NUMERICAL SIMULATION ON PLASMA-BASED BEAM DUMPS USING Smilei

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Abstract

The active plasma beam dump utilizes a laser to generate a plasma wakefield and decelerate an externally injected beam to low energy. We use the particle-in-cell code "Smilei" for the investigation on electron beam energy loss in plasma. In this research work we optimize the laser and plasma parameters to investigate the active plasma beam dump scheme. In doing so, most of the beam energy will be deposited in the plasma. The optimization strategy for the beam energy loss in plasma is presented.

INTRODUCTION

In plasma-based accelerators a high intensity laser pulse or a relativistic electron bunch can induce a plasma wakefield with accelerating gradient on the order of 100 GV/m, which is much larger compared to the conventional accelerator and achieved in short distance. It has been shown that the electrons can be accelerated in high gradient plasma wakefield and can achieve the kinetic energies up to the GeV level over a few centimetres scale acceleration length [1–7]. The plasma-based accelerators are a milestone to make the accelerator compact and transportable [8]. However, the compactness of particle accelerator still limited by large and heavy conventional beam dump techniques. The plasma-based beam dump is a scheme to depose the relativistic beam kinetic energy in plasma medium, after the accelerated particle beam being used purposefully. Compared to the conventional beam dump, the plasma-based beam dump offers compact footprint, low radiation hazards and therefore low costs. In the conventional beam dump techniques, for disposing of particle beam energy one has to impinge it on a high-density material - a solid or liquid, which will rapidly stop the beam's constituent particles and produce the ionization radiations that could be harmful for the environment. It is then necessary to avoid the production of dangerous chemicals or the radio activation of materials that can result from exposure to radiation. In addition, the radiation hazards due to particle scattering in plasma beam dump are much smaller than that in conventional beam dump. Plasma based beam dump were first introduced by Tajima *et al.*, in 2010 [9]. In the recent couple of years, the plasma-based beam dump [9–14] has been investigated for the development of compact particle accelerators with GeV range energies that is a great interest to fulfil the requirement for free-electron lasers, high-quality x-ray production, terahertz-radiation generation.

PLASMA BEAM DUMP

The plasma-based beam dump can be categorized in two types based on sources used to induce the wakefield: passive plasma beam dump (PPBD); and active plasma beam dump (APBD). In passive plasma beam dump [9–14] a relativistic particle bunch propagates in an undisturbed plasma and loses its energy. In this scheme, particles in the head of the bunch will experience no decelerating field due to the finite response time of the plasma, while particles at the bunch tail will experience a deceleration and will become non-relativistic. As the particles start decelerating, after some time, these non-relativistic charge particles fall behind the rest of the bunch and move to an accelerating phase region of wakefield that is commonly referred to as second accelerating phase of the plasma wave. This re-acceleration of the beam particles, which eventually leads to saturation of beam net energy loss. Recently, to avoid the re-acceleration during the beam dumping, several schemes have been proposed, such as inserting foils in the plasma to absorb the re-accelerated particles and tailoring the plasma density along the beam propagation direction to change the rela-tive phases of wakefield along the beam driver [10–12]. The present study shown that the beam energy deposition in plasma can be faster in an active plasma beam dump scheme [11] where a laser pulse is introduced to excite the wakefield in plasma before an electron beam is injected in decelerating phase of the plasma wakefield for energy loss. In this research work, we will investigate the active plasma beam dump using PIC code "Smilei" and do comparison with passive plasma beam dump [10].

ANALYTICAL MODEL

In this study an analytical model developed by Bonatto, et al [11] being used. To investigate the plasma-based beam dump, we considered the bi-Gaussian electron bunch density profile given by $\frac{n_b(\xi,r)}{n_0} = \frac{n_b}{n_0} exp(-\frac{\xi^2}{2\sigma_z^2}) exp(-\frac{r^2}{2\sigma_r^2})$, where n_b and n_0 are the bunch peak density and plasma density, respectively. σ_z and σ_r are the bunch longitudinal and transverse RMS size, respectively. For active plasma

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beam dump a bi-Gaussian laser driver is introduced to induce the plasma wakefield. Laser envelope profile is defined by $a^2(\xi, r) = a_0^2 exp(-\frac{\xi^2}{\sigma_l^2}) exp(-\frac{r^2}{r_w^2})$, where $\xi \equiv z - ct$ is the comoving coordinate in the moving direction. a_0 is the laser amplitude, σ_l and r_w are laser pulse length and waist, respectively. In principle, the wakefield induced by the bunch driver can be improved by considering the laser-driven wakefield. In APBD the net decelerating wakefield is stronger and more uniformed than the wakefield in PPBD because the wakefield is improved by laser driver. On choosing the appropriate conditions such as laser parameters and the phase of the laser driven wakefield for beam injection, the net wakefield $E_z/E_0 = (E_{zb} + E_0)/E_0$, where E_{zb} and E_{zl} are the bunch self-driven longitudinal plasma wakefield and laser-driven longitudinal plasma wakefield respectively, and $E_0 = (cm_e\omega_p)/e$ is the cold plasma non-relativistic wave breaking electric field, c is speed of light, m_e is the electron rest mass, ω_p is plasma frequency, and e is electron charge. The analytical solution for the excitation of plasma wakefield induced by electron bunch and laser pulse is well described in literature [1, 15, 16]. From the plasma fluid equation of momentum and Lorentz force, the action of electric field on relativistic electron bunch

$$\frac{d}{dt}(\gamma m v) = -eE_z, \tag{1}$$

where γ is relativistic factor. A new variable $s = ct$ is introduced. Now the equation of motion for highly relativistic case ($v \simeq c$) becomes,

$$\frac{d\gamma}{ds} \simeq -\frac{e}{mc^2}E_z = -k_p\frac{E_z}{E_0} \tag{2}$$

$$\frac{d\gamma}{ds} = -k_p(E_{zb} + E_{zl})/E_0, \tag{3}$$

where k_p is the plasma wave number. Integrating the Eq. (3) over a distance s, assuming the initial energy distribution inside the beam is uniform and all the electrons have the initial$\gamma \gg_0 1$, the expression for γ leads to

$$\gamma(s) = \gamma_0 - \frac{k_p}{E_0}(sE_{zb} + \int dsE_{zl}. \tag{4}$$

The normalized total energy of the beam $U(s)$ can be defined as,

$$U(s) = \int_V dV\gamma(s)n_b(\xi, r)/n_0, \tag{5}$$

$$U(s = 0) = U_0 = \gamma_0 \int_V dVn_b(\xi, r)/n_0. \tag{6}$$

The total beam energy loss in active plasma beam dumping can be obtained from Eqs. (4), (5) and (7), on defining laser-driver and beam-driver induced wakefield. The evolution of normalized total beam energy can be expressed as,

$$\frac{U(s)}{U_0} = 1 - k_p s\frac{\int_V dV[E_{zb}/E_0][n_b(\xi, r)/n_0]}{\gamma_0 \int_V dVn_b(\xi, r)/n_0} - k_p\frac{\int^s ds \int_V dV[E_{zl}/E_0][n_b(\xi, r)/n_0]}{\gamma_0 \int_V dVn_b(\xi, r)/n_0}. \tag{7}$$

SIMULATION

To investigate the beam energy loss, 2D particle-in-cell (PIC) simulation was performed with Smilei [17]. Simulation was conducted for the electron beam with peak density $n_b/n_0 \sim 3$ and $\gamma_0 = 1960$ (electrons with energy ~1 GeV) propagating in a uniform plasma with density $n_0 = 1 \times 10^{18}$ cm^{-3}. The other beam parameters (adopted from EuPRAXIA Conceptual Design Report [18]) are shown in Table 1. We considered the linearly polarized pulse with $a_0 = 2$, $\sigma_l = 7.5$ µm, and waist size $r_w = 17$ µm. For the optimum parameters, maximum amplitude for the laser excited wake is $E_z/E_0 = 0.61$.

Table 1: Electron Beam Parameters

Parameters	
Bunch charge (Q)	30 pC
Transverse bunch size (σ_r)	1.4 µm
Longitudinal bunch size (σ_z)	2.0 µm
Energy spread	1.0 %
Angular divergence (rad)	1×10^{-5}

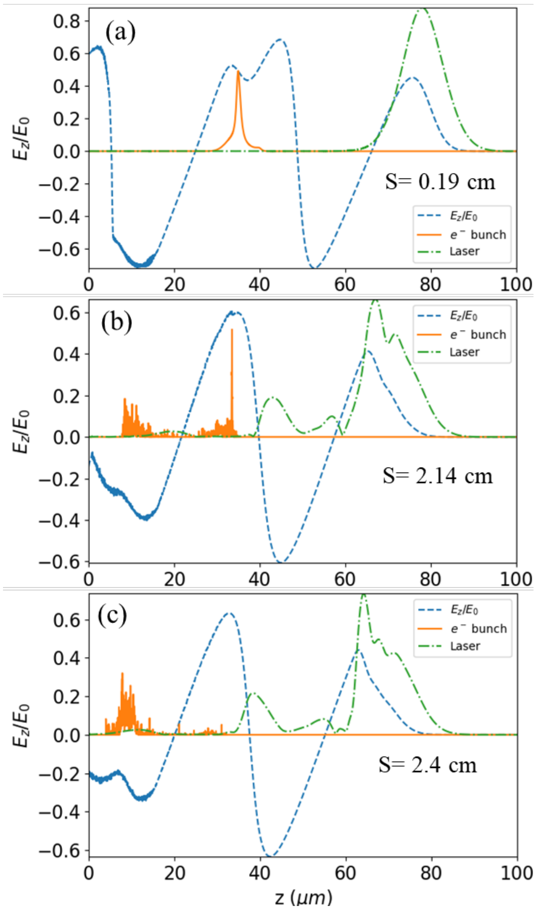

Figure 1: Beam spatial distribution (orange curve), net longitudinal wakefield (blue curve) and the laser envelope (green curve) at (a) $s = 0.19$ cm, and (b)$s = 2.14$ cm (c) $s = 2.4$ cm, bunch moved toward the acceleration phase of wakefield.

Figure 1(a) shows the electron beam distribution (orange curve), the net wakefield $E_z/E_0 = (E_{zb} + E_{zzl})/E_0$ (blue curve), and the laser envelope (green curve) at $s = 0.19$ cm. The electron beam is placed at the beginning of decelerating phase of laser wake. Figure 1(b) shows at $s = 2.14$ cm the electrons at the bunch tail reaches to the accelerating region. Figure 1(c) shows at$s = 2.4$ cm most of the bunch electrons moved to acceleration region of the wakefield.

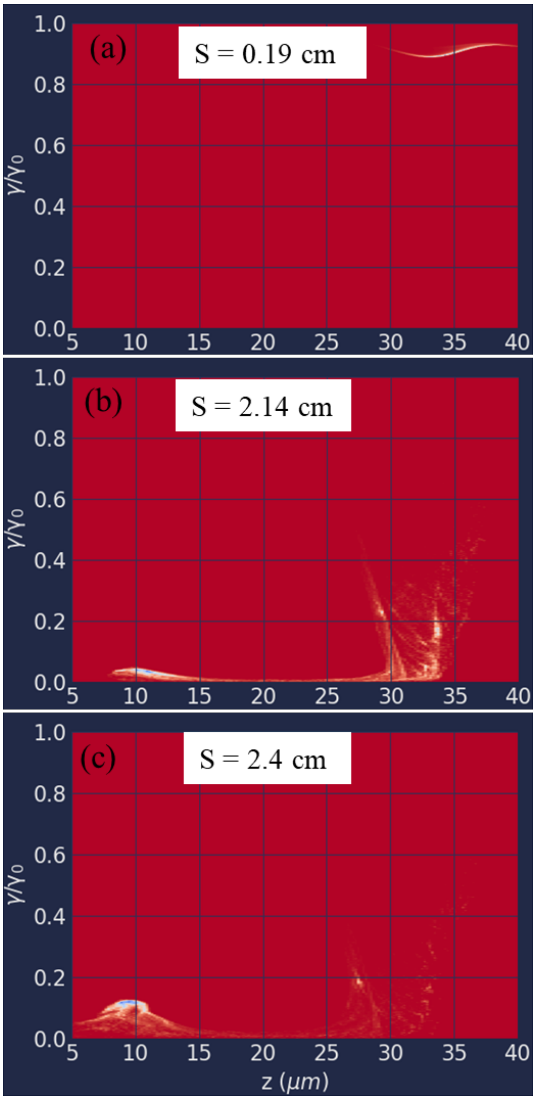

Figure 2: Phase space showing the normalized energy (γ/γ_0) (a) initially at $s = 0.19$ cm, (b) In comparison to results from the passive case, the energy chirp is much lower in this phase space obtained for the APBD at $s = 2.14$ cm, and (c) at $s = 2.4$ cm phase space shows that most of the beam energy was absorbed in plasma wakefield and electrons at the tail of bunch start gain the energy.

Figure 2(a) shows the initial phase space with $\gamma/\gamma_0 \sim 0.9$ at $s = 0.19$ cm. Figure 2(b) shows the beam reaches its minimum energy $(\gamma/\gamma_0 \ll 1)$ at $s = 2.14$ cm cm along the whole length of bunch resulting a uniform energy loss in APBD as compared to the PPBD. Figure 2(c) depicts the phase space at $s = 2.4$ cm, where electron beam loses most of its energy, and slips into the reacceleration phase region and starts gaining energy. The evolution of the electron beam total energy (U/U_0) at $s = 2.4$ cm along the beam propagation shown in Fig. 3. The minimum beam energy $U = 26$ MeV is observed at $s = 2.2$ cm

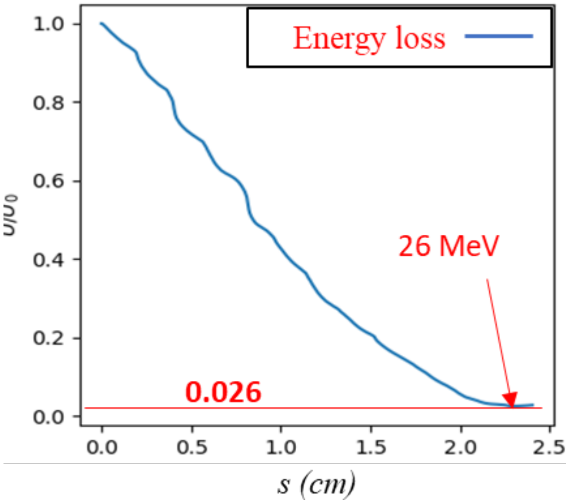

Figure 3: The beam total energy (U/U_0) evolution along the beam propagation in plasma.

CONCLUSION

In this study, we observed that the electron beam losing its maximum energy at $s = 2.2$ cm, reaching to a minimum average energy of 26 MeV. Whereas the previous study shows in passive plasma beam dump scheme for the same configuration of optimum parameters electron beam reaches to its minimum energy at a distance of 6 cm. Therefore, in active plasma beam dump, the electrons in the bunch lose their energy faster as compared to the passive beam dump scheme that could lead to the more compactness of the plasma particle accelerators. We also observed the high intensity laser envelope deformed may be due to the nonlinear effect in plasma such as self-steepening, self-focusing and self-phase modulation instabilities [19, 20]. To avoid the laser deformation because of nonlinear effect further simulation has to be done with lower laser intensity.

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