TRAPPING OF BACKGROUND PLASMA ELECTRONS BY PLASMA WAKEFIELDS

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Abstract

Plasma-based advanced accelerators are actively studied in recent years as they can provide a much higher acceleration gradient than in conventional accelerators. However, there are still several critical issues to be addressed and one of them is an injection method. This paper describes a new injection method based on self-trapping of background plasma electrons by plasma wakefields.

1 INTRODUCTION

It has been known for a long time that a plasma wave can produce a very strong electric field. In 1979, Tajima and Dawson [1] proposed to use such a plasma wave to accelerate electrons to a high energy. Since then, remarkable advances have been made for the past two decades. So far, it was demonstrated that electrons can be accelerated to a few tens of MeV. In order for plasma-based advanced accelerators to be realistic, however, there are still several problems that should be solved. One of them is an injection issue. For a small energy spread, the injected beam must be much shorter than the plasma wavelength so that the loaded beam occupies a small phase of the plasma wave. However, it is very difficult to generate such a short injection beam, especially for high density plasmas in which the plasma wavelength λ_p is small. As a result, an energy spread $\Delta E / E$ in plasma-based advanced accelerators is generally large and in some cases it reaches almost 100 %, which is not good. Furthermore, the external beam injection method requires a separate injection accelerator and an extremely accurate time synchronization that is almost impossible to date. In order to overcome this kind of problems, the self-injection method based on wave breaking was proposed by Bulanov *et al*. [2] in recent years. In addition, Suk *et al.* [3] recently proposed a new trapping mechanism for self-injection in a plasma wakefield when a sharp downward plasma-density is present.

In this paper, several types of plasma-based advanced accelerators are reviewed first, and then simulation results and the planned experiment are described.

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2 BRIEF REVIEW OF PLASMA-BASED ADVANCED ACCELERATORS

Wakefields in a plasma can be generated by a short pulse laser beam or an electron beam. Depending on how the plasma wakefield is generated, the plasma-based advanced accelerators can be classified as two major types: laser-based advanced accelerators and electron-beam-based advanced accelerators.

A. *Laser-based advanced accelerators*

When a laser beam propagates in an underdense plasma (laser frequency > natural plasma frequency, i.e., $\omega_0 > \omega_p$), plasma electrons are pushed out due to the ponderomotive force, which is given by $F_{pond} = -\nabla P$. Here P is the light pressure of the laser beam. The density perturbation causes a plasma wave and the wave propagates at the speed of the laser beam, which is given by $v_g = c[1-(\omega_p / \omega_0)^2]^{1/2}$. In this equation, c is the velocity of light and ω_p is the natural plasma oscillation frequency given by $\omega_p = (n_0 e^2 / \gamma_p m_e \varepsilon_0)^{1/2}$, where n_0 is the plasma density, e is the electron charge, γ_p is the Lorentz energy factor of the oscillating plasma electrons, m_e is the electron mass, and ε_0 is the permittivity of free space. In the 1-dimensional wave-breaking limit, the longitudinal electric field of the plasma wave is given by

$$E_z = \sqrt{2}(\gamma_p - 1)^{1/2} \frac{m_e c \omega_p}{e}.$$

The plasma wave can be generated by various ways such as the plasma beat wave, laser wake wave, self-modulated laser wake wave, etc. During the early period of the research in plasma-based advanced accelerators, the plasma beat wave acceleration (PBWA) was studied first. This is because during that period a high power (but rather long pulse) CO_2 laser was available. In PBWA a large plasma wave is excited when the resonant condition $\omega_p = \omega_1 - \omega_2$ is satisfied, in which ω_1 and ω_2 are the two laser frequencies, respectively. Based on

PBWA, the UCLA group succeeded in obtaining an energy of 30 MeV in the past and now they are trying to achieve as high as 100 MeV.

If a single long laser pulse propagates in an underdense plasma, the laser pulse decays into three waves. One is the plasma oscillation with the frequency of ω_p, and the other two waves are the forward ($\omega_0 - \omega_p$, $k_0 - k_p$) and backward waves resulting from the stimulated Raman scattering instability. In the case of a long laser pulse (pulse length $c\tau_{laser}$ >> plasma wavelength λ_p), the laser pulse is modulated to a series of bunches with a periodic distance of λ_p and the plasma wave is also modulated. In this case, some plasma electrons are self-injected into the acceleration phases of the plasma wave due to wave-breaking, Raman backscattering, sideband instability, etc. These electrons are then accelerated by the plasma wave and this is called the self-modulated laser wakefield acceleration (SMLWFA). A number of groups have succeeded in obtaining high energy electron beams by using the SMLWFA. So far the SMLWFA method produced electron beams in the range of a few MeV. In the case of SMLWFA, an external injection accelerator is not needed, which is simple and very good. However, the beam quality is poor as the plasma electrons are injected randomly into the acceleration phase of the plasma wave. Therefore, the energy spread of the accelerated particles is almost 100 % and this is not good for most applications.

If the laser pulse is shorter than λ_p, the laser pulse is not modulated anymore and the resulting plasma wave can be used for acceleration. In this case, the accelerated electrons should be injected externally from a separate accelerator. This kind of acceleration technique, called the laser wakefield acceleration (LWFA), requires an injection accelerator which can produce ultrashort ($c\tau_{laser} < \lambda_p$) electron beam pulses. However, this requirement is very difficult to meet since ω_p^{-1} is less than 1 ps in LWFA. Thus, injection of plasma electrons with two or three laser pulses was proposed, but still the injection is very difficult due to timing jitter.

B. Electron-beam-based acceleration

An electron beam can be also used to generate a plasma wakefield and an electron beam can be injected externally for acceleration. This kind of acceleration is known as the plasma wakefield acceleration (PWFA) [4]. As an electron beam propagates in a plasma, nearby electrons are expelled from the beam path due to the beam space-charge force and the perturbation causes a plasma wake wave. The plasma wake wave propagates at the speed of $v_p \cong v_b$, where v_p and v_b are the phase velocity of the plasma wave and the beam velocity, respectively. In the case of the linear regime, where the overdense condition ($n_0 > n_b$) is satisfied, the plasma physics phenomena are linear, while in the case of the underdense regime ($n_0 < n_b$) the phenomena are highly nonlinear and complicated. In the underdense regime, almost all plasma electrons are ejected from the beam path and a pure ion channel is produced behind the drive beam. The ion channel provides a purely electrostatic linear focusing force $F_r = n_0 e^2 r / 2\varepsilon_0$ to the injected beam, where r is the distance from the beam axis. Due to the linear focusing force, injected electron beam motion is linear and this leads to an emittance conservation.

In the PWFA, the drive beam loses the energy and the injected beam gains an energy. In order for this acceleration scheme to be useful, the energy gain must be larger than the energy loss. Therefore, the transformer ratio, which is defined by $R_t = E_+ / E_-$, is an important concept. Here, E_+ and E_- are the gained and lost beam energies, respectively. In the 1-D optimal case for $n_b = n_0 / 2$, for example, a square drive beam of length $N_b = L_b / \lambda_p$ leads to $R_t \approx \sqrt{2\pi N_b}$, which can be much larger than unity.

As mentioned above, an electron beam should be injected into the acceleration of a wakefield for the PWFA . However, this kind of injection requires a separate external accelerator. Thus a new self-injection method, which can produce a good beam quality, can be found, it will be very good. Suk *et al*. suggested a new self-injection scheme that could produce fairly good quality beams. This method is described in the subsequent sections.

3 NEW SELF-INJECTION SCHEME AND 2-D SIMULATIONS

The wavelength of a wake wave is dependent on n_0, so that it increases if the wake wave propagates in a downward density transition. In the case of a sharp downward transition (from n_0^{I} to n_0^{II} with a transition scale length L_p) with $L_p / \lambda_p << 1$, a nonadiabatic process occurs at the transition and the plasma wavelength increases to $\lambda_p^{II} = \lambda_p^{I} \sqrt{n_0^{I} / n_0^{II}}$. In this case, it was shown that some plasma electrons are transversely injected into the acceleration phase of the wakefield and they are trapped by the strong wake. Eventually the trapped electrons are accelerated to a high energy.

Some useful theories exist in the linear regime that is valid for $n_0 > n_b$. However, there is no satisfactory theory in the nonlinear regime. Hence, the research in the nonlinear regime should be heavily dependent on numerical simulations. For 2-D PIC simulations, the fully relativistic and electromagnetic code named the MAGIC [5] was used. In order to investigate the characteristics of plasma wakefields and the trapping phenomenon in the nonlinear regime, extensive simulations have been performed in a wide range of parameters. One example for plasma wakefield generation is shown in Fig. 1. In this example, the electron beam has an energy of E_b =16 MeV and a density profile of

$$n_b(z,r;t) = n_{b,0}\exp(-(z - v_b t)^2 / 2\sigma_z{}^2)$$
$$\exp(-r^2 / 2\sigma_r{}^2)$$

The beam propagates in a uniform plasma with a density of $n_0 = 10^{16}$ cm^{-3}. The peak beam density is higher than the plasma density, so that this case is in the nonlinear regime. To excite a plasma wake wave efficiently, the beam length should be about $\lambda_p / 2$. The transverse beam size is given by $k_p\sigma_r = 0.5$, which implies that the beam is thin. Figure 1 shows that an ultrastrong nonlinear plasma wakefield is produced behind the beam pulse when the beam propagates in the underdense plasma.

The longitudinal electric field E_z is shown in the figure, in which the maximum electric reaches 10 GV/m that is approximately equal to the 1-D nonrelativistic wavebreaking limit.

In the electron-beam-driven plasma wakefield accelerations (PWFA), the driver beam energy is transferred to the energy of accelerated particles. As mentioned above, the transformer ratio R_{tr} should be greater than unity in order for the PWFA to be a useful acceleration method. Figure 1 implies that the maximum R_t is about 3.3, while the maximum transformer ratio in the lilear regime is limited by $R_t \le 2$. Hence, the simulation result indicates that the nonlinear regime is more efficient than the linear regime.

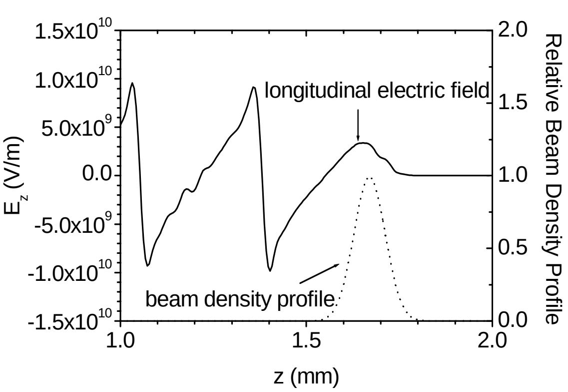

Figure 1: Wakefield for a uniform plasma with $n_0 = 10^{16}$ cm^{-3} and $n_{b,0} / n_0 = 2$.

Table I: Beam and plasma parameters for the simulation.

Beam energy E_b	16 MeV
Peak beam density $n_{b,0}$	10^{14} cm^{-3}
Beam radius σ_r	450 μm ($k_p\sigma_r{}^{II}$ =0.5)
Beam length σ_z	1 mm ($k_p\sigma_z{}^{II}$ =1.1)
Plasma density n_0	$n_0{}^I$ =5$\times10^{13}$ cm^{-3} $n_0{}^{II}$ =3.5$\times10^{13}$ cm^{-3}
Plasma electron temperature kT_e	3 eV

To investigate the trapping phenomena at a density transition, the downward density profile of Fig. 2 and the simulation parameters of Table I were used. When an electron beam enters a sharp vacuum-plasma boundary, some plasma electrons are trapped by the wakefield. But these electrons have a large energy spread and the charge is small. In order to avoid such an unnecessary trapping at the vacuum-plasma boundary, a slowly increasing density profile, as shown in Fig. 2, is used in the simulation, in which the density gradient scale is larger than λ_p. Therefore, when the electron beam enters the vacuum-plasma boundary, plasma electrons are adiabatically expelled so that trapping of the stray electrons at the boundary can be avoided. Since the driver beam is short ($k_p\sigma_z{}^{II} < 2$), it excites a highly nonlinear and strong wakefield. When the wake wave passes the density transition, a significant amount of background plasma electrons are trapped by the wakefield as the plasma wavelength becomes larger at the downward density transition.

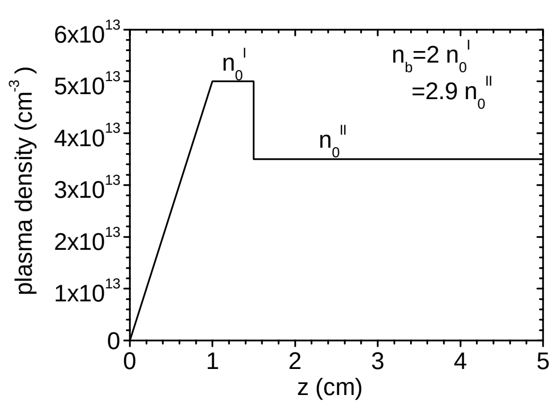

Figure 2: Plasma density profile used for the simulation.

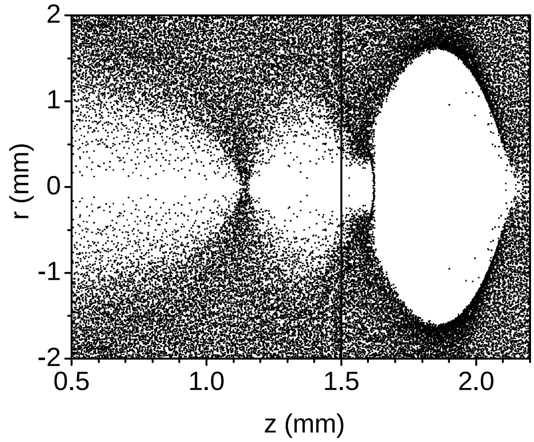

Figure 3: Plot of phasespace (r, z) for the plasma electrons. In the figure, the solid line represents the downward density transition location and the dots are the plasma electrons.

Figure 3 shows the plot of phasespace (*r, z*) for the background plasma electrons. As shown in the figure, the plasma wake wave is generated behind the drive beam. If the figure is examined carefully, it shows that the plasma wavelength increases as the wave passes the downward density transition. In this process, some plasma electrons are automatically injected into the acceleration phase of the wakefield and this phenomenon is shown in the figure. The trapped electrons are linearly focused by the ions, so that the beam quality will be good. The trapped electrons are accelerated and this is shown in Fig. 4. It shows that the electrons are accelerated to over 16 MeV. When the driver beam exits from the plasma, the wake wave disappears beyond the plasma boundary. However, the trapped plasma electron beam has a high energy already so that it continues to propagate. This situation is shown in the figure, in which the first plasma oscillation period passed the plasma boundary and it disappeared already, while the plasma electron beam is moving out of the background plasma.

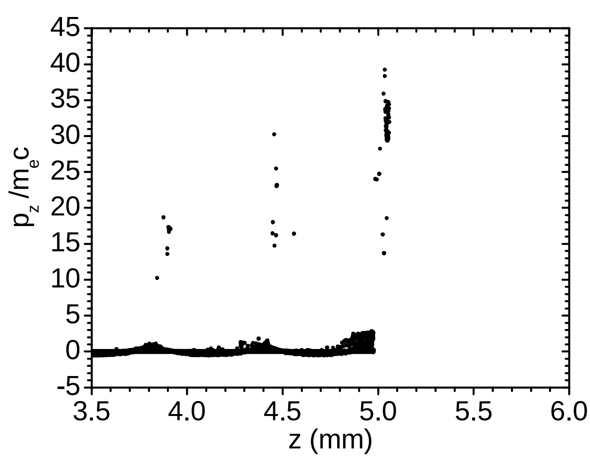

Figure 4: Plot of phasespace (p_z, z) for the plasma electrons.

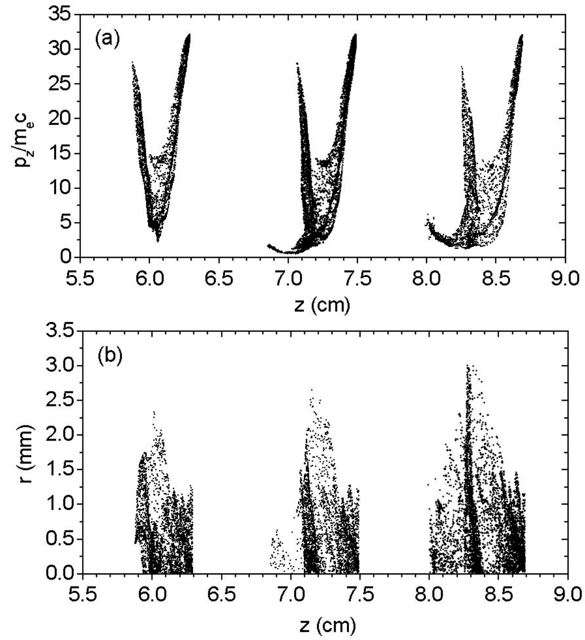

Figure 5: Disruption process of the driver beam. (a) Plot of phase space (p_z, z) for the driver beam. (b) Plot of phase space (*r*, *z*) for the driver beam.

As the driver beam continues to propagate through the plasma, the beam loses its energy continuously and the instability also grows. Eventually energy of some electrons in the central part of the beam reach almost zero, so they slip to the acceleration phase of the wakefield and they are slightly accelerated. This is shown in Fig. 5(a). If this phenomenon occurs, the slipped particles mix with the trapped plasma electron beam, which leads to a detrimental effect to the beam quality of the originally trapped plasma electron beam. Hence, the trapped plasma electron beam must be ejected from the background plasma before this kind of mixing occurs. If the beam propagates further, more electrons flow to the acceleration phase of the first period and eventually they slip to the second period again. As the beam loses its energy, a space-charge effect becomes more important and the beam radius increases. This is clearly shown in Fig. 5(b), i.e., the low-energy beam part expands transversely.

Beam quality of the trapped plasma electrons is an important issue. Quality of the trapped electrons, especially energy spread of the trapped beam, can be improved with a slowly decreasing plasma density that leads to a rephasing in the plasma wakefield. Figure 6 shows a comparison of the two cases with E_b =16 MeV. As shown in the figure, the slowly decreasing density profile in Fig. 6(c) results in a significantly smaller energy spread in comparison with Fig. 6(a). Hence, this kind of momentum compression method seems to be a good way for energy-spread reduction.

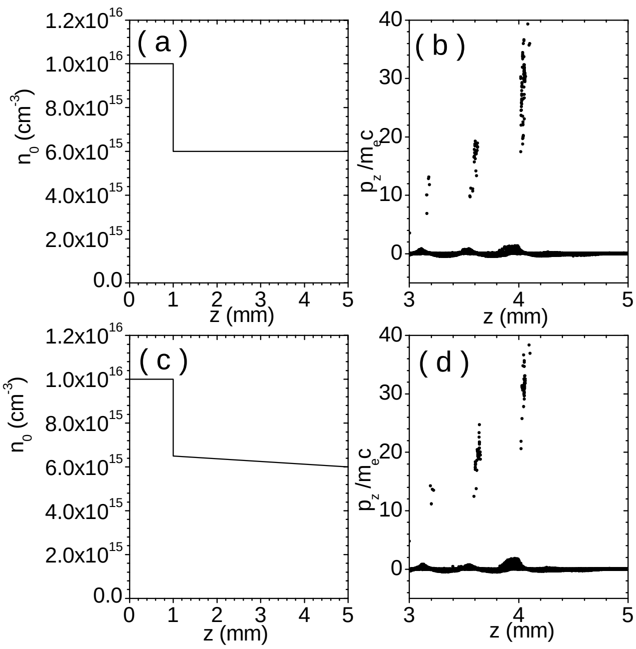

Fig. 6. Comparison of energy spreads for two different plasma density profiles. A flat plasma-density profile (a) and the resulting momentum of the plasma electrons (b), and a slowly decreasing density profile (c) and the resulting momentum of the plasma electrons (d).

4 PLANNED EXPERIMENT

In order to verify the self-trapping-based acceleration mechanism, experiments are planned at the Center for Advanced Accelerators. In this section, the planned experiments are introduced. For the experiments, an intense laser beam will be used instead of an electron beam. For this purpose, the so-called T^3 (Table-Top Terawatt) Nd:glass laser system based on the CPA (Chirped-Pulse Amplification) scheme will be used. The T^3 laser system at the Center for Advanced Accelerators is expected to provide a pulse duration of about 700 fs so that the optimum plasma density is around $n_0 = 6.3\times10^{15}$ cm^{-3}. Under this condition, the maximum acceleration gradient is calculated to be about 7.6 GeV/m. The planned experimental parameters imply that the normalized vector potential $a_0 = p_0 / m_e c$, in which p_0 is the quiver velocity, is about 0.5. Hence, the wake wave will have significant relativistic effects.

In the trapping and acceleration experiments, a lot of relevant research issues will be studied. One of them is to find the optimum trapping condition, which will be dependent on various parameters. Quality of the accelerated electrons is another very important issue. Generally self-trapping-based acceleration method is believed that beam quality of accelerated particles is not as good as that of external-injection-based acceleration. Hence, it is important to find methods for beam quality improvement. One way may be to find the optimum beam profile for most efficient wakefield generation. This may be done with an asymmetric intensity profile with a slowly-increasing front part and a sharply-falling rear part. This kind of profile may expel plasma electrons adiabatically and generate a large wake wave in the plasma. Another very important research will be to study media effects of the plasma, which include the relativistic self-focusing effect, optical guiding effect, etc. If the optical guiding is not employed, the laser beam diffracts naturally. As a result, the laser and trapped-electron interaction range is limited to the Rayleigh range $2z_R = 2\pi w_0^{\ 2} / \omega_0$, where w_0 is the beam waist size. This kind of limitation in interaction range can be removed if the optical guiding method is employed, so that a much higher energy will be achieved. In addition to the optical guiding, there are a lot of important research issues that are not well known to date and they will be intensively studied both experimentally and theoretically at the Center for Advanced Accelerators.

5 SUMMARY

The trapping method for self-injection of plasma electrons was studied. The simulation results show that the proposed injection method may produce fairly good quality beams that can be used for applications. Furthermore, quality of the produced beams may be improved with the suggested density variation method. The proposed injection method and other relevant research issues will be studied at the Center for Advanced Accelerators.

6 REFERENCES

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