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A PASSIVE PLASMA BEAM DUMP STUDY WITH APPLICATION TO EuPRAXIA

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Abstract

This work presents a study about a passive plasma dumping scheme applied to the beam generated by the accelerator stage of the EuPRAXIA experiment. Particle-in-cell simulations have been carried out and its results are compared with analytical estimates, showing a reasonable agreement.

INTRODUCTION

The advent of the laser-plasma accelerator technique [1] has allowed the construction of more compact machines that produces more energetic beams for the most diverse applications. The wakefield produced by an intense laser in an underdense plasma is strong enough to accelerate particles to GeV energies in a few centimeters. Besides of being used to accelerate particles, the wakefield generated by the laser (active system), or evenly by the beam itself (passive system), can be used to dump the highly energetic beam to energies that could be safely discarded [2].

The purpose of the present work is to study a passive scheme for dumping the electron beam of the EuPRAXIA experiment. The beam output by the accelerator stage of EuPRAXIA has the following characteristics [3]: Q=30 pC of total charge, electrons with uniform energy e_k=5 GeV, beam size of σ_r=1.4 µm, and beam length of σ_z=σ_ξ=2 µm. These quantities will be used in the following sections for both the analytical calculations and the Particle-in-Cell (PIC) numerical simulations. Both analytical and numerical calculations have been carried out for a 1D system, which produces reasonable results while the beam density remains almost invariant.

ANALYTICAL MODEL

A charged beam propagating in a plasma channel produces a wakefield E_z. Since the charged beam has finite dimensions, the wakefield E_z produced by its propagation will interact with its own particles, realizing work over these particles, and then decreasing its kinetic energy if proper conditions are assured.

A simple model to describe this kinetic energy loss process along the plasma channel can be developed considering initially the dynamics of an individual particle and further extending the result for the whole beam. From the Newton second law in one dimension, for a relativistic electron under the action of an electric field E_z

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

in which $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor, $\beta = v/c$ is the relativistic factor, m is the electron mass, q_e is the electron charge, v its one-dimensional velocity, and c the speed of light. Introducing a new variable, the propagated distance $s = ct$, the Eq. (1) right above becomes

$$\frac{d}{ds}(\gamma v) = -\frac{q_e}{mc}E_z. \tag{2}$$

The Eq. (2) can be readily integrated along the propagated distance s. Proceeding in this way, considering also that the wakefield E_z is invariant along s

$$\gamma v = \gamma_0 v_0 - \frac{q_e}{mc}E_z s, \tag{3}$$

in which $\gamma_0 v_0 = \gamma(s=0)v(s=0)$.Through algebra over the Lorentz factor

$$\gamma v = c\sqrt{\gamma^2 - 1}. \tag{4}$$

By inserting the Eq. (4) in the Eq. (3) one has that

$$\sqrt{\gamma^2-1} = \sqrt{\gamma_0^2 - 1} - \frac{q_e}{mc^2}E_z s. \tag{5}$$

Since the particle is highly relativistic, then $\gamma >> 1$ and Eq. (5) can be approximated as

$$\gamma \approx \gamma_0 - \frac{q_e}{mc^2}E_z s, \tag{6}$$

being the relativistic particle kinetic energy e_k [4]

$$e_k = (\gamma - 1)mc^2. \tag{7}$$

The above results for an individual particle can be extended to the whole beam assuming that its interactions with the wakefield is dominant among the others. For that, considering a relativistic beam of particle density n_b, one has that its overall kinetic energy E_k can be obtained by integrating Eq. (7) for e_k along the beam

$$E_k = \int e_k n_b(\xi) d\xi, \tag{8}$$

in which $\xi = z - v_b t$, being $v_b = v(s=0)$ the initial beam velocity, considered initially uniform for all the particles. Note that E_k depends on n_b, which depends on γ, which in its

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turn depends on s. Resuming, by this approach $E_k = E_k(s)$. By inserting Eq. (6) into Eq. (7), and its result in Eq. (8)

$$E_k(s)/E_{k0} = 1 - \alpha s, \tag{9}$$

in which

$$\alpha = \frac{q_e}{E_{k0}} \int E_z n_b(\xi) d\xi. \tag{10}$$

The integration in Eq. (10) can be performed once the wakefield E_z produced by the beam propagation is obtained. For a gaussian beam of charge Q and standard deviation σ_ξ

$$n_b(\xi) = \frac{Q}{q_e\sqrt{2\pi}\sigma_\xi} e^{-\frac{\xi^2}{2\sigma_\xi^2}} \tag{11}$$

the produced wakefield E_z is [5]

$$E_z(\xi) = \frac{\pi^{1/2}}{2^{3/2}} E_0 k_p n_{b0} \sigma_\xi e^{-\frac{k_p}{2}(2\mathrm{i}\xi + k_p\sigma_\xi^2)} \left[\mathrm{erfc}\left(\frac{\xi - \mathrm{i}k_p\sigma_\xi^2}{\sqrt{2}\sigma_\xi}\right) + e^{2\mathrm{i}k_p\xi}\mathrm{erfc}\left(\frac{\xi + \mathrm{i}k_p\sigma_\xi^2}{\sqrt{2}\sigma_\xi}\right)\right], \tag{12}$$

in which $E_0 = c^2 k_p m_e/q_e$ is the cold non-relativistic wave breaking electric field, $k_p = (1/c)\sqrt{(n_0 q_e^2)/(\epsilon_0 m_e)}$ is the angular plasma wave number, ϵ_0 is electric permittivity of vacuum, $n_{b0} \equiv n_b/n_0$, n_0 is the plasma particle density, i is the imaginary number, and erfc is the complementary error function.

THE NUMERICAL SIMULATIONS

The numerical simulations are performed through the Epoch PIC code [6]. For simplicity, and as a first analysis, 1D simulations were chosen to be carried out, since they are less time consuming and they provide valid information about the beam dump process while the beam density n_b remains almost invariant [2].

Since the real beam is strictly 3D, for the 1D simulations to be physically equivalent to the real case, it is necessary to match the wakefield E_z produced in these both 1D and 3D dimensional representations of the same system. By this match, one can find that the Q_{1d} charge that produces the same wakefield of the charge Q of the real beam is

$$Q_{1d} = Q\left[1 - \frac{4}{(2k_p\sigma_r)^2} + 2K_2(2k_p\sigma_r)\right], \tag{13}$$

in which K is the modified second kind Bessel function.

It has been executed three distinct PIC simulations, varying the plasma density n_0 to control the wakefield produced over the beam density n_b in order to increase the rate of the beam kinetic energy loss. The three PIC satisfies respectively $k_pL = 1.1$, $k_pL = 2.1$, and $k_pL = 3.1$, in which L specifies the effective beam length. $L = 5.15\sigma_\xi$ in the present case.

THE RESULTS AND CONCLUSIONS

The preliminary numerical results of the study are presented in the following figures. Figures 1, 2, and 3 contain the results for E_k/E_{k0} and n_b at the initial, panel (a), and at the final , panel (b), of the PIC numerical simulation for $k_pL = 1.1$, $k_pL = 2.1$, and $k_pL = 3.1$, respectively. In the panel (b) of these Figures, there are also secondaries beams resulted from the deceleration of the original beam.

It is possible to see the effect of increasing k_p, and in this way n_0, comparing the panels (a) of these figures. As k_p is increased, the wakefield E_z advances over a greater amount of beam particles, increasing the negative work done over the entire beam and producing a faster dump of its overall kinetic energy.

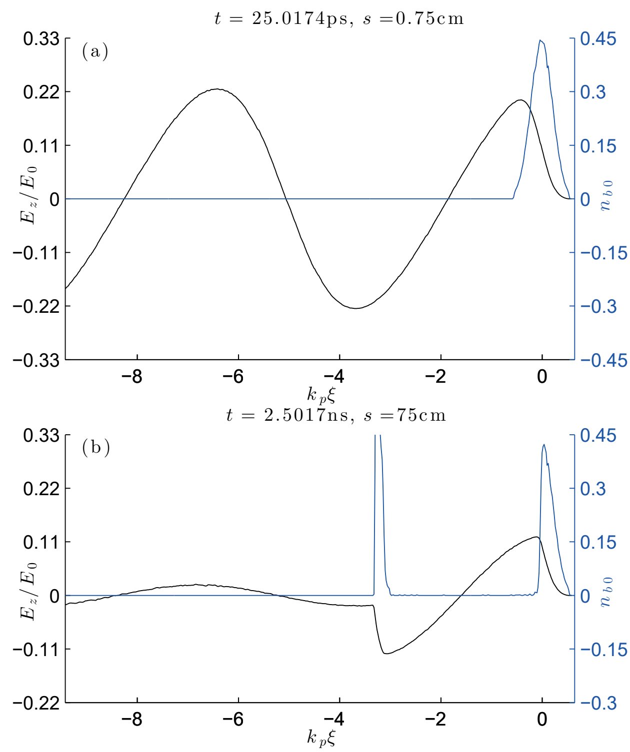

Figure 1: The beam density profile n_{b0} and the wakefield E_z/E_0 at the initial, panel (a), and at the final, panel (b), of the simulation. Results are for $k_pL = 1.1$.

Figure 4 presents PIC results for the beam kinetic energy E_k/E_{k0} along s for respectively $k_pL = 1.1$, $k_pL = 2.1$, and $k_pL = 3.1$. The reference black dotted line is for E_k/E_{k0}=0.43 and denotes approximately the saturation value for the kinetic energy in all cases. In this figure, it has been also plotted the analytical results of the simple model synthetized by Eq. (8). For almost the same amount of kinetic energy dump, the plasma stage length is reduced from approximately 45cm to 17.5cm when the angular plasma wave number k_p is changed from $k_pL = 1.1$ to $k_pL = 3.1$.

Although the analytical model predicts reasonably the behaviour observed in 1D PIC simulations, it is necessary

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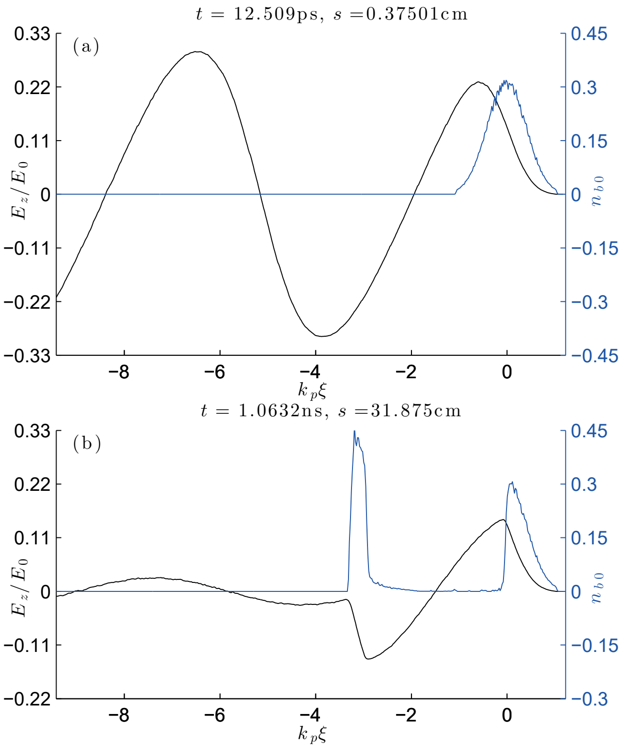

Figure 2: The beam density profile n_{b0} and the wakefield E_z/E_0 at the initial, panel (a), and at the final, panel (b), of the simulation. Results are for $k_pL = 2.1$.

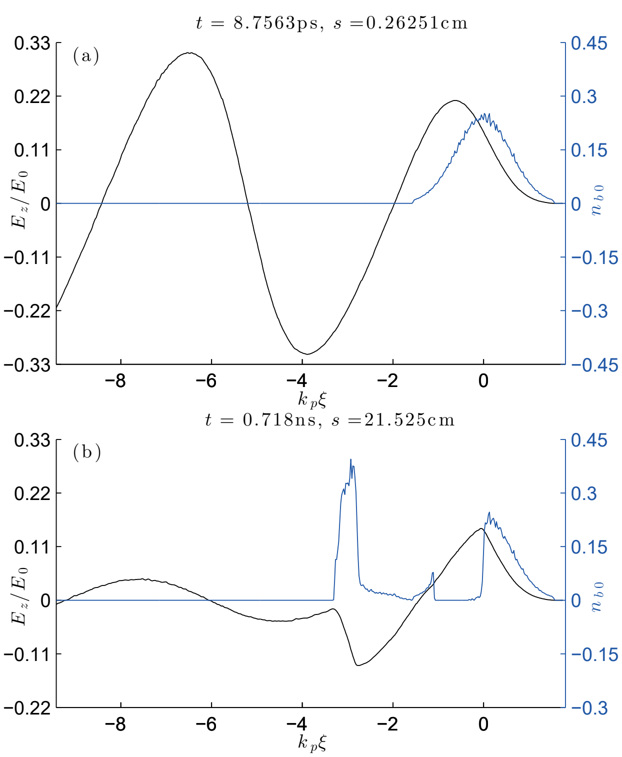

Figure 3: The beam density profile n_{b0} and the wakefield E_z/E_0 at the initial, panel (a), and at the final, panel (b), of the simulation. Results are for $k_pL = 3.1$.

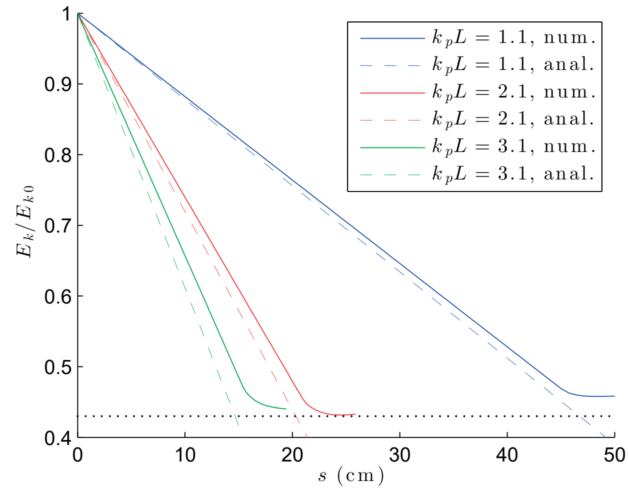

Figure 4: The beam kinetic energy E_k/E_{k0} along s for k_pL = 1.1 in blue, for k_pL = 2.1 in red, and for k_pL = 3.1 in green. The solid and dashed lines represent respectively the numerical and analytical results.

to carry out 3D PIC simulations for full validation of the developed approach. This will be the next step of the work.

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