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Laser wake field acceleration with controlled self-injection by sharp density transition*

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Abstract

Laser Wake Field Acceleration of relativistic electron bunches is a promising method to produce a large amount of energetic particles with table top equipment. One of the possible methods to inject particles in the appropriate acceleration phase of the wake behind the pulse takes advantage of the partial longitudinal breaking of the wake crests across a density downramp. In this paper results of 2.5D PIC simulations, showing the production of an electron bunch with reduced energy spread, are reported. Also, a possible method to produce the required plasma density transition by laser explosion of a suitable couple of thin foils is discussed.

Keywords: Laser-plasma accelerators, Wave breaking

1. INTRODUCTION

Several mechanisms to obtain a controlled self-injection of electrons in the accelerating phase of the longitudinal electron-plasma wave excited by a short laser pulse are currently subject of active studies (Umstadter *et al.*, 1996; Esarey *et al.*, 1997; Kotaki *et al.*, 2003; Bulanov *et al.*, 1998; Suk *et al.*, 2003; Tomassini *et al.*, 2003). Among these, controlled injection with partial longitudinal breaking of the Langmuir wave after a density downramp (Bulanov *et al.*, 1997; Suk *et al.*, 2003; Tomassini *et al.*, 2003; Hafz *et al.*, 2003), is the mechanism which uses only one laser pulse. Nevertheless, the intrinsic simplicity of the scheme on the laser system side is paid by the necessity of producing a plasma whose electron density presents two contiguous plateaux separated by a steep transition.

In this paper we present the results of two 2.5D Particle In Cell (PIC) simulations in which relativistic electron bunches with a low energy spread are produced by means of the Laser Wake Field Acceleration (LWFA) process. The preformed plasma density profile is chosen in order to enable the partial breaking of the wake behind the laser pulse, with a scalelength of the density transition L much smaller than the Langmuir wave number λ_{pe} (sharp density transition). The two simulations differ by the peak amplitude of the laser pulse and the results clearly show that, in order to obtain a good beam quality, a limit on the laser pulse intensity has to be applied.

The generation of a plasma with the required tailored plasma density profile is, to date, a challenge. Recently, Hosokai *et al.* (2003) employed a gas-jet system and produced a density transition by inducing in the plasma a shock wave produced by the laser pulse ASE. They demonstrated the trapping and acceleration of electron bunches with low angular divergence, but still having a large energy spread.

Here we present, an alternative method to generate a plasma with electron density profile presenting a sharp downramp between two plateaux. The method uses the thin-foils laser explosion technique with two closely placed plastic foils of different thicknesses. A simulation with the hydrodynamic 2D code POLLUX (Perl, 1981) was performed in order to find the expected profile, as discussed in the last section of this paper.

2. 2.5D PIC SIMULATIONS

We used a fully relativistic PIC code developed by H. Ruhl (2000), which runs on 16 processors of an SP4 system at

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CINECA, Italy (2004). The laser pulse propagates along the z direction and it is polarized along y, has wavelength $\lambda_l = 1\ \mu$m, duration $\tau_{FWHM} = 17$ fs full width at half maximum and waist $w_0 = 20\ \mu$m. The preformed plasma has longitudinal density profile presenting two contiguous plateaux with a transition having scalelength $L = 2\ \mu$m located at $z = 50\ \mu$m (see Fig. 1). The electronic densities of the first plateau (region I), where a regular wake develops, and the second plateau (region II) where the trapped particles are accelerated are $n_e^I = 2.1 \times 10^{19}$ cm^{-3} and $n_e^{II} = 1.1 \times 10^{19}$ cm^{-3}, respectively. The simulation box was 40 μm $\times$ 200 μm large, with a resolution of $0.05\lambda_l$ in both directions. About 10^8 particles are left to move for about 5000 timesteps.

2.1. Simulation 1

In the first simulation the laser pulse peak intensity was $I_1 = 1 \times 10^{19}$ W/cm^2, corresponding to a normalized pulse amplitude $a_0 = 8.5 \times 10^{-10}\sqrt{I_1 \lambda_l^2} \simeq 2.6$. The pulse amplitude is slightly below the threshold for the relativistic trapping process (Bulanov *et al.*, 1991), which takes place when the quivering speed exceeds the phase speed of the plasma wave, i.e., when $a_0^R > (n_c/n_e)^{1/4} \simeq 2.7$, being n_c is the critical electron density at the laser wavelength. In Figure 2 a snapshot at $t \simeq 200$ fs (time in which the laser pulse is crossing the density transition) of the electron density (a), the transverse component of the electric field (b), and the longitudinal electric field (c) is shown. The crests of Langmuir wave behind the pulse present the well-known "horse-shoe shape" feature, which is characteristics of a transverse-wave-breaking regime (Bulanov *et al.*, 1998). In such a regime an uncontrolled particle trapping can occur, thus injecting electrons in the accelerating phase of the wake. The phase-space plot confirms this picture (see Fig. 3, where a line-out at the pulse propagation axis of the $z - p_z$ phase-space plot is shown). Despite the plasma wave is still in region I, i.e., no

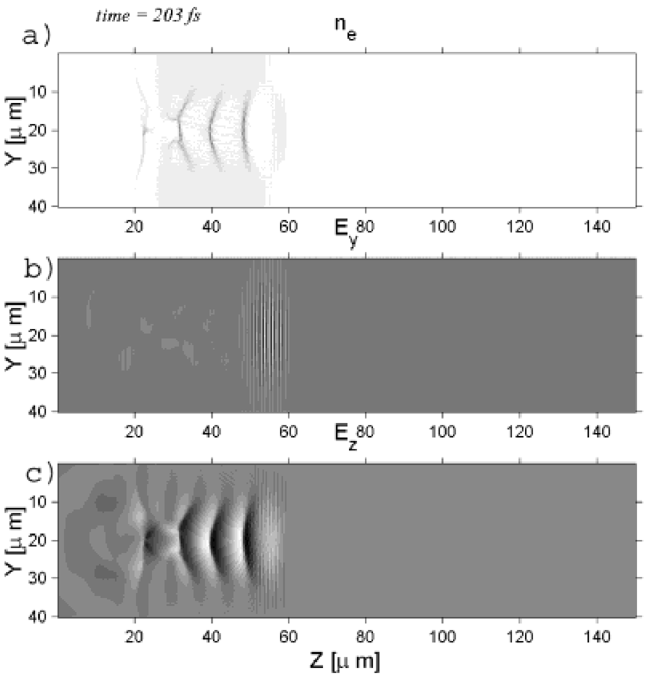

Fig. 2. *Simulation 1*. Snapshot at $t \simeq 200$ fs . The crests of the wake present an 'horse-shoe' feature. (a) Electron density. (b) Transverse electric field. (c) Longitudinal electric field.

longitudinal wave-breaking occurred yet, some particles have already been trapped by the wake and accelerated up to some MeV's.

In Figure 4 the density maps at times 220 fs (a), 260 fs (b), 340 fs (c), and 510 fs (d), are shown. At $t \simeq 220$ fs the first crest behind the pulse is starting to experience a partial breaking while it is crossing the density transition at $z =$

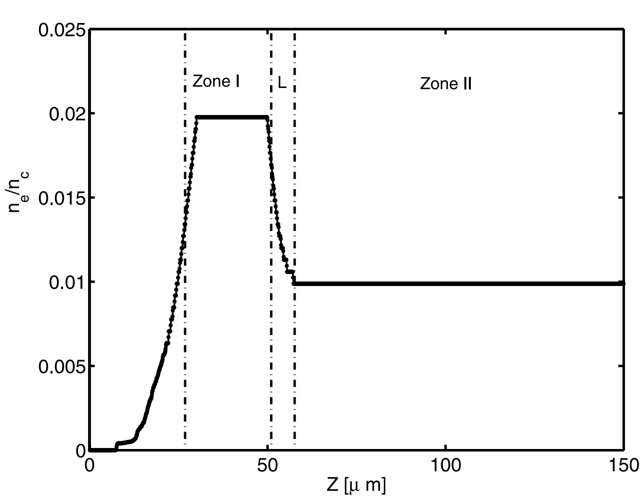

Fig. 1. Longitudinal line-out of the initial plasma electron density profile. The laser pulse will propagate from left to right.

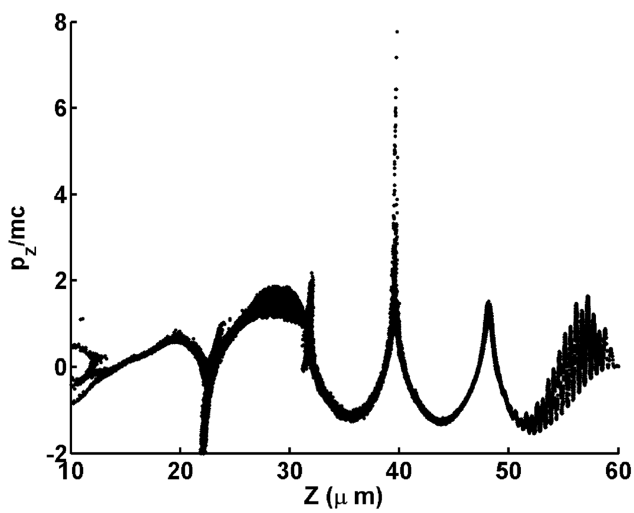

Fig. 3. *Simulation 1*. Snapshot at $t \simeq 200$ fs. Longitudinal phase-space plot $z - p_z$, showing the spurious trapping of particles, before the wake has crossed the density transition at $z = 50\ \mu$m, probably due to transverse wave-breaking.

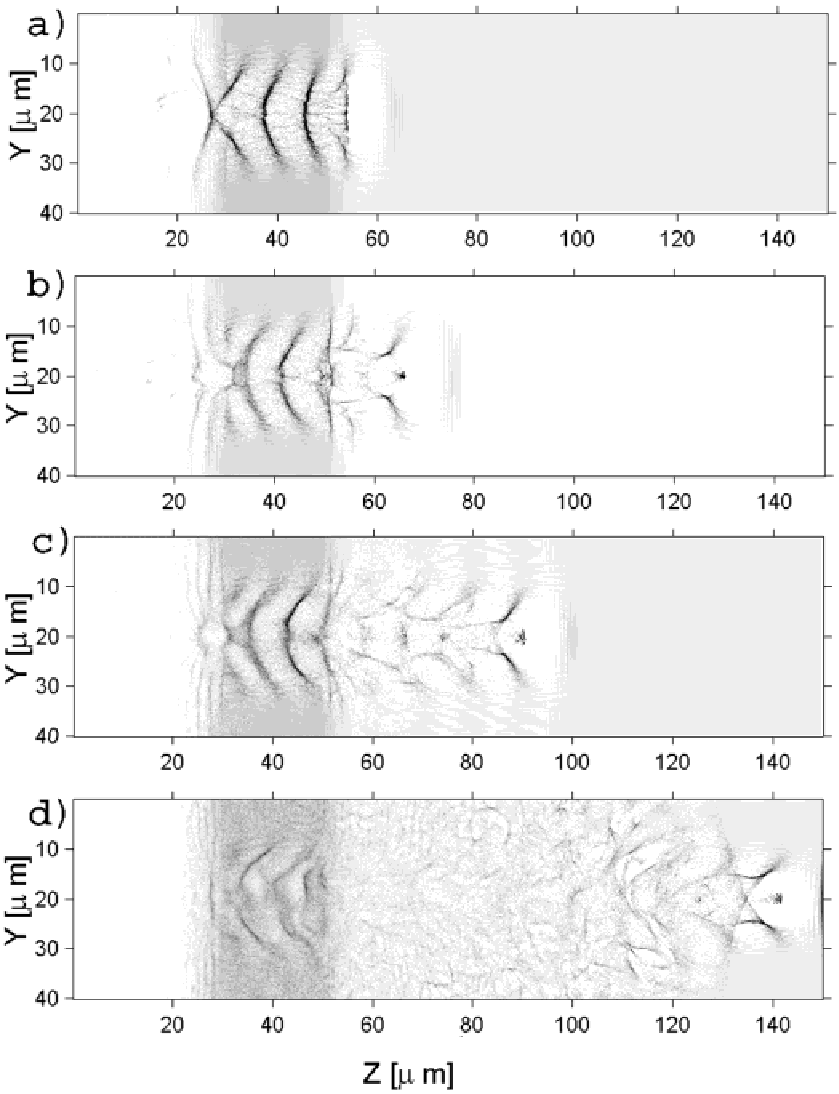

Fig. 4. *Simulation 1*. Electron density maps at $t \simeq 220$ fs (a), $t \simeq 260$ fs (b), $t \simeq 310$ fs (c) and $t \simeq 510$ fs (d).

50 μm. The trapped particles are then focused by the transverse wake electric field (see Fig. 4b) and accelerated. However, since the electron density in region II is lower than the one in region I, transverse wave breaking is more effective in destroying the regular wake behind the pulse (see Figs. 4c and 4d). At the final time of the simulation a set of bunches of accelerated particles, each one having a large energy spread, is found (see Fig. 5).

2.2. Simulation 2

In the second simulation the laser pulse peak intensity was $I_2 = 2.5 \times 10^{18}$ W/cm^2, corresponding to a normalized pulse amplitude $a_0 \simeq 1.3$. The value of the peak intensity was reduced in order to suppress the trasverse wave breaking process, which was responsible of the uncontrolled injection of particles and the degradation of the wake field quality in the first simulation. In Figure 6 a snapshot at $t \simeq$ 220 fs of the electron density (a), the transverse component

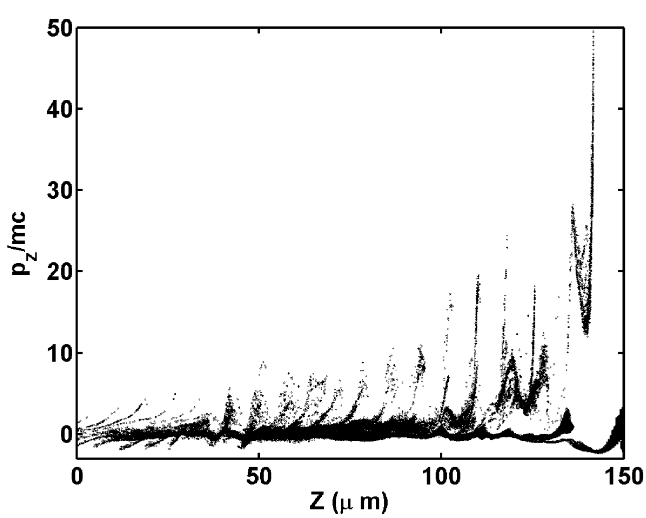

Fig. 5. *Simulation 1*. Snapshot at the final simulation time $t \simeq 510$ fs. Longitudinal phase-space plot $z - p_z$, showing the bunch of the most accelerated particles ($z > 130$ μm).

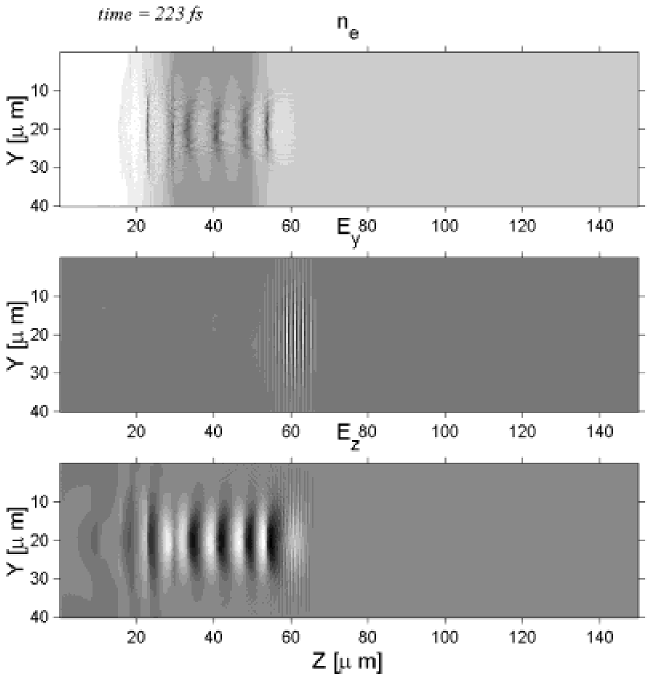

Fig. 6. *Simulation 2*. Snapshot at $t \simeq 220$ fs. The wave crests are now not curved and the first crest behind the pulse is as about to break while crossing the transition. (a) Electron density. (b) Transverse electric field. (c) Longitudinal electric field.

of the electric field (b), and the longitudinal electric field (c) is shown. Here the crests of Langmuir wave behind the pulse are not curved so that transverse wave breaking does not take place. The phase-space plot (see Fig. 7) confirms that no uncontrolled trapping of particles occurred yet.

At $t \simeq 240$ fs the crest behind the pulse is partially broken and about 10^8 electrons have been injected in the acceleration phase. The electron density map (see Fig. 8a) shows cusp-like structure developed at the density transition. The longitudinal phase-space plot (see Fig. 8b) confirms the trapping of particles at the density transition. We stress that no transverse effect is apparent, so that a pure longitudinal nonlinear wavebreaking occurred.

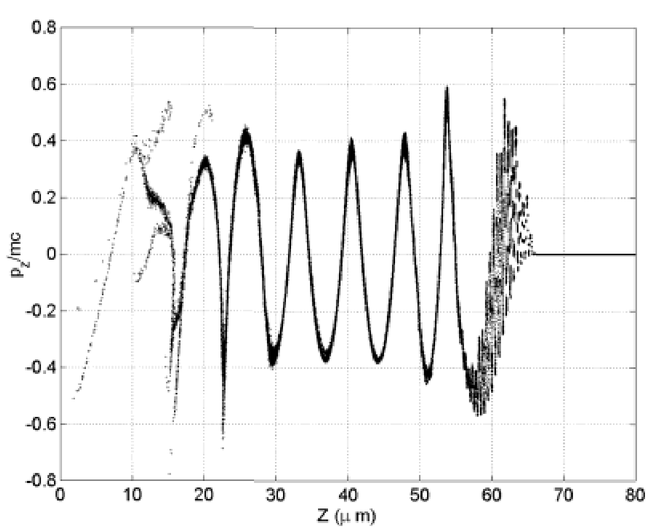

Fig. 7. *Simulation 2*. Snapshot at $t \simeq 220$ fs. Longitudinal phase-space plot $z - p_z$, showing that in this regime no spurious trapping occurred yet.

At the final simulation time $t \simeq 510$ fs the wake is regular still far beyond the pulse, even if an inverted curvature of the constant-phase lines due to beam loading developed (Fig. 9a and 9c). The trapped bunch is well localized in the phase-space plot, both longitudinally and transversally (see Fig. 10). The final energy spectrum consists of a narrow peak with energy spread $\Delta E/E \simeq 5\%$ full width at half maximum and a background containing a second bunch with a lower energy and beam quality (see Fig. 11). See Suk *et al.*, (2003) for a detailed discussion.

3. TAILORING THE PLASMA PROFILE WITH THE EXPLODING FOILS TECHNIQUE

A possible method to produce a plasma with an electronic density presenting a sharp downramp employes a couple of plastic thin foils, which explode by the irradiation with a heating laser pulse before the arrival of the femtosecond main pulse. We considered a heating pulse of duration 3 ns, peak intensity 1×10^{14} W/cm^2, wavelength 0.8 μm and focal spot of about 10 μm, counter-propagating with respect to the main pulse (see Fig. 12). The two parallel plastic foils are placed about 200 μm far away and have different thickness (0.2 μm for the first foil exploded by the pulse and left foil and 0.1 μm for the second one).

The simulation has been performed with the hydrodynamic eulerian code POLLUX (Pert, 1981) in 2D with azimuthal symmetry. The code does not take into account atomic physics processes, so we are forced to initialize the simulated system with two thin foils of completely ionized matter at solid density. After about 1 ns the arrival of the heating pulse peak the plasma electron density presents two plateaux separated by a very short scalelength transition ($L \approx 5$ μm), which is probably the effect of a shock caused by the collision between the expanding plasma regions of the rear side of the first foil and the front side of the second foil. The radial density profile is flat within a radius exceeding 30 μm.

As a result, a long acceleration region (about 500 μm) with a good flattness of the electron density, as well a density transition with a short scalelength, are obtained. The value of the electron density in the accelerating region is optimal for a laser pulse of duration not exceeding $\tau \simeq \lambda_{pe}/c \simeq 35$ fs, being $c = 0.3$ μm/fs the light speed.

4. CONCLUSIONS

We have presented 2D numerical simulations concerning the production of high quality electron beams by means of

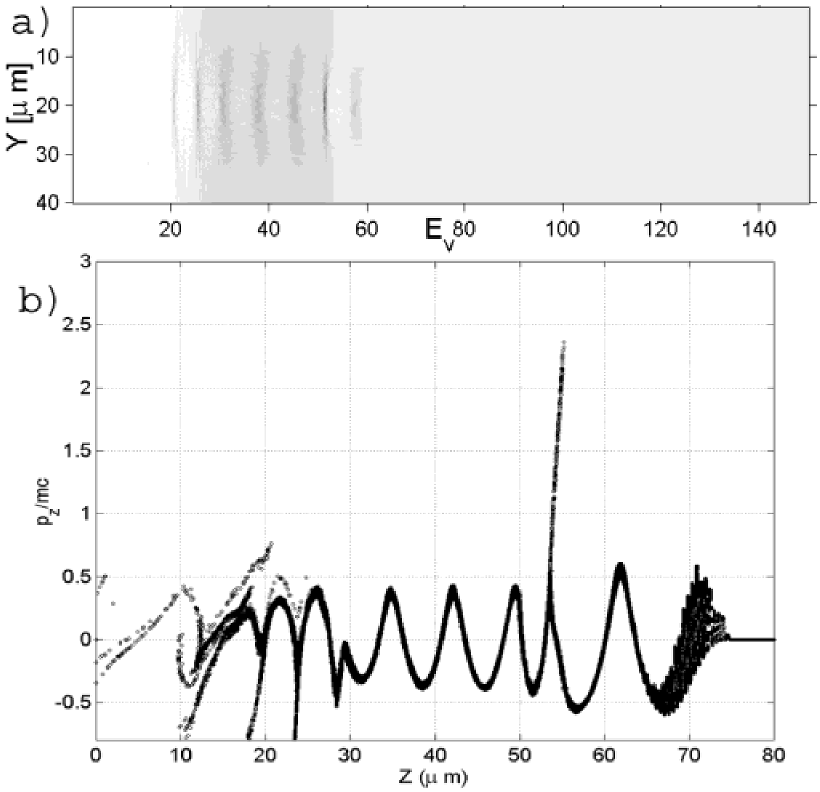

Fig. 8. *Simulation 2*. Snapshot at $t \simeq 240$ fs. A partial longitudinal breaking of the first crest occurred and about 10^8 electrons have been injected. (a) Electron density map. (b) Longitudinal phase-space plot.

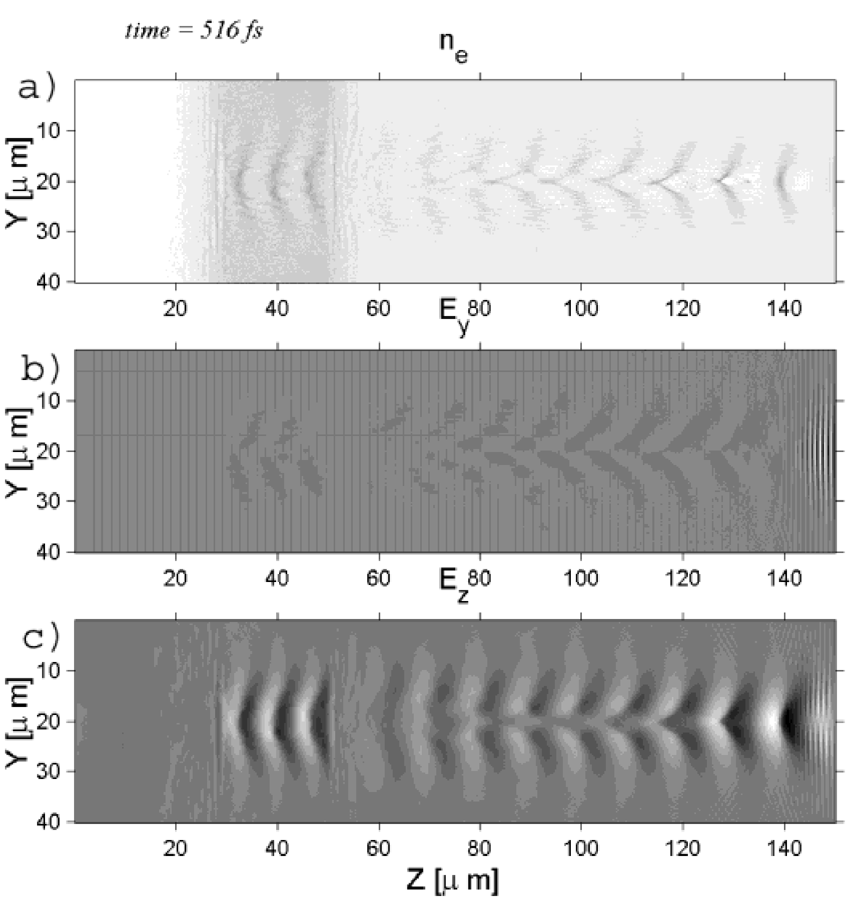

Fig. 9. *Simulation 2*. Snapshot at the final simulation $t \simeq 510$ fs. The wake field is regular, even if an inverted curvature of the wake crests due to beam-loading is apparent. (a) Electron density. (b) Transverse electric field. (c) Longitudinal electric field.

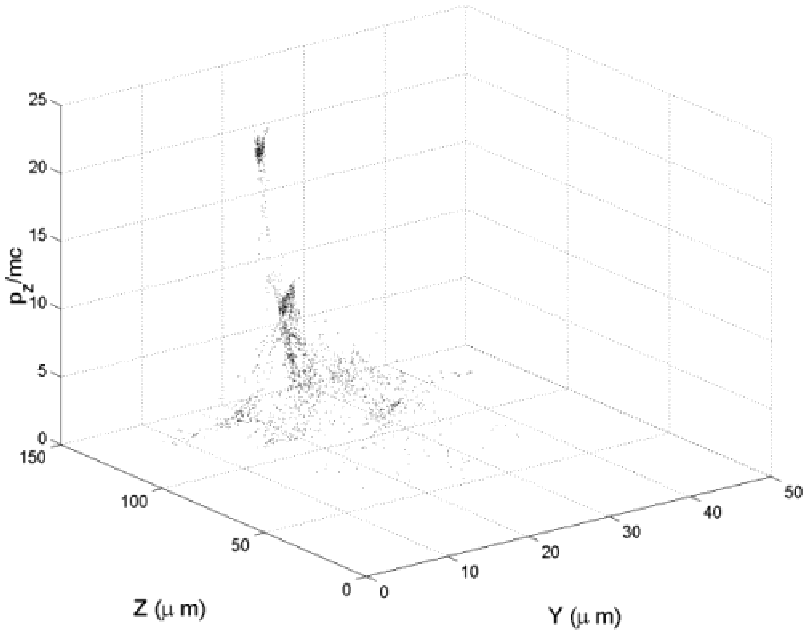

Fig. 10. *Simulation 2*. Snapshot at the final simulation $t \simeq 510$ fs. Phase space plot p_z *versus* (y, z), showing the production of a compact bullet of particles.

LWFA with controlled trapping obtained with a sharp electron density transition. Both the process of production of the tailored plasma profile and the femtosecond laser pulse interaction with the plasma have been studied with hydrodynamic and PIC simulations, respectively.

On the laser-plasma interaction side, we have reported the results of two runs, obtained with the H. Ruhl's code, differing by the laser pulse peak intensity. The first run was obtained with a relatively high intensity $I_1 = 1 \times 10^{19}$ W/cm^2 and the results showed that, despite the successful injection of particles at the density transition, such a high intensity regime enabled the developing of unwanted multidimensional features as transverse wave-breaking, which resulted in both wake field degradation and spurious injection of a sizable amount of particles. The final beam quality was poor.

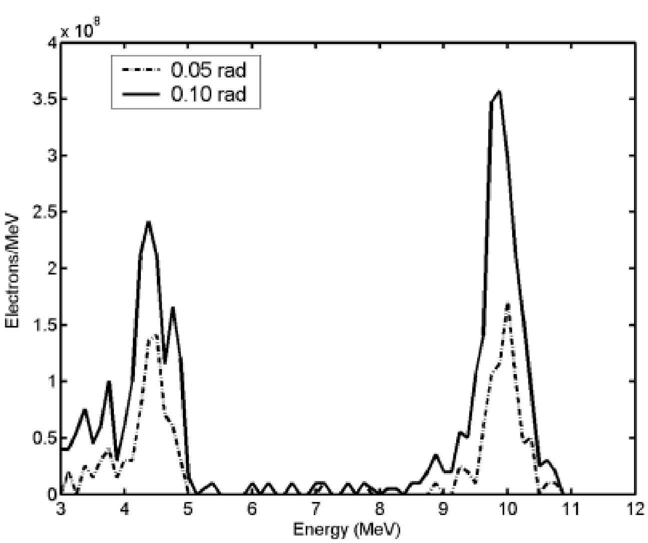

Fig. 11. *Simulation 2*. Final simulation time. Energy spectra of the accelerated particles, obtained with two angular acceptances of $\theta_M = 50$ mrad and $\theta_M = 100$ mrad.

In the second run a pulse with peak intensity $I_2 = 2.5 \times 10^{18}$ W/cm^2 was employed. Here transverse effects do not play a relevant role and a clear partial longitudinal wave-breaking at the density transition of the Langmuir wave was observed. The trapped particles were focused and accelerated by the electric field of the wake, which resulted much more regular than the one of the first simulation. At the final simulation time an electron beam with mean energy of 10 MeV and extremely good quality was produced.

An hydrodynamic simulation with the code POLLUX of the production of a preformed plasma with a suitable electron density profile is also reported. We simulated the explosion of a couple of plastic foils with different thickness. The results of the simulation show that the required plasma density profile can be obtained in this way.

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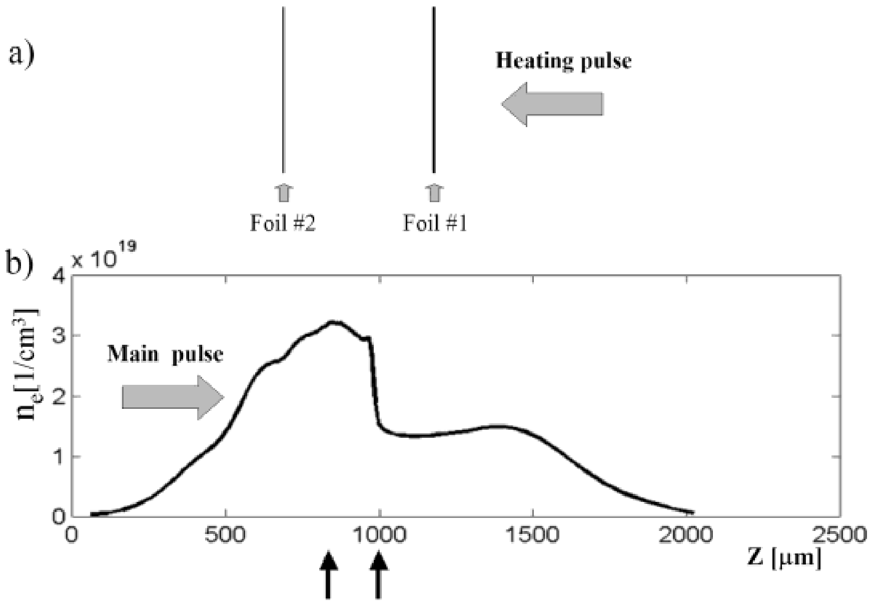

Fig. 12. Exploding foils production of the preformed plasma. (a) Setup. Two foils of thickness 0.1 μm (left) and 0.2 μm (right) are heated by a nanosecond pulse moving from right to left. (b) Results of the POLLUX simulation, showing the production of a preformed plasma suitable for controlled injection experiments. The arrows show the initial position of the foils.

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