Simulation Studies Of Sub-Terawatt Laser Wakefield Acceleration

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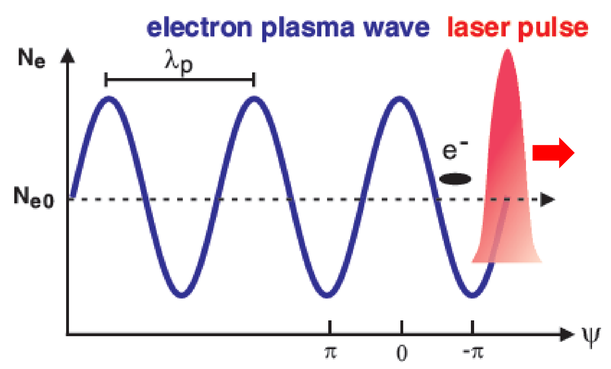
Laser wakefield acceleration (LWFA) can be operated at a high repetition rate to generate MeV electron beams by injecting sub-terawatt (TW) laser pulses into high-density gas target. A three-dimensional (3-D) particle-in-cell (PIC) model was developed to simulate the process of highly nonlinear and complicated laser-plasma interaction in sub-TW LWFA. Since the front foot of the laser pulse ionizes the gas target, the field ionization model is considered. Based on the finite-difference time-domain (FDTD) method, the governing equations including Maxwell's equations and Lorentz force equations are used to describe the evolution of electromagnetic fields and plasma dynamics. Each simulation is performed in a moving frame co-propagating with the laser pulse. The simulation box is defined as Lx=80 μm along the (x-)direction of the laser propagation, while Ly=Lz =40 μm in the transverse y- and z-directions. To ensure a high accuracy, the cell sizes are determined as Δx≅ 32 nm and Δy=Δz=200 nm while the particle number per cell is set as 8, which gives up to 8×10^9 particles in the simulation domain. This is a computing intensive task, therefore, the parallelization with message passing interface (MPI) is conducted to improve the simulation efficiency. Finally, the numerical results of the sub-TW LWFA will be demonstrated and discussed.

Introduction of sub-TW laser wakefield acceleration (LWFA)

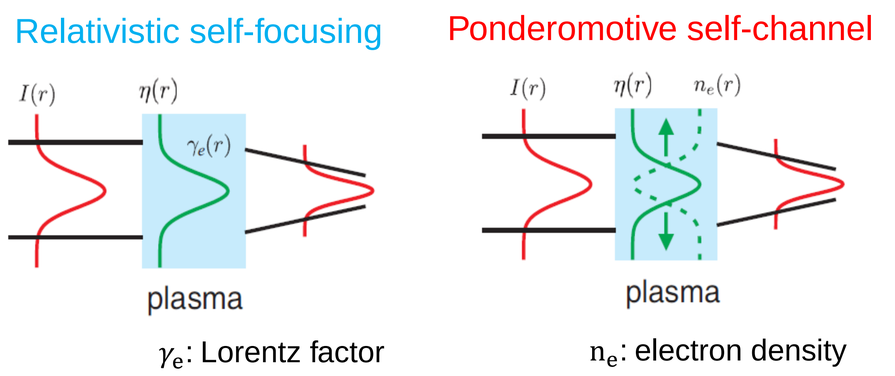
Schematic of laser wakefield acceleration



When an intense laser pulse propagates through the plasma, the ponderomotive force of the laser pulse may generate the plasma waves to efficiently accelerate the injected electrons.

- In order to achieve high-repetition-rate LWFA, one of solutions is to inject a laser pulse of moderate peak power (sub-terawatt (TW)) to interact with a high-density gas target.

Effects of self-focusing and self-modulating to enhance laser peak power



The refractive index $\eta(r)$ of the plasma is characterized by the distribution of the laser intensity $I(r)$, which acts as a focusing lens to focus the laser pulse and increase its intensity.

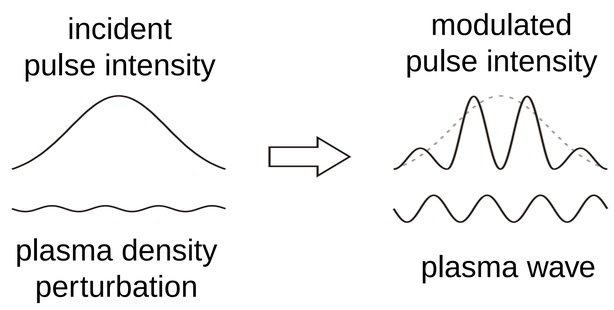
- Self-focusing occurs when the laser power exceeds a critical power.

$$P_{cr} \approx 17.4\left(\frac{\omega^2}{\omega_{pe}^2}\right) GW$$

ω: laser frequency ω_{pe}: plasma frequency

G. Z. Sun et al., Phys. Fluids **30**, 526 (1987).

- The self-modulated effect occur when
  1. Laser power P_L > critical power P_{cr}
  2. Pulse length L_{laser} > plasma length L_{pe}



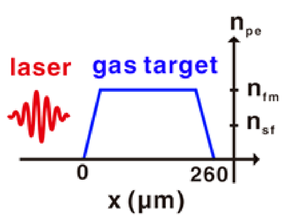
- The self-modulated effect shapes the laser pulse into a series of pulse train.
- The pulse duration is compressed.

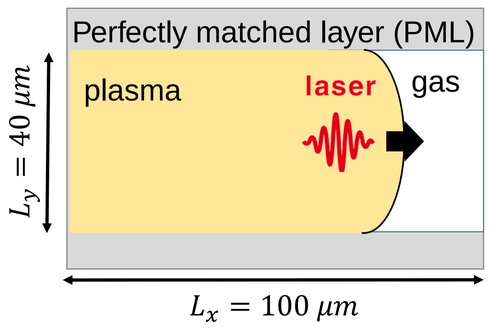
Three-dimensional simulation model for sub-TW LWFA

Three-dimensional simulation model

- The sub-TW laser hits dense hydrogen gas with flat-top density profiles.

Distribution of gas target





Three major mechanisms

1. Electromagnetic fields
2. Plasma dynamics
3. Gas ionization

- Moving window in x-direction is applied to reduce the size of simulation box.
- Δx≅32 nm; Δy=Δz=200 nm
- Particle number per cell =8
- Up to 8×10^9 particles

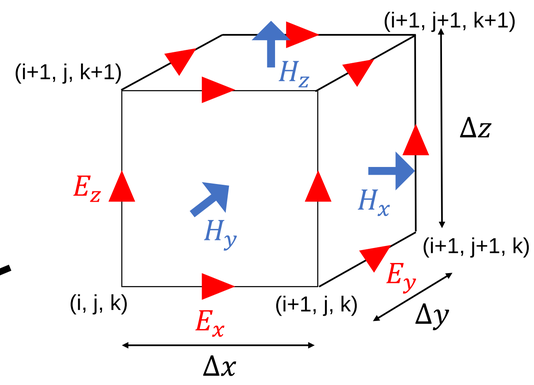
◆ Maxwell's equations

$$\frac{\partial \boldsymbol{E}}{\partial t} = \frac{1}{\varepsilon_0}(\nabla \times \boldsymbol{H} - \boldsymbol{j});\ \boldsymbol{j} = \sum_\alpha \boldsymbol{j}_\alpha(\boldsymbol{r}_\alpha) W(\boldsymbol{r} - \boldsymbol{r}_\alpha)$$

$$\frac{\partial \boldsymbol{H}}{\partial t} = -\frac{1}{\mu_0}(\nabla \times \boldsymbol{E});\ \mathbf{B} = \mu_0 \boldsymbol{H}$$

W: weighting function of charged particles

Finite-difference approximations of Maxwell's equations on a Yee grid



Integration of field equations on grid

Interpolation of particle sources to field

Interpolation of fields to particles

Integration of equations of motion

Electric field ionized the gas atoms.

◆ Lorentz force equations

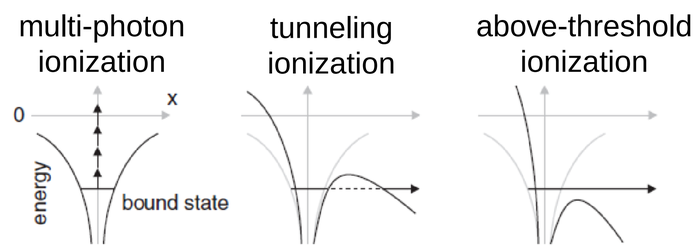
$$\frac{\partial \boldsymbol{P}_\alpha}{\partial t} = q_\alpha\left(\boldsymbol{E}_\alpha + \frac{\boldsymbol{P}_\alpha}{m_\alpha \gamma_\alpha} \times \mathbf{B}_\alpha\right)$$

$$v_\alpha = \frac{P_\alpha}{m_\alpha \gamma_\alpha};\ \gamma_\alpha = \sqrt{1 + \left(\frac{\boldsymbol{P}_\alpha}{c m_\alpha}\right)^2}$$

α is the spices of macro particles

Charged particles are generated.

◆ Field ionization model



MPI parallelization efficiency

MPI Parallelization (3D domain with 3D decomposition)

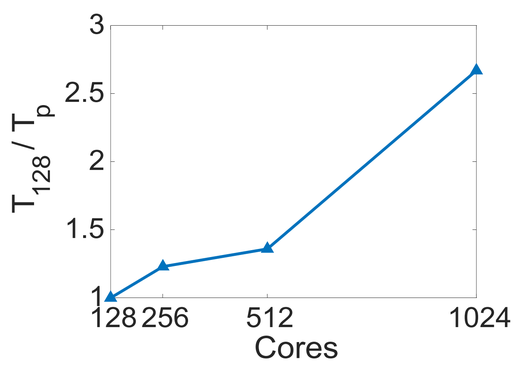
- We have used the Advanced Large-scale Parallel Supercluster (ALPS) in National Center for High-Performance Computing in Taiwan to test the three-dimensional model.

The grid number is 200×200×2485.

The initial particle number is 4.9×10^8.

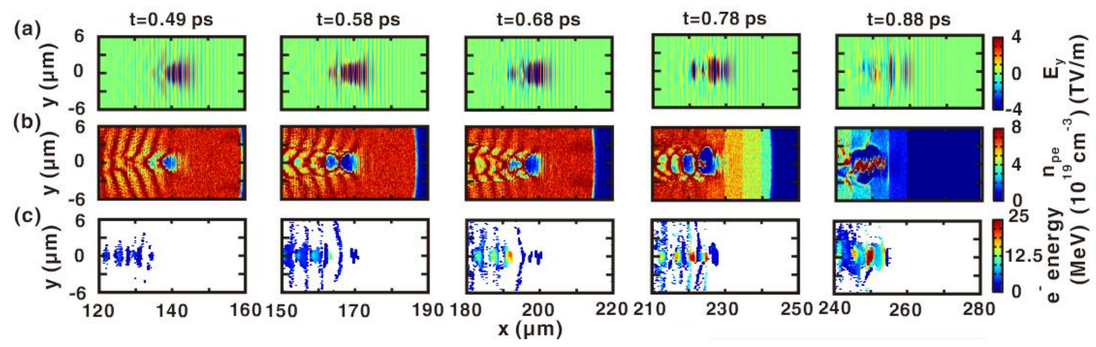
The simulation time step is 64.

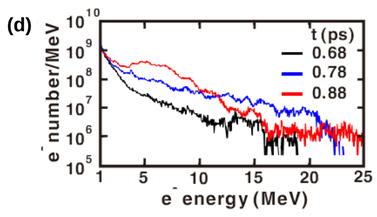
T_p is the simulation time of p cores.



- The scalability of this simulation model is good enough with MPI parallelization.

Simulation results of sub-TW LWFA





- The focused laser pulse gradually evolves into few filaments.
- The corresponding plasma wave provides the electron injection and acceleration.
- The accelerated electrons spectrum can be obtained.

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