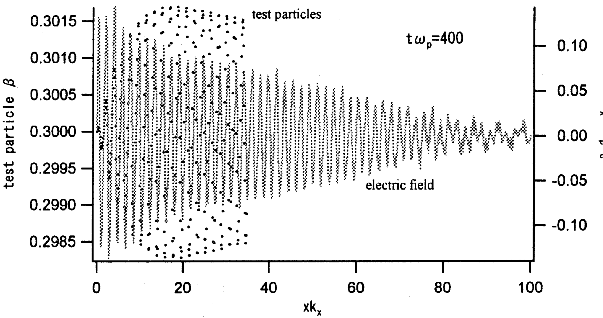

Fig.3.Test proton beam (dot) and electric field of the plasma wave (line).

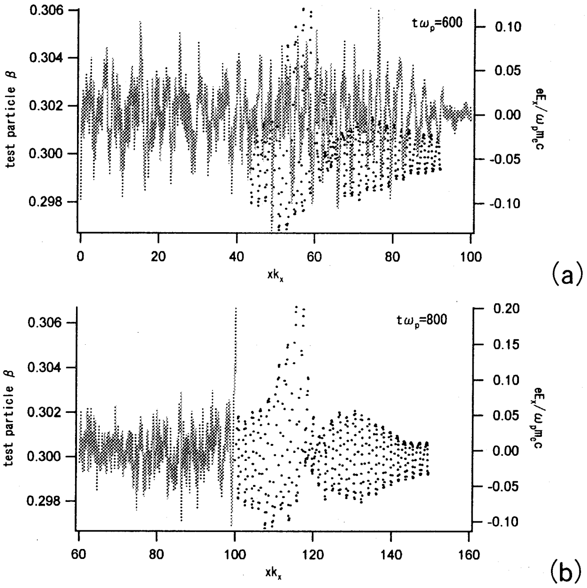

Fig.4.Phase spce plot of the proton beam injected into the plasma. (a) $t = 600/\varpi_p$. (b) $t = 800/\varpi_p$.

5.Growth Process of the Plasma Wave

Figs.5-6 summarize some results of simulations. Fig.5 shows the time evolution of electric field of the plasma wave at various ϖ_p/ϖ_L ratio. We find that, in a plasma with a higher density, the waves grow more quickly, and are saturated more quickly. Fig.6 shows the electric field at the saturation as a function of the ϖ_p/ϖ_L.

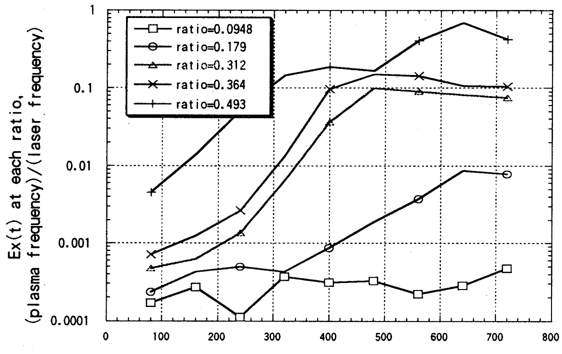

Fig.5. Growth of E_x at each ratio, ϖ_p/ϖ_L.

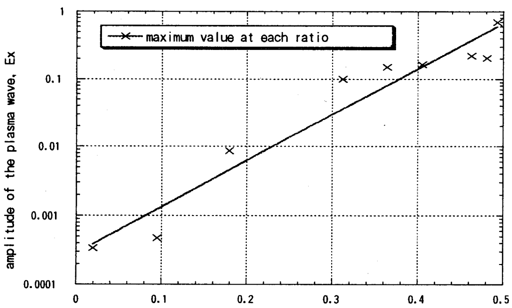

Fig.6. electric field at the saturation as a function of the ϖ_p/ϖ_L.

6. Summary and Discussion

A method is proposed to accelerate protons by a slow plasma wave produced by the backward Raman scattering. It adjusts the plasma density so that the phase velocity of the plasma wave harmonized with the group velocity of the accelerated protons. Using a uniform plasma, we succeed in proton acceleration in the simulation. About synchronizing the phase velocity with the proton velocity in the inhomogeneous plasma, more simulation study is needed.

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