NEAR-GEV ELECTRON BEAMS FROM THE LASER WAKEFIELD ACCELERATOR IN THE "BUBBLE" REGIME

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Abstract

This paper describes a 2D-PIC simulation of a laser wakefield accelerator in which an ultrashort, petawatt-class laser is focused and propagated through an underdense preformed plasma. We are looking at the phase-spaces of a large number of background plasma electrons that are accelerated to very high energies by the laser-induced plasma bubble. The result shows the possibility of generating a GeV-level electron beam in a few millimeters plasma size.

There are many interesting simulation and experimental studies for the generation of high-energy electron beams from the laser wakefield accelerator (LWFA) scheme [1]. In particular, electrons self-trapping in the self-modulated (SM) LWFA [2], forced laser wakefield (FLWF) [3] and several other acceleration schemes have drawn a great attention. In all these schemes, some background plasma electrons are self-trapped and gain high longitudinal momentum from the wake wave behind the laser pulse or from the laser pulse directly. As an important experimental example, an electron beam with a wide energy distribution from 0 to 200 MeV have been observed from the FLWF scheme [3] however, most of the electrons were in the low energy ranges and a very small number were in the high energy ranges. Such a 100 per cent energy spread was the weak point for e-beams produced from the laser-plasma interactions. Very recently [4] a breakthrough has been made in the electron beam generation from the LWFA; quasi-monoenergitic beams have been observed experimentally by a *careful* selection of parameters such as, plasma density, laser intensity and pulse duration, acceleration and dephasing lengths etc…. By quasi-monoenergitic, we mean a high quality electron beam having a fairly high charge (> 200 pC or so) and a small energy spread. In this section, we present a 2D simulation study [5] for the generation of near-*GeV*-energy electrons when an ultrashort petawatt-class laser interacts with underdense plasma. At such ultrahigh intensities, the laser wakefield accelerator is working in the so called "bubble" regime, which was recently observed in the simulations [6,7]. The main feature of the bubble regime is the generation of a dense bunch (of the order of 1nC) of ultrarelativistic electron beam. The plasma density plays a crucial role [8] in the formation of the bubble (cavity) and on the quality of the generated electron beam. For a laser pulse with intensity and pulse duration of 10^{20} W/cm^2 and 20 fs respectively, as the density increases beyond 10^{19} cm^{-3} the cavity breaks resulting in a low quality beam generation, therefore a lower plasma density is better. For our laser-plasma interaction simulations we use the OSIRIS code [9]. The simulation parameters are: laser power P = 500 TW [10] with pulse length τ = 40 fs ($L = c\tau$ = 12 μm), wavelength λ = 800 nm and focused intensity (in vacuum) $I = 3.1\times10^{20}$ W/cm^2. The plasma size was d = 2.5 mm long with a density of $n_0 = 8.1\times10^{18}$ cm^{-3} (so, the plasma wavelength, $\lambda_p \approx L$ = 12 μm). The plasma density ramps from 0 (vacuum) to n_0 within 100 μm then the density is kept uniform for about 2.4 mm. The laser pulse is initialized in vacuum then propagated through the plasma for about 20000 time steps (corresponding to 2.5 mm distance). Figures (1) and (2) shows simulation results after the laser has propagated through the plasma distances of 350 μm and 2.5 mm, respectively.

In Fig 1(a) the laser intensity parameter, defined as $a_0 = 8.6\times10^{-10}\lambda$ [μm] $I^{1/2}$ [W.cm^{-2}], has a value of 17. 6 while it were initialized in vacuum as a_0 = 12.2. This means that the laser pulse has experienced a well-known self-focusing effect through the plasma. Regular oscillating wakefield (with several cycles), which is typically produced in case of lower laser intensities, was not produced here. In such a high intensity regime, the laser's ponderomotive force pushes all plasma electrons surrounding the pulse (in front and on the sides of the pulse) and produces an ion cavity or "bubble" with no electrons inside.

Electromagnetic fields on the sheath (i.e. transverse fields) region are very strong so that they keep the bubble structure through the plasma. Approximate expressions for the fields inside the ion cavity can be found in Ref. [7]. Compressed cold electrons from the plasma fluid are self-injected longitudinally into the bubble and gain extremely high energies by the electrostatic field shown in Fig. 1b (the wakefield is normalized to the focused laser's electric field).

These electrons acquired energy (max.) of about 216 MeV up to this point as shown in Fig. 1(d). As the laser propagates further, the relativistic bubble also follows and moves at the group velocity of the laser pulse. Electrons

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are continuously accelerated to higher energies and a lot of fresh electrons enter the cavity from the left and they are also getting accelerated to high energies. After propagating 2.5 mm, Fig. 2, the leading electrons achieve a maximum energy of 772 MeV while a tremendous number of other electrons follow with energies from 0 through ~ 640 MeV.

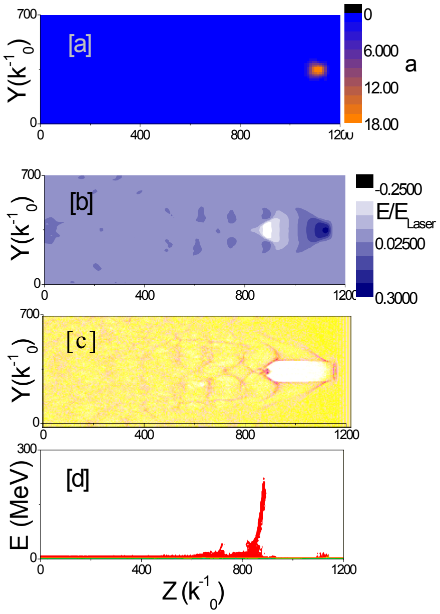

Figure 1: Simulation results after the laser has propagated a distance of 350 µm through the plasma; (a) the laser intensity parameter a_0; (b) wakefield produced as a result of the laser propagation; (c) plasma electrons spatial distribution inside plasma (d) phase space of the electrons energy distribution.

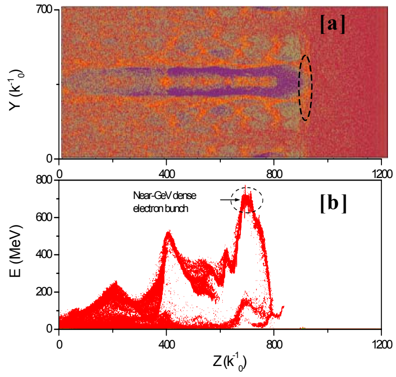

Figure 2: Similar to Fig. 1 (c)-(d) for a laser propagating 2.5 mm through a plasma having a density of 8×10^{18} cm^{-3}.

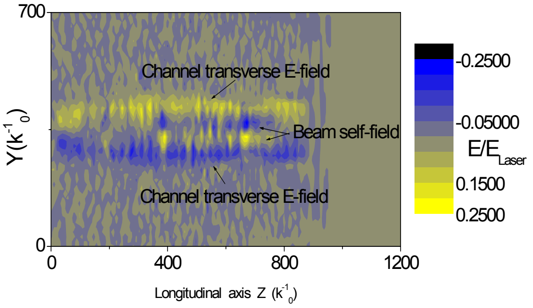

Figure 3: Transverse electrostatic field of the cavity and the self-fields of the ultrarelativistic electron beam.

Electrons with energy range 640-772 MeV (shown inside a circle in Fig. 2b) form a very dense bunch with a total charge exceeding 1 nC. This opens the door for applications that require ultrashort, high-brightness, near-GeV electron beams.

The plasma fluid continuously injects fresh electrons into the relativistic channel resulting in a huge amount of relativistic electrons. The bubble is elongated, Fig. 2a, as it propagates making a cylindrical ion channel with the accelerated electrons are moving on its axis. The channel's transverse fields and the beam self-fields are balanced, Fig. 3, so that the beam transverse size is kept almost constant. However, the beam seems to experience a slight Bennet pinch [11] in some regions where the self-fields are larger (due to high concentration of electrons) than the cavity transverse fields.

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laser system is currently under construction at GIST (Gwangju Institute of Science and Technology) in Korea and will be used for laser-matter interactions.

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