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Simulation studies of laser wakefield acceleration based on typical 100 TW laser facilities*

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Abstract: In this paper, 2-D Particle-In-Cell simulations are made for Laser Wakefield Accelerations (LWFA). As in a real experiment, we perform plasma density scanning for typical 100 TW laser facilities. Several basic laws for self-injected acceleration in a bubble regime are presented. According to these laws, we choose a proper plasma density and then obtain a high quality quasi-monoenergetic electron bunch with a rms energy of more than 650 MeV and a bunch length of less than 1.5 μm.

Key words: LWFA, self-injection, bubble, OOPIC, typical 100 TW laser facilities

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1 Introduction

It has been more than 30 years since Tajima and Dawson proposed using laser pulses to excite large plasma waves for electron acceleration [1]. Since then, the laser plasma accelerator has aroused great interest from the accelerator community for its extremely high accelerating gradient. Ionized plasmas can sustain plasma electron waves with longitudinal electric fields on the order of the non-relativistic wave breaking field, $E_0 = cm_e\omega_p/c$, or $E_0[\mathrm{V/cm}]=0.96n_0^{1/2}[\mathrm{cm}^{-3}]$, where $\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$ is the electron plasma frequency and n_0 is the ambient electron density [2]. For example, if $n_0=1\times10^{18}$ cm^{-3}, we can obtain a peak accelerating field of $E_0 \approx 100$ GV/m, which is 2–3 orders of magnitude greater than traditional accelerators using RF accelerating structures.

Plasma-based accelerations have made amazing progress in recent 10 years. One of the most important reasons is the rapid development of laser facilities. Ultrashort (<100 fs) and ultraintense ($>10^{18}$ W/cm^2) laser pulses can easily be acquired in many laboratories. For example, the Xtreme Light III (XL-III) is a typical multi-hundred TW laser system at the Institute of Physics, Chinese Academy of Science (IoP, CAS), which can produce a compressed 11 J/31 fs output pulse every twenty minutes, with a corresponding peak power of 355 TW [3]. In such condition, the requirement of laser wakefield acceleration (pulse length<plasma wave length) and self-focusing ($P > P_c[\mathrm{GW}]\approx17(\omega/\omega_p)^2$) can be satisfied. Since the laser-plasma interaction is highly nonlinear and relativistic at this time, it is so complicated to find an analytical solution that we have to introduce particle simulations as an aid. We used a two-dimensional PIC code called OOPIC for our investigation [4].

The rest of this paper is organized as follows: in Sec. 2 we introduce OOPIC and several other existing PIC codes for simulating laser-plasma/beam-plasma interactions; in Sec. 3 we give a simple description of the theoretical background, such as LWFA, bubble regime, self-injection etc.; in Sec. 4 several simulation results are presented and a brief conclusion is shown in the last section.

2 Object-oriented particle in cell→ OOPIC

OOPIC was co-developed by the University of California, Berkeley and the Tech-X Corporation[2)].

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2) The code we used was OOPIC pro, version 1.2.0. This simulation code was originally developed at the University of California at Berkeley, beginning in 1995, by members of the Plasma Theory and Simulation Group (PTSG). Since 1998, Tech-X Corporation has been working in collaboration with PTSG staff to improve and generalize the XOOPIC physics kernel.

It is an object-oriented fully explicit two-dimensional relativistic electromagnetic particle-in-cell code written in C++ and can simulate many physical systems including plasmas, beams of charged particles with self-consistent and externally generated electric and magnetic fields, low-to-moderate density neutral gases and wide variety of boundary conditions [4]. It has electrostatic and electromagnetic field solvers for 2D geometries in both x-y (slab) and r-z (cylindrical) coordinates, and includes Monte Carlo collision and ionization models. The code can also run on parallel machines by using a Message Passing Interface (MPI).

There are several other PIC codes besides OOPIC, including VORPAL [5] (fully explicit, multi-dimensional, also written in C++ and successfully benchmarked against OOPIC [6]), OSIRIS [7] (fully explicit, multi-dimensional, fully relativistic, parallelized PIC code and written in FORTRAN95), QuickPIC [7] (3-D, fully relativistic and parallelized PIC code with high efficiency by introducing quasi-static approximation and well benchmarked against conventional full explicit code [8]), etc.

3 Theoretical backgrounds

When an ultrashort and ultraintense laser pulse propagates into underdense plasmas, ponderomotive force can push the plasma electrons away from the axis. Meanwhile, due to their larger mass, the ions are hardly moved and exert restoring forces to draw the electrons back. An ultrahigh longitudinal electric field is then generated due to the imbalance of the electrons and ions. This electric field always follows the drive beam (the so called “wakefield”) with a phase velocity that equals the drive beam's group velocity, $v_{\rm p} = v_{\rm g} = c(1-\omega_{\rm p}^2/\omega^2)^{1/2}$, where ω is the laser frequency. Electrons at proper phases, either background or externally injected, can be continuously accelerated by this field until they outrun the plasma wave and move into the decelerating phase region. In order to obtain high quality (high energy, low energy spread, large charge) beams, we face the following three problems [9]:

1) How can we produce a strong and stable accelerating field?

Research has proven that using a single ultrashort ultrahigh intensity laser pulse as a drive beam is the best and simplest way, both theoretically and experimentally. Plenty of the instabilities that occur during the propagation can be constrained for the comparatively short length of the drive beam.

2) How can we capture enough electrons?

There are several ways to “inject” the electrons into the plasma wave, such as wave-breaking injection [1, 10], blow-out/bubble injection [11, 12], external injection [13], optical injection [14], density transition injection [15], etc. Optical injection and density transition injection are complicated for an experimental setup and with regard to the technique today it is hard to externally inject the charged particles into a plasma wave with the wavelength of only several millimeters. In addition, wave-breaking injection can hardly obtain mono-energetic bunches. Considering all these problems, bubble injection is the most practical way; although it has some drawbacks in stability and reproducibility. It is actually used in most experiments at present which successfully generate high energy mono-energetic electron beams. Kostyukov and Pukhov did detailed research on this area and found that the electrons can be captured when $p_x \geqslant v_0\gamma_0^2$, where v_0 is the bubble velocity and $\gamma_0 = (1-v_0^2/c^2)^{-1/2}$ is the relativistic factor of the bubble [11].

3) How can we extend the efficient accelerating length as long as possible?

There are three characteristic lengths in LWFA, namely dephasing length ($L_{\rm deph}$), diffraction length ($L_{\rm diff}$) and pump depletion length ($L_{\rm pd}$) [2, 9, 16]. We can estimate them as follows:

$$L_{\rm deph} \approx \frac{\lambda_{\rm p}/2}{c-v_{\rm ph}}c = (\omega_0^2/\omega_{\rm p}^2)\lambda_{\rm p}\begin{cases}1 & (a_0^2\ll 1)\\ 2a_0/\pi & (a_0^2\gg 1)\end{cases}, \tag{1}$$

$$L_{\rm diff} = \pi Z_{\rm R} = \pi^2 w_0^2/\lambda_0, \tag{2}$$

$$L_{\rm pd} \approx E_{\rm L}^2 L/E_z^2 = (\omega_0^2/\omega_{\rm p}^2)\lambda_{\rm p}\begin{cases}a_0^{-2} & (a_0^2\ll 1)\\ a_0/3\pi & (a_0^2\gg 1)\end{cases}, \tag{3}$$

where $a_0 = (2e^2\lambda^2 I/\pi m_{\rm e}^2c^5)^{1/2} \approx 8.6\times10^{-10}\lambda[\mu\rm m]\ I^{1/2}$ [W/cm^2] is the laser strength parameter. $Z_{\rm R}$ stands for the Rayleigh length and w_0 is laser focal spot radius. For typical 100 TW laser facilities, a_0 is usually more than 3.

The efficient accelerating length $L_{\rm acc}$=min ($L_{\rm deph}$, $L_{\rm diff}$, $L_{\rm pd}$) is limited by all these three parameters. From the above expressions we can easily increase $L_{\rm deph}$ and $L_{\rm pd}$ by using lower plasma density and higher laser intensity if $a_0 \gg 1$. However, if we fix the peak power of a laser, since $a_0 \propto I^{1/2}$ and $I \propto w_0^{-2}$, we should use a lower laser intensity to obtain a longer dephasing length. It seems we face a dilemma. Fortunately, we still have some alternative ways to increase $L_{\rm diff}$, such as guiding lasers by preformed plasma channels [17].

In summary, based on the presently available techniques, one ultrashort ultrahigh laser pulse according with bubble mode self-injection and preformed plasma channel is the most practical scheme to obtain GeV monoenergetic electron bunches in LWFA experiments. In the next section, we will focus on the bubble formation and self-injection process. The preformed plasma channel simulation is not included in this paper.

4 Simulation results

In our simulations, laser pulses are linearly polarized in z-direction and launched into underdense plasmas from $x=0$ plane with transverse and longitudinal Gaussian profiles. In the 2-D Cartesian coordinates, the simulation box is 100 μm in x-direction and 80 μm in y-direction and meshed into 2500×400 cells which gives dx=λ/20. The laser pulses have amplitude and duration variations with a fixed wavelength λ=800 nm. The power of the pulses is 100 TW and focuses on a 15 μm spot, which gives I=2.83×10^{19} W/cm^2 and $a_0=3.68$. To avoid edge effects, laser pulses are launched into a vacuum region of 10 μm following a rise density of 90 μm and then a flat density region. The moving window technique is also used in our simulations.

Figure 1 shows the typical density distributions and evolutions of the bubble regime. The wakefields behind the laser pulse take the form of a solitary cavity, which is free from plasma electrons. The cavity is surrounded by a high density sheath of compressed electron fluid. Later, a beam of accelerated electrons is trapped from the sheath and injected into the bubble. When more and more electrons are trapped, the self-injection will be closed due to beam loading effects. Meanwhile, the captured electrons will be continuously accelerated until dephasing occurs.

In our simulations we fix the laser's parameters and change the plasma density, as in a real LWFA experiment, then we get relations between bunch quality and plasma density so as to find a matched condition for a typical 100 TW laser facility. Fig. 2 shows that:

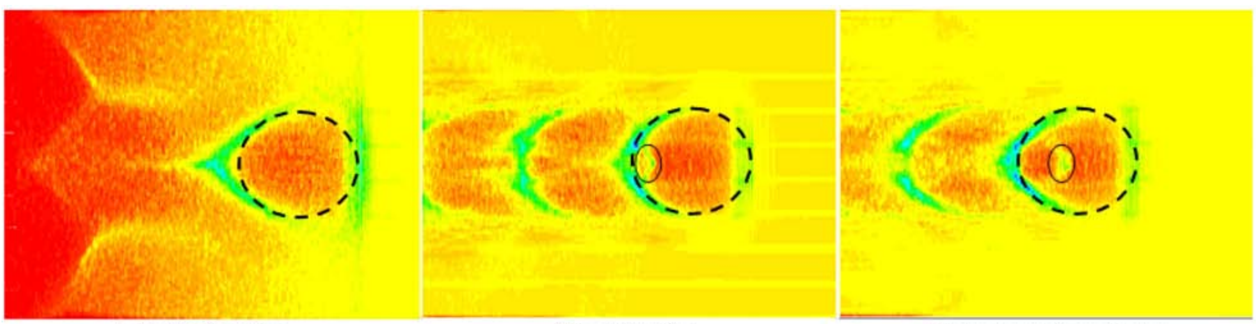

Fig. 1. On-axis cuts of the electron density n_e in the x-y plane from PIC simulation at the time when the laser travels a) t=100 μm/c; b) $t=250$ μm/c; c) $t=500$ μm/c. The laser we used here is 30 fs, 100 TW and focus on a 15 μm spot, the plasma density is 3×10^{18}cm^{-3}.

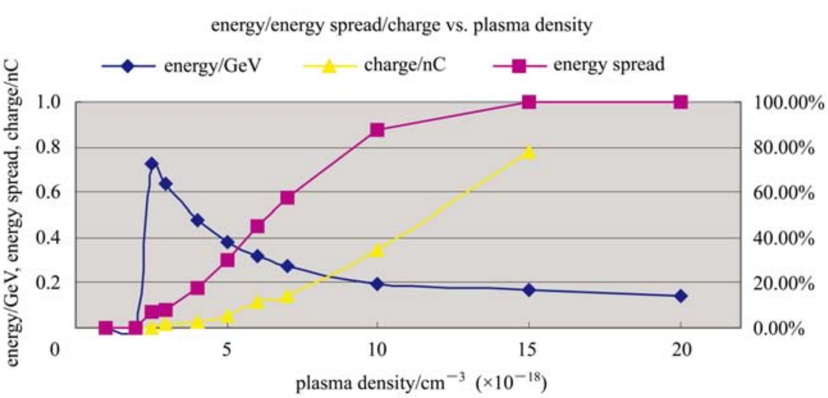

Fig. 2. Plasma density scanning for 100 TW, 30 fs laser facilities, the unit for plasma density is 10^{18} cm^{-3}.

We can get some important conclusions from Fig. 2:

1) As the plasma density increases, the energy of the captured bunch decreases. It can easily be explained by simple theoretical analysis. As shown in Eqs. (1) and (3), the dephasing length and the depletion length are proportional to $n_{\rm p}^{-3/2}$ while the wakefields are proportional to $n_{\rm p}^{1/2}$. So we can estimate the energy of the captured particles linearly by $E_{\rm gain} \approx E_{\rm acc} \times L_{\rm acc} \propto n_{\rm p}^{-1}$.

2) But on the other side, the number of the captured electrons is related to the plasma density. The higher the density is, the more the electrons can be self-injected. When the plasma density is lower than 2×10^{18} cm^{-3}, no electrons can be captured at all. It can be inferred that there is a plasma density threshold $n_{\rm th}$ for a given laser system. When the plasma densities $n_{\rm p} < n_{\rm th}$, the electrical field in the plasma is not big enough to produce wavebreaking, then no self-injection happens. Using the nonlinear relativistic cold fluid equations in 1-D, we can obtain the maximum amplitude of a plasma wave, which is given by:

$$E_{\rm WB} = \sqrt{2(\gamma_{\rm p}-1)}E_0, \tag{4}$$

where $\gamma_{\rm p} = (1 - v_{\rm p}^2/c^2)^{-1/2}$ is the relativistic factor associated with the phase velocity of the plasma wave. Considering the multi-dimension effect, the wavebreaking threshold in the simulation and the experiment is much less than theoretical result. In our simulation $n_{\rm th}$=2.5×10^{18} cm^{-3}, $E_{\rm th}$≈0.29 $E_{\rm WB}$, which agrees with Bulanov's results [10].

3) Another conclusion we draw from Fig. 2 is that the energy spread is increasing rapidly with the growth of the plasma density. This is because higher plasma density leads to shorter plasma wavelength, which means the longitudinal electric fields felt by the head particles of the bunch are quite different from the tail ones. On the contrary, the difference is not so huge at lower plasma densities.

To compromise all these restrictions, we recommend that a lower plasma density (but a little higher than $n_{\rm th}$) be chosen if we focus on beam energy and energy spread and higher plasma density chosen if we care more about the bunch charge. Fig. 3 shows a good result for the first case. In a real LWFA experiment, we should use a higher plasma density first in order to find the electrons and test the diagnostic systems and then lower the plasma density step by step to optimize the bunch quality.

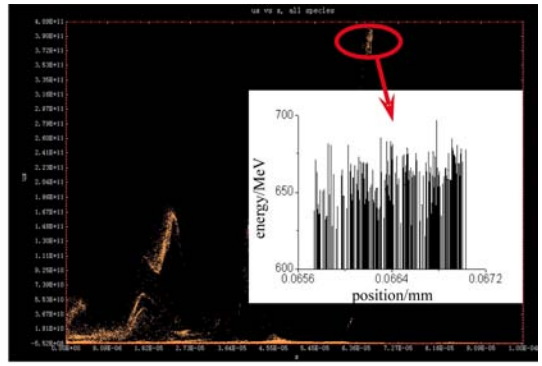

Fig. 3. Energy spectrum of electrons @ t= 3.5 mm/c and $n_{\rm p}$=3×10^{18} cm^{-3}.

As seen in Fig. 3, we select a plasma density of 3×10^{18} cm^{-3} and get an electron bunch with the rms energy of 656 MeV and rms energy spread of ±6.61% at t_1 ≈3.5 mm/c. The charge of this bunch is about 15.4 pC, the rms bunch length is about 1.3 μm and the emittance is about 0.3 πmm·mrad. As time goes on, the longitudinal fields are changed because of the breakdown of the bubble structure. Most particles in the bunch are decelerated for dephasing and only a few particles (∼0.5 pC) are continuously accelerated to 1 GeV at t_2 ≈6.5 mm/c. The average efficient accelerating field is about 190 GV/m.

5 Summaries and conclusions

The 2-D PIC simulation results for a self-injected LWFA experiment are shown. We have performed plasma density scanning for typical 100 TW laser facilities by using a new code named OOPIC. According to our simulations, the optimum plasma density for such laser facilities should be controlled from 3×10^{18} cm^{-3} to 6×10^{18} cm^{-3}. A short (<5 fs) and high energy (>650 MeV) electron bunch with the charge of 15 pC and a small energy spread (<7%) is obtained then. We compare these simulation results with the experiment in CAEP in 2006 [18].

Table 1. Comparison of the simulation and the experiment parameters.

	laser				plasma	beam			
	λ/nm	P/TW	$w_{0x,y}$/μm	τ/fs	$n_{\rm p}$/cm^{-3}	energy/MeV	Q/pC	energy spread(%)	emittance
Exp.	785	140	21×13	27	3×10^{18}	560	/	1.2	0.1 πmm·mrad
Sim.	800	100	15×15	30	3×10^{18}	656	15.4	6.67	0.3 πmm·mrad

As Table 1 shows, the laser parameters in the experiment are similar to our simulations. The energies of the output beam in the experiment and in the simulation are also close. Due to the complexities of the laser-plasma interaction, some of the results from the experiment do not agree well with the simulations. However, from a matching point of view we believe that using plasmas with a density of about 3×10^{18} cm^{-3} for a typical 100 TW laser system is proper.

In our simulations, we also observe that the captured bunch may execute remarkable betatron oscillations during its longitudinal accelerations. These betatron oscillations draw widespread interest for their X-ray radiation capabilities, which need more detailed studies and further investigations in the future. In addition, we also want to carry out more investigations on the effects of the laser parameters on beam qualities in the near future.

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