Generation and propagation of hot electrons in laser-plasmas

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1 Introduction

The availability of the high intensity ultrashort laser systems based on the technique of the chirped pulse amplification (CPA) has opened the door to fundamentally new opportunities in science and technology [1]. One of their important applications is in the fast ignition scheme for inertial confinement fusion (ICF), as proposed by Tabak et al. [2]. In Tabak’s design, the fast ignition scheme for ICF consists three phases. First, the capsule is imploded to assemble a high-density fuel configuration as in the conventional approach to the inertial fusion. The second phase consists of boring a hole through the corona and pushing the critical density surface close to the compressed core, so that in the third phase, the interacting high-intensity laser pulse can pass the hole without energy loss and hit the high density capsule core to produce abundant energetic electrons triggering the ignition. The latter two phases in the scheme were referred to as the fast ignition concept correspond to two different regimes in the laser-plasma interaction research. The second phase is related to the interaction of intense laser pulses with underdense plasmas, while in the third the ultra-high short laser pulse is interacting with dense plasmas near critical density.

The propagation of the boring laser pulse in the underdense plasma is susceptible to various instabilities, among which, some processes like the stimulated Raman Scattering can produce abundant hot electrons. The hot electrons produced in this phase can preheat or even destroy the compressed core before the arrival of the ignition pulse, and should be avoided. But on other viewpoints, plasma waves related to such instabilities are used to accelerate electrons in the promising new generation of table-top laser-plasma based particle accelerator [3]. The plasma-based particle acceleration has been attracting great interests because plasmas are capable of sustaining extremely large acceleration gradients, which are on the order of the non-relativistic wave breaking limit [4], $E_0 = c m_e \omega_p/\pi$, where $\omega_p^2 = 4 \pi e^2 N_e/m_e$ is the electron plasma frequency with $N_e, m_e$ and $e$ as the ambient electron density, electron mass and charge, respectively. Taking $N_e = 10^{18}$ cm$^{-3}$ for instance. It gives $E_0 = 100$ GV/m, approximately three orders of magnitude larger than that obtained principally in the conventional radio frequency linear accelerators (RF linacs). The laser-plasma based accelerator contains two aspects to realize the collimated energetic electron beam. Firstly, a large amplitude plasma wave should be excited. Secondly, the seed electron bunch should be injected into the plasma wave at a proper time so that it can be in phase with the latter. Various schemes have been proposed to excite large amplitude plasma waves by making use of heat waves (PBWA)[3, 5] and laser wake fields (LWFA)[6–9]. The developments of plasma waves and instabilities are usually monitored through measurements of the scattered laser spectrum, on which the $n$-th order satellites exhibit at frequencies $(\omega \pm n \cdot \omega_p)$ with $\omega$ as the laser frequency [10]. The wave amplitude is limited by the wave-breaking, during which a large number of hot electrons are generated. The process signature is the broadening of the peaks on the scattered laser spectrum. In the scheme of LWFA, when the duration of the driving laser pulse is half of the non-linear plasma wavelength, $t_d = 0.5 \lambda_{NL}^2 c$, the laser wake field can be optimally driven to the largest amplitude [11]. The phase velocity of the excited plasma wave can be approximated by the group velocity of the driving laser pulse in the plasma. The de-phasing length, which is defined as the distance relativistic electrons travel when they overtake the driving laser pulse, limits the maximum energy electrons can obtain through non-linear wave acceleration to $\gamma_{\text{max}} = 4 \gamma_p^3 - 3 \gamma_p$, where $\gamma_p = 1/\sqrt{1 - \nu_p^2/c^2} \approx \omega/\omega_p$ with plasma wave phase velocity $\nu_p$ [12]. Experiments conducted under various conditions have shown that there exist threshold values of plasma density and laser intensity for the plasma wave to reach the stage of breaking. With gas plasmas, by controlling the uniform plasma density and the driving laser pulse intensity just above threshold values, one achieved single mono-energetic electron bunch with energy up to hundreds of MeV and the energy spread less than 3% when only a small
proportion of electrons break from the wave and the wave structure is maintained but reduced to a smaller amplitude by the electron loading effects [13, 14].

In underdense plasmas, electrons can also be accelerated directly by the intense laser pulse (LDA). People have observed double Maxwellian distribution of hot electrons with the higher effective temperature of 3 MeV and the maximum energy up to 20 MeV [15]. This distribution feature is attributed to intensity enhancement by the relativistic self-focusing of the interacting laser pulse. A betatron resonance acceleration process was predicted by Pukhov et al. [16], and observed in experiments with cluster plasmas [17, 18]. When the plasma density goes further lower and the relativistic interacting laser pulse is sufficiently short so that $t_H < \lambda_p^{NL}$, the interacting laser pulse can rarely experience self-focusing process. This condition also significantly suppress the laser wake field. It is interesting to find that the intense short laser pulse can trap electrons and carry them with it like a soliton-like system. The trapped electron bunch can be extracted by blocking the laser pulse with a plasma separator, as simple as a foil that is thick enough [19, 20].

When the plasma density goes higher to near-critical density as the igniting laser pulse encounters in the third phase of the fast ignition concept, the intense interacting laser pulse is more susceptible to instabilities and most excited waves tend to break, as the growth rate of these instabilities are proportional to the plasma density. Raman Forward Instability, which normally competes with the two plasmon decay instability (TPD) [21] as the laser pulse approaches the region of quarter-critical density. Its growth rate is $\Gamma_{SRFS} = \frac{\omega_p^2}{\omega} \frac{a}{\sqrt{1 + a^2 / \gamma_p}} \frac{1}{\sqrt{1 - \nu_{th}^2 / c^2}}$, where $\nu_{th}$ represents the electron maximum thermal velocity [?]. We are interested in situations of intense laser beams with sub-ps durations. Using Mori’s spatial-temporal theory, the gain of the stimulated instability can be obtained. For a 400 fs, 1.05μm interacting laser pulse with an intensity of $10^{16}$W/cm$^2$ and a Rayleigh length of 650μm in plasmas after being focused by an off-axis paraboloid mirror, the gain of SRFS in plasmas with $\omega_p/\omega = 0.1$ can exceed $10^5$ and should be able to be observed. Another nonlinear process the interacting laser pulse is likely to experience is self-focusing, which may be due to the relativistic effects when its power exceeds the critical value $P_c \approx 17(\omega_p/\omega)^2$ [23, 24], or due to the density fluctuation in preformed plasmas. The interacting laser pulse is also very likely to suffer the stimulated Brillouin scattering (SBS) [25]. Scattering or decaying mechanisms of driving pulses play detrimental roles in the fast ignition concept as they scatter a significant portion of laser pulses and reduce the coupling of laser energy into the fuel capsule. Techniques using combined spatial, temporal and polarization beam smoothing were introduced to improve the beam uniformity and effectively reduced SBS and SRS. Based of physical experiments, those processes render the interpretation of experimental results a complicated work. Models have to be invoked for understanding of possible mechanisms underlying the observation. Experiments with strictly controlled conditions need to be conducted for proof of even a simple theoretical prediction.

This review article mostly concentrates on experimental works about intense short laser pulse interaction with plasmas from flat solid targets. Reasons for studies on this interaction regime is partially because this subject is very important to the fast ignition concept of the inertial confinement fusion and because the physical rules obtained under long laser pulse approximation are confronted with suspicious arguments about their applications in the interpretation of phenomena observed in ultra-short high intensity CPA laser experiments.

Experiments were carried out mainly at the Laboratory of Optical Physics of the Institute of Physics, CAS. The laser systems include home-made XL (Extreme Light) series, which can deliver 50–650 mJ energy in a 30 fs FWHM duration. The contrast ratios of laser pulses with different energy are well controlled under $10^{-5}$–$10^{-4}$. Home-built laser pulse diagnostics, such as SPIDER, FROG and single-shot auto-correlator, are used to monitor every laser pulse incident on the target. The focusing geometry mainly consists of an off-axis paraboloid mirror and focus spot monitoring systems. In experiments, we controlled plasma density profiles by introducing pre-pulses in advance of the interacting pulse. Shadowgraphy and interferometry techniques are applied to measure the plasma density profile. The plasma density profile are approximately exponential with scale length varying from ten percent of laser wavelength $\lambda$ to tens of $\lambda s$. Details of the experiments setup are described in Sect. 3.

In experiments, large numbers of energetic electrons are known to be generated. Measurements and characterization of the energetic electron emission is important because it provides useful information about the interacting mechanism (producing mechanism). For a single electron, its behavior and trajectory are determined by the intensity, shape and polarization state of the laser pulse. In a sub-relativistic laser intensity of $I^{2/3} < 1.37 \times 10^{18}$ W/cm$^2$ ($a \ll 1$), where $I$ is the laser intensity in W/cm$^2$, and $\lambda$ is the laser wavelength in μm, the electron mainly responds to the electric component of the laser pulse. The magnetic component plays an increasingly important role as the intensity of the laser increases. When $a \sim 1$, electric and magnetic components exert forces of the same order on the electron and push it along the gradient direction of the laser intensity as the electron quivers in the polarization plane [26]. While with plasma targets, behavior of electrons in laser fields is determined by the combination effects of the laser field and collective plasma functions. The production mechanisms of hot electrons are rather difficult to identify. For example, the component of the non-relativistic laser electric field along the plasma density gradient can resonantly drive the plasma wave to break, producing large amount of hot electrons with an effective temperature larger than $T_{He} \sim 6 \times 10^{-5} (I / \lambda)^{0.33}$ eV [27] deduced for long pulse approximation. While for a relativistic laser intensity of $I^{2/3} > 1.37 \times 10^{18}$ W/cm$^2$ ($a > 1$), the laser ponderomotive force or $V \times B$ force dominates the interacting mechanism with a solid density plasma. Such interaction produces hot electrons with a Maxwellian distribution characterized by an effective temperature the same as the laser ponderomotive potential $T_{He} \sim 0.511 \times (\sqrt{1 + a^2 / 2} - 1)$ MeV [28]. Electrons are mainly accelerated in the longitudinal direction. If a large scale length pre-plasma is formed before the