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Efficient plasma heating by kilojoule petawatt lasers with a lateral confinement of fast electrons

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ABSTRACT

- An efficient high energy density (HED) plasma creation in a kJ-class relativistic intensity lasers and thin foil interaction is demonstrated by 2D particle-in-cell (PIC) simulations.
- In the laser-foil interactions, the lateral motion of fast electrons recirculating in the foil can be a random walk, being scattered by the fluctuating surface fields. The stochastic interaction reduces the loss of fast electrons from the spot area.
- We found that the reduced particle loss results a HED plasma creation with over-gigabar electron pressures with a several-picosecond lifetime, which will benefit for fusion studies and applications such as intense x-ray source.

BACKGROUND

- High power lasers with relativistic intensities $I > 10^{18}$ W/cm^2 can heat dense matters isochorically and create HED plasmas with Gbar pressures. Since the heating is driven by fast electrons accelerated by the laser at the target surface, to confine of fast electrons for longer time is crucial for many applications.
- Recently, kJ-class relativistic lasers with multi-picosecond (ps) pulse durations and large focal spot exceeding 50 μm are available such as LFEX, NIF-ARC, and LMJ-PETAL. Experiments demonstrate efficient TNSA ion accelerations [1,2] and plasma heating [3]. A key to understand the high efficiencies is the enhancement of energetic electrons under the over-ps laser irradiation [4]. However, the mechanism to generate the copious energetic electrons including multi-dimensional effects has not been fully understood.

ELECTRON CONFINEMENT MECHAMISM

In laser-foil interactions, the majority of fast electrons are trapped by the sheath electric potential and recirculate around the foil as the blue lines in Fig. 1. For small spot lasers (a), the electrons escape from the spot almost ballistically. For wide spot lasers, the average flow velocity reduces as (b), owing to the random angular scattering at the surfaces where fluctuating fields exist. The spot radius w has to be much wider than the step size Δy as in (b). The stochastic interaction works as a confinement of fast electrons in the spot region [5].

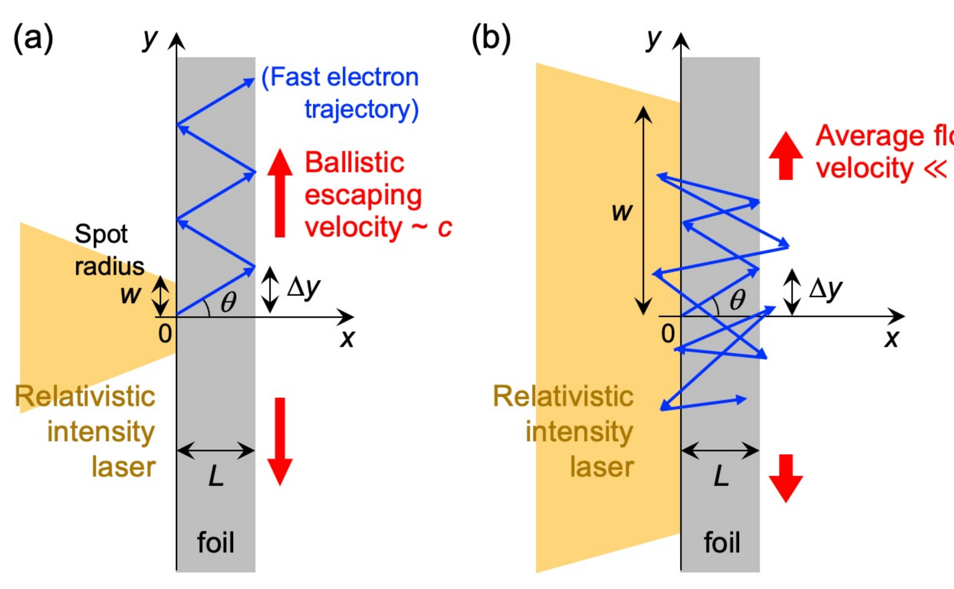

FIG. 1. (a) Small and (b) wide spot laser-foil interactions.

PIC SIMULATION SETTING

By using the PICLS code [6], we execute 2D PIC simulations of continuous laser irradiation on 5 μm-thick foil plasmas with ion and plasma densities of 100 n_c. The foil is uniformly distributed in y, and located from x = 102 μm with zero temperature initially. (Simulation box size (x, y) = (200 μm, 160 μm); Cell size 10 × 10 nm^2; 20 PIC particles/cell/species)

HIGH ENERGY DENSITY PLASMA CREATION

- Small spot (a_0 = 1.4, w = 1.4 μm; Fig. 2 (a)): Fast electrons do not accumulate in the spot, resulting an energy density $P_e \simeq 1.5$ Gbar which is almost same as the laser photon pressure.
- Wide spot (a_0 = 1.4, w = 35 μm; Fig. 2 (c,d)): $P_e \simeq 5$ Gbar at t = 1.2 ps increases continuously to 9 Gbar at t = 2.5 ps. The significant increase of P_e is associated with the effective confinement of fast electrons.
- Tight focusing (a_0 = 7, w = 1.4 μm; Fig. 2 (b)): The laser has the same power with the wide spot case. $P_e \simeq 25$ Gbar is achieved. The life time of the HED state is short due to a quick target disassembly after t = 1.8 ps.

Wider spot has a benefit to create a large volume HED state with an over-ps lifetime. For fusion applications, one can convert electrons' energy to ion kinetic energy with structured targets (e.g. clusters, layers). With high-Z materials, radiative plasmas can be created for intense x-ray sources [7].

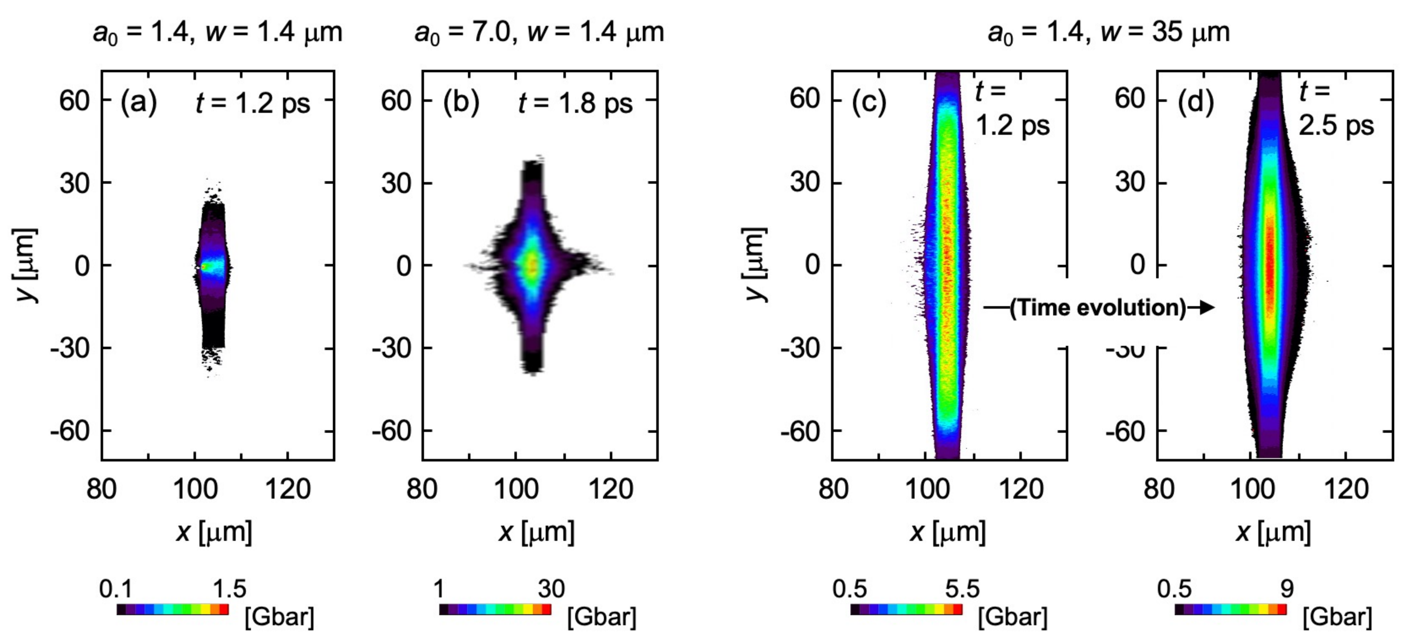

FIG. 2. Electron energy densities for (a,b) small and (c,d) wide spot cases.

Electron number and energy are enhanced in the wide spot as Fig. 3, owing to the confinement effect. Here, we multiplied the ratio of w (35/1.4 = 25) to the spectrum for the small spot to compare the efficiencies of the high energy electron production.

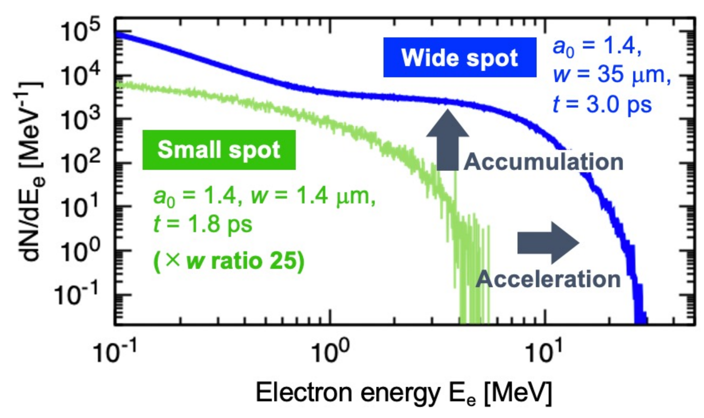

FIG. 3. Normalized energy spectra of electrons in the spot.

CONCLUSION

- We demonstrated a large volume, Gbar-level HED plasma creation by using 2D PIC simulations.
- The reduction of the lateral loss of fast electrons from the laser spot owing to the random walk enhances both the density and the average energy of fast electrons in the foil target.
- The Gbar electron energy density in the foil plasma is maintained in several picoseconds under the laser irradiation. In the long lifetime, large volume HED state can contribute to fusion studies and applications such as intense x-ray radiation source.

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