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Prepulse and amplified spontaneous emission effects on the interaction of a petawatt class laser with thin solid targets

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ABSTRACT

When a finite contrast petawatt laser pulse irradiates a micron-thick foil, a prepulse (including amplified spontaneous emission) creates a preplasma, where an ultrashort relativistically strong portion of the laser pulse (the main pulse) acquires higher intensity due to relativistic self-focusing and undergoes fast depletion transferring energy to fast electrons. If the preplasma thickness is optimal, the main pulse can reach the target accelerating fast ions more efficiently than an ideal, infinite contrast, laser pulse. A simple analytical model of a target with preplasma formation is developed and the radiation pressure dominant acceleration of ions in this target is predicted. The preplasma formation by a nanosecond prepulse is analyzed with dissipative hydrodynamic simulations. The main pulse interaction with the preplasma is studied with multi-parametric particle-in-cell simulations. The optimal conditions for hundreds of MeV ion acceleration are found with accompanying effects important for diagnostics, including high-order harmonics generation.

1. Introduction

Petawatt (PW) power class laser interaction with various targets enables novel regimes of high energy charged particle acceleration and high brightness coherent and incoherent electromagnetic radiation generation over a wide range of photon energies [1–6].

One of the central scientific goals of studying relativistic laser plasmas is to obtain high-quality ion beams accelerated to hundreds mega-electron-volt (MeV) per nucleon, because this is a crucial milestone on the road towards the laser ion accelerator for applications in hadron therapy [7]. Various laser ion acceleration mechanisms have been discussed in theoretical and experimental papers (see review articles [1,8–10] and literature cited therein).

Apparently the maximum ion energy increases with the laser focused intensity which is in turn proportional to the laser power. Protons of 60 MeV from 100 μm foils irradiated by 400 J subpicosecond laser pulses of a PW class laser system have been detected in Ref. [11]. With laser pulses under 10 J, the highest proton energy obtained so far is 40 MeV [12], for a micron-thick metal foil irradiated by an ultra-short 200 TW femtosecond pulse laser ($\tau_{las} \approx 40$ fs) at an intensity of about 10^{21} W/cm^2. A 85 MeV proton generation has been detected with the petawatt laser at APRI-GIST, Korea [13].

According to the theoretical concept formulated in Ref. [14], a femtosecond petawatt class laser pulse focused onto a thin solid density proton-containing target can blow off almost all the electrons creating a Coulomb potential which accelerates protons to the energy of $\mathcal{E}_p$, which scales with the laser power, $\mathcal{P}$, as

$$\mathcal{E}_p = m_e c^2 \sqrt{\chi \mathcal{P}/\mathcal{P}_{rel}} \approx 173 \sqrt{\chi \mathcal{P}[\text{petawatt}]}\ \text{MeV}. \quad (1)$$

Here the coefficient χ is of the order of unity and depends on the laser pulse shape and its energy absorption; $\mathcal{P}_{rel} = m_e^2 c^5/e^2 \approx 8.71$ GW is

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proportional to the critical power for relativistic self-focusing [15]; e and m_e are the electron charge and mass; c is the speed of light in vacuum. The laser radiation with the power of $\mathcal{P}_{rel}$ focused into a spot with the diameter of the laser wavelength, λ, produces the intensity of $I_{rel} \approx 0.87 \times 10^{18}$ W/cm$^2 \times (1\ \mu\text{m}/\lambda)^2$ and the corresponding electric field of $E_{rel} = 2m_e\omega c/\pi e$ reaching the relativistic limit [1]. In terms of the dimensionless amplitude, $a = eE/m_e\omega c = 0.85 \sqrt{I_{las}[\text{exawatt/cm}^2]}(\lambda[\mu\text{m}])$, where $\omega = 2\pi c/\lambda$ is the laser frequency and I_{las} is the focused intensity, the relativistic limit is $a = 1$. The relationship in Eq. (1) shows that the 200 MeV proton energy can be achieved with ≈ 1.3 PW laser power on the target.

A femtosecond petawatt laser pulse (the *main pulse*) obtained with the present-day laser technology [1] is typically accompanied by a relatively low-energy nanosecond *prepulse* which is a combination of sub-picosecond pulses, a picosecond ramp and nanosecond amplified spontaneous emission (ASE). Recent theoretical studies have been carried out on the nanosecond *prepulse* [16,17]. The *prepulse* heats, melts and evaporates a portion of an initially solid density target creating a preplasma at the target front on the timescale of nanoseconds. The *main pulse* then interacts with the preplasma before it can reach the solid density region. These effects can substantially modify the laser—thin solid target interaction (e.g., see experimental and theoretical results on the ion acceleration in Refs. [18,19,20], where the *prepulse* transforms a micron foil into a finite thickness near-critical plasma layer, and in Ref. [21], where a low-contrast of a 3 TW *main pulse* impedes ion acceleration). Research into optimization of the prepulse for picosecond laser-irradiation of thin foil targets has been previously performed [19].

A fast depletion of the *main pulse* propagating in preplasma can diminish the ion acceleration efficiency. However the *main pulse* also undergoes relativistic self-focusing which increases its intensity and decreases the volume of the laser field immediate interaction (tightening the pulse waist). The mutual interplay between these effects can lead to the enhancement of ion acceleration efficiency, as we show below.

In this paper we investigate how the *prepulse* modifies the interaction of petawatt class laser with thin solid targets. We find optimal conditions for the ion acceleration and reveal accompanying effects which are useful for diagnostics in experimental searches for the optimal regimes.

In order to accomplish this task, we performed two kinds of numerical simulations strongly separated by the timescale. The study of the interaction of a nanosecond sub-mJ *prepulse* with a micron foil has required simulations using dissipative hydrodynamic algorithms described in Refs. [22–25]. The interaction of a femtosecond several joule *main pulse* with preplasma modelled following dissipative hydrodynamics simulations have been studied with multi-parametric particle-in-cell (PIC) simulations similar to Refs. [18,27].

In the present paper we briefly review the ion acceleration mechanisms in Section 2; describe typical parameters of the laser pulse components in Section 3; formulate a simple analytical model for preplasma formation and ion acceleration in Section 4; present dissipative hydrodynamic simulation results in Section 5; summarize the multi-parametric PIC simulation results in Section 6; discuss the outcomes and conclude in Section 7.

2. Ion acceleration mechanisms

Several basic laser ion acceleration mechanisms have been established, depending on the laser pulse and target parameters. They can be categorized into several groups.

The most actively studied regime so far is Target Normal Sheath Acceleration (TNSA) [28]. TNSA is realized, when a low contrast laser pulse interacts with a thick solid density slab target. This implies that a portion of the laser-heated electrons leave the target in the forward direction with respect to the laser pulse propagation and establish a longitudinal electric field at the target rear surface. In the quasistatic limit the ion energy is determined by the electrostatic potential there. In the dynamical regime not only hot electrons leave the target but also a plasma cloud formed at the target rear side expands into vacuum. The fast ions are accelerated at the front of the expanding plasma cloud [29]. The resulting ion beam has a broad quasi-thermal energy spectrum with a cut-off. Most of the experimental results on laser proton acceleration obtained so far can be attributed to the TNSA scheme.

A high contrast strong enough laser pulse can push away all the electrons from a thin or mass limited solid density target in a time shorter than the ion response time. Then ions undergo a Coulomb explosion due to the repulsion of the positive electric charge [30]. The resulting ion beam has a nonthermal energy distribution with a cutoff at the energy determined by the maximum of the electrostatic potential of the ion core. The ion energy scaling given by Eq. (1) corresponds to this regime, and can be realized when the laser pulse irradiates a thin double layer target (consisting of high-Z layer and a much thinner proton-containing layer). In the Coulomb explosion of high-Z layer, protons acquire the highest energy. The double layer target can secure obtaining high-quality (quasi-monoenergetic and low-emittance) ion beams [7,14,27,31]. The proton-containing layer can be prepared in a controllable way as in Ref. [32] or can be a water contamination layer usually present on metal foils.

Radiation Pressure Dominated Acceleration [33] comes into play when the laser is able to push the foil as a whole by the electromagnetic radiation pressure. This mechanism is a realization of the relativistic receding mirror concept [5]. The laser pulse is reflected by a co-moving mirror with its energy transferred to the mirror. Recently, several papers have reported on the experimental indication of the onset of this regime of laser ion acceleration, [34]. The transition from the TNSA to the RPDA regime has been observed in the PW class laser beam interaction with nanoscale solid foil targets, when 45 MeV protons have been detected [35].

The Magnetic Vortex Acceleration [36] regime occurs when the laser interacts with a near-critical density target, where it makes a channel in both electron and ion density. Exiting from the plasma the laser pulse establishes a strong longitudinal electric field sustained by a quasistatic magnetic field associated with the vortex motion of electrons. This electric field accelerates the ions. In the case of sub-picosecond pulses the acceleration of helium ions up to 40 MeV from underdense plasma by the VULCAN laser [37] and the acceleration of protons up to 50 MeV by the Omega EP laser [38] have been observed. Also experiments with femtosecond pulses irradiating cluster jet targets show that 10–20 MeV per nucleon ions can be generated [39]. He^{1+} and He^{2+} ion acceleration with minimum energies of 1.2 and 4 MeV, respectively, has also been observed in dilute mixtures of He and N_2 gases with a modest TW class laser [40].

A combination of the basic laser ion acceleration mechanisms can enhance the maximum ion energy, or increase the number of accelerated ions, or modify the ion beam spectrum. For example, the accelerated ion energy can be substantially increased with the Directed Coulomb Explosion scheme [41], which is the combination of Radiation Pressure Acceleration and Coulomb Explosion mechanisms. Another example can be found in Ref. [42].

Target micro- (and nano-) structuring can enhance the laser pulse coupling with the target [43,44] and improve the accelerated ion beam quality [7,14,31,32].