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Progress on the Simulation Study of Sub-Terawatt Laser Wakefield Acceleration Driven by Ytterbium-Doped Lasers

C.-Y. Hsieh[1], M.-W. Lin[2], and S.-H. Chen[1]
[1] Department of Physics, National Central University,
[2] Institute of Nuclear Engineering and Science, National Tsing Hua University
e-mail (speaker):101222011@cc.ncu.edu.tw

Laser wakefield accelerator (LWFA) can be achieved by introducing a sub-terawatt (TW) laser pulse into a high-density gas target, where the combination of the self-focusing effect and the self-modulation instability can greatly enhance the laser peak power to a level capable of driving nonlinear plasma waves for accelerating electrons. The self-focusing effect occurs to reduce the transverse size of the pulse when the laser power exceeds a critical power $P_c \approx 17.4(n_{cr}/n_e)\ GW$, where the plasma critical density $n_{cr} = \epsilon_0 m_e \omega_L^2/q_e^2$ depending on the frequency ω_L of the laser field. Increasing the value of n_e results in $P_L > P_{cr}$ and enhances the self-focusing effect of the laser pulse. The transverse diameter of the pulse will be gradually reduced to the scale $2w \sim \lambda_p$. When plasma waves are excited, the self-modulation instability gradually shapes the pulse with a multi-cycle pulse duration of tens fs ($\tau_L > \lambda_p/c$) into a few micropulses with compressed ultrashort durations ($\sim\lambda_p/c$). Based on this principle, electrons up to 10 MeV energies can be produced from the LWFA when focusing an 800-nm laser pulse with a peak power $\sim$ 0.6 TW into a hydrogen gas target with a peak density $n_{e0} \geq 2 \times 10^{20}\ cm^{-3}$.[1]

Meeting the requirements with an increased radiation output from LWFA motivates the use of novel TW lasers to drive LWFA at a higher rate, such as a diode-pumped, ytterbium (Yb)-doped laser system that can produce 1030-nm pulses with an energy >100 mJ at 100 Hz.[2] These 1030-nm pulses are considered as potential driving forces to promote LWFA performance at kHz-level frequencies;[3] however, they are typically produced with relatively long durations $\sim$ 200 fs, making them less efficient to drive plasma waves due to the smaller ponderomotive force $F_N \propto \lambda_L^2 \nabla E^2$ they can provide at the front edge than that of 800-nm pulses usually < 50 fs. A spectral broadening technique, such as the multiplate continuum technique, [4] can be applied to reduce the duration of a 1030-nm pulse; in this way, an appropriate duration that can significantly improve the LWFA performance has to be identified.

In this work, particle-in-cell simulations have been conducted to study the scheme in which 1030-nm pulses are introduced into a gas cell with a flat-top density profile, where the plateau region allows the self-focusing and the self-modulation of the laser pulse to evolve in a relatively stable condition. [3] The density of plateau region is $7.3 \times 10^{19}\ cm^{-3}$, which gives a ratio P_L/P_{cr} = 2 favorable for realizing the self-focusing of incident 0.5-TW pulse. Simulation results show that reducing the pulse duration from 200 fs to 50 fs can effectively increase the ponderomotive force F_N and improve the LWFA performance as shown in Figs. 1(a) -1(d). The manifest formation of plasma bubbles and electron acceleration can be successfully accomplished with τ_p= 50 fs. In contrast, using an ultrashort pulse to drive LWFA will encounter the problem of severe pulse depletion because the depletion length is generally proportional to the duration of a driving pulse. When a short pulse with duration $\leq$ 25 fs is utilized, this depletion effect will become prominent. As a result, the properties of accelerated electrons acquired with a 25-fs pulse cannot be further improved with respect to the results driven by a 50-fs pulse. In the case that an ultrashort pulse of 10 fs is applied, the depletion effect can rapidly destruct the pulse and terminate the LWFA process. Finally, the simulation results of the sub-TW LWFA will be demonstrated and discussed in the poster.

References

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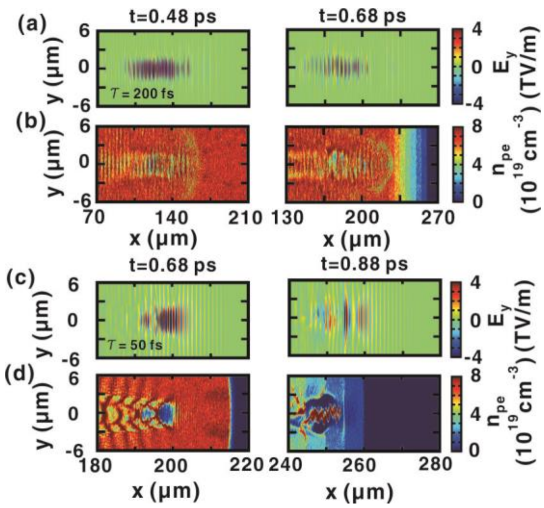

Figure 1 Variations of laser E_y field and the density distribution of plasma electrons for τ_p = 200 fs, (a) and (b); results for τ_p= 50 fs, (c) and (d).