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Acceleration of electrons in the relativistic regime through multi-wave interactions

Z. -M. Sheng[1], K. Mima[2], J. Zhang[1], J. Meyer-ter-Vehn[3], D. Umstadter[4]

1. Institute of Physics, Chinese Academy of Science, Beijing 100080, China
2. Institute of Laser Engineering, Osaka University, Osaka 565-0871, Japan
3. Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
4. FOCUS Center, University of Michigan, Ann Arbor, Michigan 48109, USA

1. Introduction

Mechanisms leading to efficient acceleration of electrons in laser-plasma interactions are of fundamental interest and important for a variety of applications. A few mechanisms of laser-driven electron acceleration have been proposed, which can be classified as the plasma wave acceleration, laser acceleration with the assistance of additional fields or by the laser ponderomotive force, and mixed acceleration from both the longitudinal and transverse fields. In this paper, we show ways to make the efficient acceleration with the help of an auxiliary laser pulse in addition to a single pumping pulse, which accelerate electrons directly or indirectly through driving a plasma wave. A suitable auxiliary pulse can be used to amplify a plasma wave driven by the pump pulse, which we call the cross-phase-modulated laser wakefield accelerator (XM-LWFA) [1]. Such a pulse may also trigger the stochastic motion of electron in the pump pulse, which leads to efficient energy transfer from the pump laser to electrons directly [2]. In addition, electrons accelerated through stochastic heating and acceleration may be injected into a plasma wave for further acceleration [3].

2. Cross-phase-modulated laser wakefield accelerator

With the advent of ultrashort laser pulses, the laser wakefield accelerator (LWFA) is supposed to be an effective way to excite a large-amplitude plasma wave for particle acceleration. The required pulse parameters to resonantly excite such a plasma wave are generally, however, still not easy to access. A variation of the laser wakefield accelerator verified experimently is the self-modulated laser wake-field accelerator (SM-LWFA). In the SM-LWFA, the plasma wave is generated through a self-modulation process of a relatively long pulse, which is usually coupled with forward Raman scattering. For the plasma wave to grow up to a high level, a time scale for forward Raman scattering $\sim(\omega_0/\omega_p^2)\gamma_0^2/a_0$ is necessary. In this case, the corresponding spatial extension is usually larger than the Rayleigh length in tenuous plasma. Therefore a guiding channel for the laser pulse is necessary.

We introduce a new scheme to generate high amplitude wake field up to wave-breaking amplitude by use of two laser pulses only at modest intensities. The pump pulse is an ultrashort laser pulse shorter than a plasma oscillation period, which produces a seed wake-field. The secondary pulse is relatively long pulse, such as a few plasma oscillation periods. During propagation, the second pulse is cross-phase-modulated by the seed wakefield, and is split up into a multi-pulse train [1], where each sub-pulse has duration close to a plasma oscillation period. This pulse train then in turn amplifies the seed wake-field up to high levels. This process can occur in a time scale much shorter than the forward Raman scattering, and there is no necessary for particular timing between the two pulses. Compared with the standard LWFA and SM-LWFA, the XM-LWFA allows for fast energy transfer from laser pulses to plasma waves.

Figure 1 is an example showing the evolution of the laser pulse and the excited plasma wave particle-in-cell (PIC) simulation. It shows that the second pulse is strongly modulated by seeding plasma wave excited by the pump pulse. When it splits into a multi-pulse train, it amplifies the seeding plasma wave up to a high level until wave-breaking sets in. Once the wave-breaking occurs (at about t=600τ_0 in this example), the resulting energetic electrons inject into the unbroken region of the plasma wave and get further accelerated at later time.

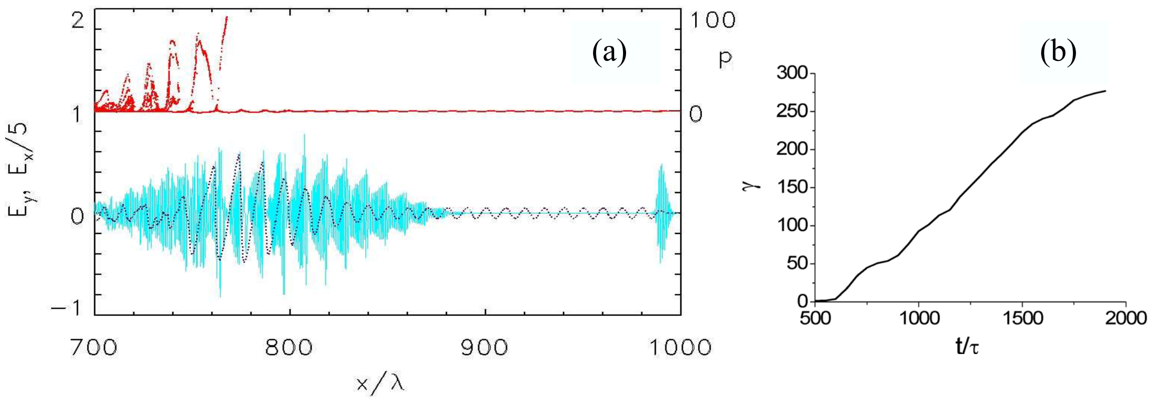

Fig. 1 1D PIC simulation showing the snapshot of the laser field , the longitudinal field, and the longitudinal momentum at t=1000τ_0 (a), as well as the maximum energy of electrons as a function time found in the simulation box (b). Both the pump pulse and the auxiliary pulse are in sine^2 profile and are with same peak amplitude at a_0=0.5. The full duration of the two pulses are 10 and 200 laser cycles, respectively.

3. Stochastic heating and acceleration

It was found earlier from particle-in-cell (PIC) simulations that, when an intense laser pulse with a slowly rising front propagates in underdense plasma, electrons can be accelerated significantly far beyond the ponderomotive potential level of the incident pulse. Meanwhile, the excited plasma wave remains at a very low level. Later it is found that there exists direct laser acceleration inside a self-focusing channel [4]. When a betatron resonance condition is satisfied, efficient energy exchange between laser and electrons is found. On the other hand, in many 1D simulations where the betatron resonance is excluded, significant acceleration of electrons is found while the electron plasma wave is not highly excited. This suggests that additional mechanisms exist in the interaction. Actually, it has been found that very efficient acceleration by the intense laser pulse also occurs in the presence of a *transverse* stochastic field [5]. The oscillation energy of electrons inside the laser pulse can be unlocked by the stochastic perturbations. The essential role of the perturbations is not to heat the electrons directly, but to dephase the electrons and thereby to allow for net energy transfer. Recently we find that the Raman backscattered wave can serve as the transverse stochastic field [2]. Moreover, we find that another counter-propagating laser field with a small amplitude can play a similar role as the stochastic perturbations in dephasing the electrons.

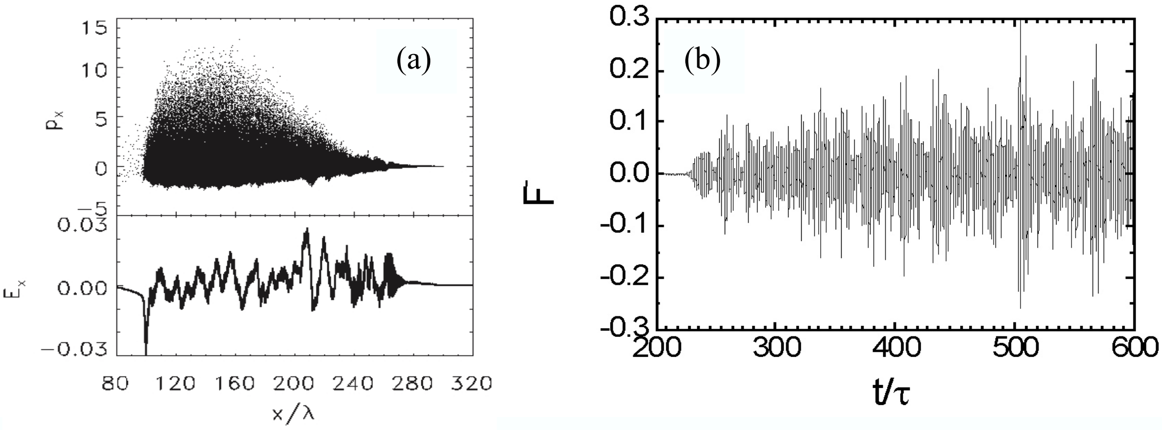

Fig. 2 An example of 1D simulations where a semi-infinite laser pulse with a peak amplitude a_0=3.0 interacts with a plasma slab, which has a length of 200λ and is with a density of n_0/n_c=0.01. (a) The longitudinal phase space of electrons and the longitudinal electric field; (b) The Raman backscattered wave of the incident pulse.

4. Laser injection of electrons into wakefields

The laser injected laser accelerator (LILAC) is a scheme to inject electrons into acceleration phase of high amplitude plasma waves, which is supposed to be able to obtain energetic electron beams with low energy spread [6].Usually two laser pulses are employed, one is the pump pulse to generate the wake field and another is injection pulse which intersects the wake to inject electrons through its ponderomotive force. Appropriate timing between the two laser pulses is necessary so that the injected electrons located in the acceleration phase of the wake field. Other injection schemes are also proposed.

Recently laser injection of electrons through stochastic heating in intersecting pulses has been suggested [3]. Electrons pre-accelerated in this way are injected into plasma waves and accelerated further. The laser pulses adopted are relatively long such as a few hundred femtoseconds and the plasma wave are excited in SM-LWFA regime. In the following, we give an example to show how intersecting pulses can serve to inject electrons into plasma waves. One first launches an intense pump laser pulse to excite a large amplitude plasma wave, and then another two pulses intersecting each other at some place behind the wake field to produce injecting electrons. In this simulation, the pump pulse has a peak amplitude of a_{10}=1.6, a duration about 10 laser cycles at FWHM, and a focus diameter of 16 laser wavelengths. The unperturbed electron density is 0.0025n_c. The two injection pulses are all with the peak amplitude a_{20}=a_{30}=1, pulse durations of 5 laser cycles, and focus diameters of 10 laser wavelengths. The two injection pulses cross each other at some position where the electron density is the minimum in the wakefield. At this position, electrons need the minimum energy for being trapped by the plasma wave for acceleration. Some electrons located just behind the injection pulses around x=155λ are trapped in the large amplitude plasma wave and accelerated up to about 10MeV at the end of this simulation. These electrons have good directionality and small energy spreading. To confirm that the observed electron injection is due to the crossing-beam interaction rather than the ponderomotive force injection, we conduct another simulation with only a single injection beam. No trapped electron is found in the wakefield, suggesting that electron injection does not occur in this case.

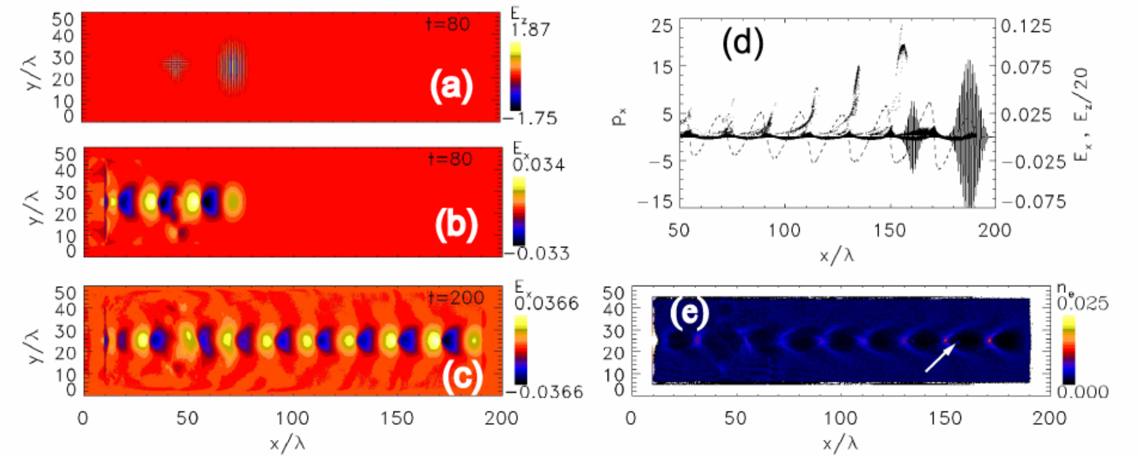

Fig. 3 Example showing electron injection by two intersecting laser pulses. (a) Snapshot of the electric field components of laser pulses at the time when the injection pulses are crossing each other; (b) and (c) snapshots of the excited wakefield; (d) The longitudinal phase space of electrons; (e) Snapshot of the electron density at t=200τ_0, where the white arrow points to trapped electrons near (x,y)=(25λ,155λ) where the electron density is higher than the surrounding region.

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