Optimization of moderate-power laser pulse interaction with plasmas using quasistatic simulations

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Introduction

The wakefield acceleration of particles in plasmas is now a hot research topic [1,2]. The electric field amplitude in plasma waves is several orders of magnitude greater than that achievable in conventional radio-frequency structures. This property makes it possible to create compact electron and radiation sources for scientific and commercial applications [3, 4]. Strongly nonlinear wakefields in the so-called bubble regime [5] can trap and accelerate plasma electrons, giving laser drivers the advantage of operating without an external electron source [6].

Numerical simulations are an important part of the research [7]. However, simulations from first principles are computationally demanding, so effective simplified models are widely used along with them. One of these models is the quasistatic approximation (QSA) [8], which significantly reduces computational costs compared to full particle-in-cell (PIC) simulations. Unfortunately, this approximation does not take into account plasma electron trapping, and further development of the model is needed.

In this paper, we use a combination of QSA and PIC codes for fast parametric optimization of some experimental scenario. We briefly review the QSA model and possible ways to extend it for taking into account the trapping of plasma electrons by the wakefield. We then optimize the interaction of a moderate-power laser pulse with the plasma using a modified version of QSA code LCODE [9, 10] and verify the results with PIC code FBPIC [11].

Quasistatic approximation

The quasistatic approximation is based on the huge difference in the evolution times of the plasma and the driver. Plasma layers encountered by the drive beam over some extended interaction length behave similarly. We can neglect driver changes at this length and assume that the plasma response depends on time t and longitudinal coordinate z only in their combination $\xi = z - ct$, where c is the speed of light. Thus, it is sufficient to calculate the plasma response only once for this driver state. Once calculated, the plasma fields are used to update the driver state before entering the next path fragment.

This model neglects interactions between adjacent plasma layers, which is acceptable for many problems, but not for the electron trapping. However, the charge of trapped electrons may be small and insufficient to perturb the plasma wave [1]. In this case, we can consider such particles as a small perturbation to QSA and calculate their trajectories using the full equations of motion. To identify which particles might be trapped, we track the energy and radial position of plasma electrons. This method was proposed in Ref. [12] along with the following thresholds for considering particles as potentially trapped: $\gamma > 1.2$ and $r < 0.15k_p^{-1}$, where γ is the relativistic factor of electron, r is the radial position, and k_p^{-1} is the plasma skin depth. A QSA code with this modification can quickly scan interaction regimes to find the onset of trapping.

Parameter optimization

Consider a laser pulse with a wavelength 810 nm, duration 12 fs, waist 14 μm, and energy 300 mJ that interacts with a 1 mm long plasma with a linear density rise over the first 50 μm, a uniform density over 900 μm, and a linear decrease over the last 50 μm [13]. We study the effect of plasma density and laser focus point position on electron beam formation from the plasma, its charge and energy.

The plasma density must be high enough for the laser pulse to remain focused along the entire interaction length. However, the electron beam is formed in the plasma with a density at least twice the density required for nonlinear self-focusing of the laser pulse (Fig. 1), which is about $2 \times 10^{18}\,\text{cm}^{-3}$ for the given parameters. The energy of accelerated electrons increases with the

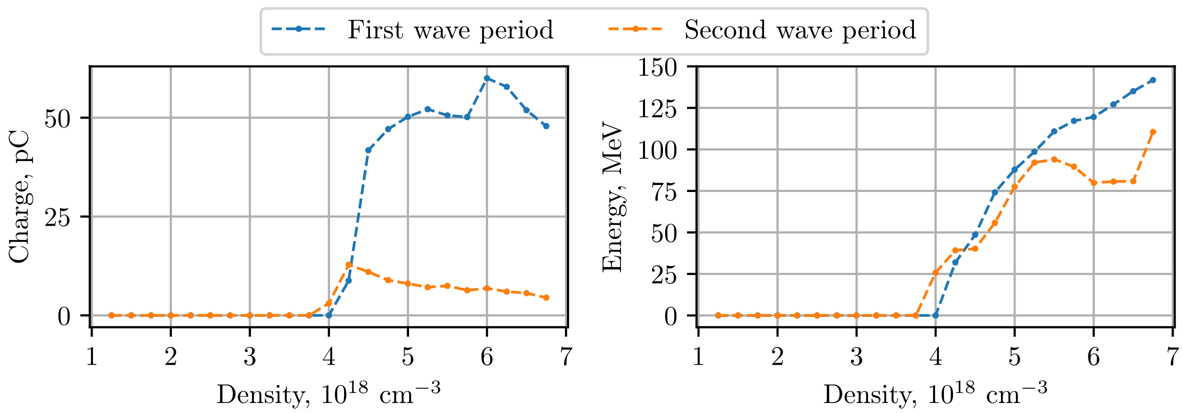

Figure 1: Dependence of the trapped charge and its average energy on the plasma density obtained from QSA simulations.

plasma density. However, at densities above $6 \times 10^{18}\,\text{cm}^{-3}$, the pulse is destroyed before it passes all the plasma. This is evidenced by a decrease in the captured charge and a change in the envelope of the laser pulse. So we consider the density of $6 \times 10^{18}\,\text{cm}^{-3}$ as optimal and fix it for further optimization.

Usually laser systems allow changing the position of the laser focus point. Moving the focus point deeper into the plasma increases the charge trapped into the second bubble, but has almost no effect on the charge in the first bubble and the electron energy (Fig. 2). This may be because the pulse is focused to a smaller radius if the plasma focusing begins before the vacuum focus point. The effect of the stronger focusing is more pronounced in the second bubble, which may indicate an overestimation of trapping into the first bubble.

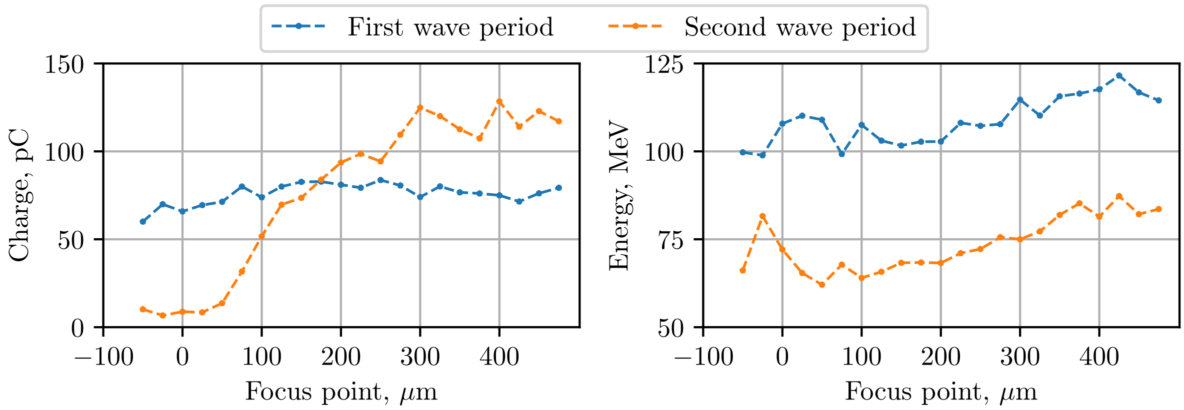

Figure 2: Dependence of the trapped charge and its energy on the position of the focus point for the plasma density of $6 \times 10^{18}\,\mathrm{cm}^{-3}$.

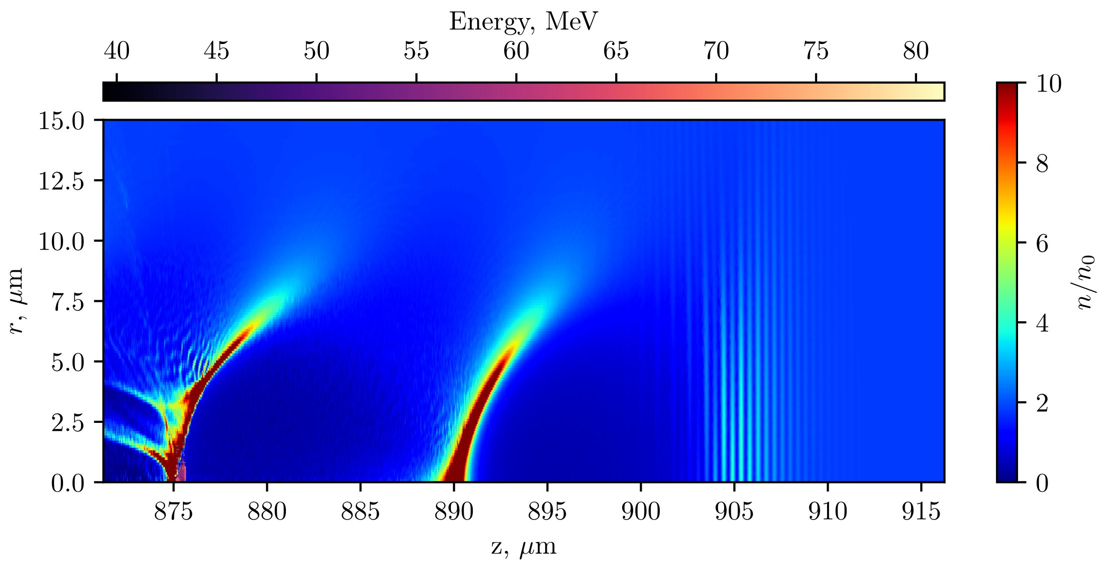

Figure 3: The trapped electron beam and the distribution of plasma electron density for the laser pulse focused at $z = 300\,\mu$m.

Figure 3 shows FBPIC simulation results for the focus point located at a depth of 300 μm in the plasma. The electrons are trapped only into the second bubble, and parameters of the accelerated beam are: 77 MeV energy and 18 pC charge. In LCODE simulations, the beam trapped and accelerated in the second bubble has the energy of 75 MeV and the charge of 120 pC. Thus, the modified QSA overestimates the trapped charge, but is qualitatively consistent with PIC simulations: trapping begins at the same plasma density, and moving the focus point allows us to control the accelerated charge.

Conclusion

Simulations with a code using a modified quasi-static approximation can speed up the optimization process by three order of magnitude. However, the modifications made to the QSA allow us to study only qualitative dependencies, and the optimization results must be cross-checked with a PIC code. To reach a quantitative agreement, further improvements to the QSA model are needed. By combining QSA and PIC simulations, we have shown that the threshold of trapping plasma electrons by the plasma wave can be lowered by focusing the laser pulse deep inside the plasma, which is especially important for laser pulses of a moderate energy.

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