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Physics of relativistic picosecond laser interaction with dense plasma

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With the advent of kilo-Joule class high power lasers, intense laser lights having relativistic intensities above 10^{18} W/cm^2 with long pulse length in the range of 1 picosecond (ps) - 10 ps become available such as LFEX, NIF-ARC, OMEGA-EP and LMJ-PETAL. Radiation pressure of relativistic laser exceeds giga-bar. The laser can penetrate into plasmas over the relativistic critical density by pushing the critical density surface, i.e., by the laser hole boring (HB). The HB is a process of surface steepening, and therefore is crucial for energy and momentum transfers from laser to electrons and for the related applications such as fast ion acceleration, intense x-/ gamma-ray generation and fast ignition-based laser fusion. How long the steepened interface is sustained is also an essential for applications such as plasma mirror and high harmonic generation.

In recent experiments using over-ps pulse relativistic lasers, the energy slope (temperature) of fast electrons is found to be enhanced when the laser pulse duration is extended from ps to multi-ps, while the peak intensity is kept same [1, 2]. Maximum energy of protons is also enhanced more than three times by extending the pulse length from 1.5 ps to 6 ps [1]. The increment of fast electrons cannot be described by the conventional theories for sub-ps laser interactions, such as the ponderomotive scaling [3] and the HB model based on the momentum transfer equation from laser to ions, which predicts the continuous laser penetration during the laser irradiation [3, 4]. The increase of proton acceleration by pulse extension with same laser intensity is also unable to be explained by the conventional target-normal sheath acceleration (TNSA) theory that assumes temporally-constant (isothermal) electron temperature during the plasma expansion [5].

We here present a new theory of the HB for ps relativistic laser-plasma interactions [6]. The theory explains the enhanced fast electron generation observed in ps laser experiments. We also describe the boosting of ion acceleration in the ps regime as a consequence of electron heating during the laser irradiation [7].

We find that a stationary state of the laser-plasma interface is established during the continuous laser heating in ps time scale, and eventually the HB stops. We describe the stationary state of the HB by the pressure balance between laser light and plasma assisted by the sheath electric field, which acts as the surface tension. By solving the pressure balance equation for the stationary state, we derive the limit density for the HB, above which the laser light cannot push beyond, as $n_s = 8Ra_0^2n_c$ where a_0 is the normalized laser amplitude, R is the reflectivity, and n_c is the critical density.

After the HB stops, the hot surface plasma starts to blowout back towards the laser. The blowout electrons interact with the intense laser directly, which results copious superthermal electron generation. The time scale t_s to reach to the blowout phase is derived theoretically in multi-ps regime. Both n_s and t_s are confirmed by a series of particle-in-cell (PIC) simulations. The transition from HB phase to blowout phase is important to control the electron energy for applications such as ion acceleration and positron generation.

We also find in ps relativistic laser interactions with thin foil that hot electrons recirculate between the front and rear surfaces of the expanding foil plasma during the laser irradiation, and accordingly the slope temperature of the hot electrons evolves in time beyond the ponderomotive scaling.

The time evolution of electron energy during laser irradiation can no longer be neglected in considering laser ion acceleration when the pulse duration exceeds ps. We develop a non-isothermal TNSA model that takes time evolution of electron temperature into account [7]. Our model can explain ion maximum energy ε_{imax} observed in the LFEX experiment [1] and also time evolution of ε_{imax} obtained in PIC simulations.

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