ELECTRON ACCELERATION IN DENSE PLASMAS HEATED BY PICOSECOND RELATIVISTIC LASER

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Abstract

Laser lights with relativistic intensities and pulse lengths exceeding picosecond (ps) have been available recently. Fast electron generation in laser-plasma interactions is found to be increased significantly when the laser pulse length exceeds picoseconds. Since the ps relativistic regime corresponds to the mesoscale between kinetic and fluid regimes, theories for sub-ps interactions cannot be scaled up simply. We here present energetic electron generation in a ps relativistic laser-foil interaction, and show the role of the limit of laser penetration by the hole boring process and electron recirculation around the foil in the acceleration. We find that the high energy tail of electrons starts to evolve beyond the conventional ponderomotive scaling after the hole boring reaches to the limit density, and the energy distribution settles in a power law function through a stochastic interaction with the laser field. The present study of superthermal electron generation in the mesoscale laser-plasma interaction can be a basis for laboratory applications and also can provide a key to understand astrophysical phenomena such as cosmic ray acceleration.

1. INTRODUCTION

With the advent of kilo-Joule (kJ) class high power lasers, laser pulses with relativistic intensities above $10^{18}$ W/cm² and pulse lengths of 1 picosecond (ps) - 10 ps range become available recently such as LFEX [1], NIF-ARC [2], OMEGA-EP [3], and LMJ-PETAL [4]. These relativistic ps lasers enable to produce high energy density plasmas by heating and accelerating plasma electrons in a large volume. Such intense laser-plasma interactions can be applied for energetic ion acceleration [5], intense x-ray generation [6-8], and fast ignition-based laser fusion [9, 10].

In recent experiments, significant enhancements of fast electron generation have been observed when the pulse duration of the relativistic laser is extended from ps to multi-ps [11, 12], while the peak intensity is kept almost same. The slope of energy distribution of laser-accelerated electrons is beyond the conventional ponderomotive scaling which has been used for sub-ps laser interactions [13]. The same feature is predicted by theoretical works for relativistic ps laser-plasma interactions [14-18].

Picosecond time scale in the relativistic laser-plasma interactions corresponds to the mesoscale between kinetic and fluid regimes. As mesoscale physics set in, such as ion fluid motion and multiple-time scattering of electrons by fields, theories established for the sub-ps interactions cannot be scaled up simply. In this regime, kinetic modeling is challenging due to the extremely-high computational cost, so that theories that can describe laser-plasma interactions in such a new mesoscale regime are anticipated.
In Fig. 1, we show a map of typical laser regimes with respect to laser intensity $I$ and interaction time $t$. We here assume near-infrared lasers of wavelength $\lambda \sim 1 \mu m$ and period $2\pi/\omega \sim 3$ femtoseconds (fs). The gray circles show the typical ranges covered by fs ultra-high intensity lasers, ps high intensity lasers, and nanosecond (ns) lasers. Black and white stars present examples of currently- and near future-operated lasers, respectively. We indicate the kinetic (blue) and fluid (red) regimes in the same plot. The blue area corresponds to the parameter regime where electrons are non-thermal, and therefore the plasma particle simulation (particle-in-cell, PIC) has been applied. Efforts to extend the applicability of PIC simulations by adding physics models are shown by blue dotted lines in Fig. 1. Namely, for higher intensity regime $I \geq 10^{23}$ W/cm$^2$, the quantum electrodynamics (QED) effects including radiation reaction have to be included [19]. For lower intensity $I \leq 10^{14}$ W/cm$^2$, atomic processes, e.g. collision, ionization, and recombination, in warm dense matters are essential. Cross-section of collisions in warm dense matters is still under discussion [20, 21]. For longer time scale interactions over ps with dense, solid density plasmas, collisional heat transport appears even for high intensity laser interactions. In this regime, radiation cooling and radiation transport of the emitted x-rays in matter become also important [22], e.g., photoionization by keV photons. On the other hand, hydrodynamic simulations have been applied in the red area, and studies to describe kinetic effects in the framework of hydrodynamics with small anisotropic assumption [23, 24], have been proceeded. We see that picosecond lasers start to step into the mesoscale which had been unexplored by both kinetic and fluid simulations. Recently, new theories and modeling for the mesoscale regime have been proposed, e.g., PIC simulation study of the superthermal electron generation [14], ion acceleration theory based on the non-isothermal plasma expansion [16], large scale hybrid simulation combining PIC and fluid schemes for laser-driven ion acceleration [17], and theory on plasma density limit of the laser hole boring [18].

**FIG. 1.** Parameter regime of laser-plasma interactions. Gray circles show the typical ranges covered by fs ultra-high intensity lasers, ps high intensity lasers, and ns lasers. Black and white stars present examples of currently- and near future-operated lasers, respectively. Kinetic and fluid regimes are indicated by blue and red areas, respectively. Blue and red dotted lines show extension of applicability of simulations by adding physics models in recent computational studies.

2. ELECTRON ACCELERATION BY PICOSECOND RELATIVISTIC LASERS

Dynamics of laser-plasma interface is a key to understand the electron acceleration mechanism. We here discuss the electron acceleration in the mesoscale interaction regime based on our theory of limit density for the hole
boring, N. Iwata et al., Nat. Commun. (2018) [18]. We found a transition of laser-plasma interaction at the interface from radiation pressure dominant phase to plasma pressure dominant phase where the surface plasma blows off toward the laser. Due to the continuous laser heating over ps, the pressure balance between plasma and laser light is established, and then, laser penetration by the hole boring process, where the laser light pushes and proceeds into overdense plasmas, stops. The balance relation is established with the sheath electric field generated by the charge separation which acts as a surface tension of the plasma. By solving the pressure balance equation for the stationary state of the hole boring, we derived the maximum limit density, above which the laser light cannot push beyond, as \( n_s = 8a_0^2n_c \), where \( a_0 \) is the normalized laser amplitude and \( n_c \) is the critical density. The transition is ruled out by the ion motion. Ions start to move in the time scale of ion plasma response, \( 2\pi a_0^{-1} \), which ranges in 10 fs -100 fs depending on the plasma density. Ion motion is thus negligible in fs laser-plasma interactions, while for the ps lasers, ions have enough time to react to the laser irradiation with sound velocity. The response scale is typically \( \mu m \) in space and ps in time. Plasma self-organizes its structure in this response scale.

After the hole boring stops, the hot plasma starts to blowout back towards the laser, and the electron acceleration is enhanced. In Fig. 2 (a), we show the time evolution of plasma ion expansion by orange contour obtained in an one-dimensional PIC simulation using EPIC code [25]. In the simulation, laser light with normalized amplitude of \( a_0 = 2 \) and wavelength of \( 1 \mu m \) is irradiated from \( x = 0 \) continuously to a \( 5 \mu m \) thick deuterum plasma of density \( 40 \, n_c \) which is located from \( x = 75 \mu m \) to \( 80 \mu m \) initially. Here, \( a_0 = eE_0/(meoe) \) where \( e \) is the fundamental charge, and \( E_0 \) is the laser electric field amplitude. In addition, we placed a linear pre-plasma of length \( 1 \mu m \) whose electron density increases from zero at \( x = 74 \mu m \) to \( 40 \, n_c \) at \( x = 75 \mu m \). As indicated in the figure, the plasma starts to blowout at around \( t = 0.7 \) ps. The black solid and dotted lines present trajectories of two electrons in the simulation. They recirculate around the foil plasma being kicked by the laser field at the front side and trapped by the sheath electric field at the rear side. We note that the frequency of recirculation increases rapidly after transition to the blowout phase where efficient electron acceleration through direct interaction with the laser field occurs. In Fig. 2 (b), time evolution of electron energy distribution in the same simulation is shown by black solid lines. During the hole boring phase (\( t = 0.4 \) ps), the energy slope agrees with the conventional ponderomotive scaling defined by \( T_e = \left( 1 + a_0^2 \right)^{1/2} - 1 \) \( meoe^2 = 0.6 \) MeV. After entering the blowout phase, copious superthermal electrons appear, and the high energy tail extends as seen from the distributions of \( t = 1.5 \) ps and 3 ps. We find that the global distribution after multi-ps interaction is fitted well with a power law function \( f \propto E_e^{-\kappa} \) with \( \kappa = 1.2 \) (red dashed line) from the sub-relativistic energy to 5 MeV. Only the high energy tail above \( \sim 4 \) MeV can still be fitted by the relativistic Maxwellian distribution (blue dotted line). We emphasize here that the global trend of the distribution exhibits power law form, which implies a stochastic acceleration similar to the Fermi acceleration [26].

**FIG. 2.** (a) Time evolution of plasma expansion and electron recirculation in the plasma obtained by the PIC simulation. The orange contour represents the distribution of ion density normalized by the critical density \( n_c \). Black solid and dotted lines are trajectories of electrons picked up from the simulation. In the simulation, a foil with density \( 40 \, n_c \) is initially distributed from \( x = 75 \mu m \) to \( 80 \mu m \), and a laser light with normalized amplitude \( a_0 = 2 \) is irradiated continuously from the \( x = 0 \) boundary. (b) Time evolution of electron energy distribution. Black lines are spectra obtained in the same simulation with (a) at time \( t = 0.4 \) ps, 1.5 ps, and 3.0 ps. The blue dashed line is 1D Maxwellian function with the ponderomotive temperature \( 0.6 \) MeV, the blue dash-dot line is 1D relativistic Maxwellian function with temperature \( 2.2 \) MeV, and the red dashed line presents the power law function with power index \( \kappa = 1.2 \).
As the foil thickness is extended, the superthermal electron generation occurs in a later time. We compare electron distributions in simulations for interactions of (a) 5 μm and (b) 30 μm foils with laser field of normalized amplitude $a_0 = 1.4$ in Fig. 3. Note that the hole boring turns to the blowout at $t = 0.7$ ps and $t = 1.5$ ps in the cases of 5 μm foil and 30 μm foil, respectively, as seen from (c) and (d). Here, the orange contour presents the ion density, and blue dots and triangles indicate positions of electron densities $n_e$ and $n_c$, respectively where $\gamma = (1+\alpha_0^2)^{1/2}$. Since the travel length of recirculation is shorter in the 5 μm foil, the plasma is heated quicker, so that the plasma pressure increases rapidly. Consequently, the transition takes place earlier in (c) than in (d). In Fig. 3 (a), both of the two distributions ($t = 1.5$ ps and 3 ps) are those after the transition to the blowout, so that the superthermal high energy tail beyond the ponderomotive temperature 0.4 MeV (blue dash-dot line) is seen. On the other hand in Fig. 3 (b), the distribution at $t = 1.5$ ps, i.e., at the transition time, still fits the Maxwellian with the ponderomotive temperature. One can then see a clear deviation from the Maxwellian after transition as seen from the distributions at $t = 3$ ps and 5 ps. Note that distributions in cases (a) and (b) reaches to the same power law function. By fitting the distributions up to 5 MeV, the power index is obtained as $\kappa = 1.4$ for the current laser amplitude $a_0 = 1.4$. For higher laser amplitude $a_0 = 2$, the power index is smaller, i.e., $\kappa = 1.2$ as in Fig. 2 (b), in other words, more energetic electrons are generated with higher laser intensity.

FIG. 3. (a) and (b) present time evolution of electron energy distribution for interactions of (a) 5 μm and (b) 30 μm thick foils with laser field of normalized amplitude $a_0 = 1.4$. Black lines are spectra obtained in the PIC simulation at times $t = 1.5$ ps and 3 ps; in (b), that at $t = 5$ ps is also shown. The blue dashed line is 1D Maxwellian function with the ponderomotive temperature 0.4 MeV, the blue dash-dot line is 1D relativistic Maxwellian function with temperature 2.2 MeV, and the red dashed line presents the power law function with power index $\kappa = 1.2$. (c) and (d) are time evolution of plasma expansion in the same simulation with (a) and (b), respectively. The orange contour represents the distribution of ion density normalized by the critical density $n_c$. Blue dots and triangles show positions of electron densities $n_e$ and $n_c$, respectively, where $\gamma = (1+\alpha_0^2)^{1/2}$. The vertical arrow indicates the time at which the transition from hole boring to blowout takes place.

The difference of distribution functions is important in determining the average energy. When we assume a power law energy distribution function with the index $\kappa$ for electrons, the average energy for energy regime where the lower and upper limits are given by $E_1$ and $E_2$, respectively, is derived as

$$\langle E_e \rangle = \frac{1}{2-\kappa} \frac{E_{2-\kappa} - 1}{E_{1-\kappa} - 1},$$

(1)
where $\bar{E} \equiv E_2/E_1$. For $E_1 = 0.5$ MeV, and $E_2 = 5$ MeV, and power index $\kappa = 1.2$, which intends the case of Fig. 2 (b), we obtain $\langle E_2 \rangle = 1.8$ MeV, which is three times higher than the ponderomotive temperature for the laser field amplitude $a_0 = 2$, i.e., 0.6 MeV. Such a difference of electron average energy is essential for laser-based applications such as ion acceleration, where the ion energy depends on the number and average energy of fast electrons which create the sheath electric field [5, 27]. For fast ignition-based laser fusion, to know the function shape and the average energy of fast electrons is important in estimating the heating of the core plasma [9, 10, 28]. The distribution function is also critical to determine the spectrum of x-/gamma-ray radiation from laser-heated interactions [6-8]. To control the energetic electron generation is a key to create electron-positron pairs through laser-plasma interactions [29-31].

3. CONCLUSION

In conclusion, we studied energetic electron generation in ps relativistic laser-foil interactions based on the theory of limit density for the laser hole boring, N. Iwata et al., Nat. Commun. (2018) [18]. Using the PIC simulations, we found that after the hole boring reaches to the limit density, the electron energy distribution becomes power law through a stochastic acceleration. This is due to the efficient electron acceleration in the blowout plasma by the multiple kick from the laser field. The average energy of fast electrons in the power law tail in a MeV energy range that is important for the applications is derived to be higher than the ponderomotive temperature by factors. The transition of surface interaction originates from the ion motion in sub-ps to ps time scale, by which the plasma changes its structure accompanying strong self-generated fields. Such dynamic evolutions of laser-heated plasmas in spatial and energy spaces correspond to the mesoscale phenomena between kinetic and fluid regimes. The mesoscale is attractive in a viewpoint of exploring common physics of structure formation and energetic particle generation in magnetic confinement fusion plasma and in relativistic laser-produced plasma. The present study provides an understanding of superthermal electron generation in the mesoscale interaction which can be a basis to control the fast electron generation for applications such as intense x-ray radiation, electron-positron plasma creation, and laser fusion. The stochastic electron acceleration in collisionless plasmas discussed here is also a key physics related to the cosmic ray acceleration in universe.

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