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Enhanced radiation pressure-assisted acceleration by temporally tuned counter-propagating pulses

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A B S T R A C T

Within the last decade, laser-ion acceleration has become a field of broad interest. The possibility to generate short proton- or heavy ion bunches with an energy of a few tens of MeV by table-top laser systems could open new opportunities for medical or technical applications. Nevertheless, today's laser-acceleration schemes lead mainly to a temperature-like energy distribution of the accelerated ions, a big disadvantage compared to mono-energetic beams from conventional accelerators. Recent results [1] of laser-ion acceleration using radiation-pressure appear promising to overcome this drawback. In this paper, we demonstrate the influence of a second counter-propagating laser pulse interacting with a nm-thick target, creating a well defined pre-plasma.

1. Introduction

The acceleration of protons and heavier ions by intense laser-matter interaction, first observed more than ten years ago, attracted a great deal of attention. The mechanism of target-normal-sheath acceleration (TNSA) allows protons to gain energy of a few tens of MeV, from an accelerating field which is only a few micrometers long, generated due to charge separation between ions and electrons from a μm−thick target foil [2,3]. The resulting distribution of particles is temperature-like with a distinct maximum energy. So far energies of up to E_{cutoff}=67 MeV have been published [4]. However most of nowadays' applications require quasi-monoenergetic spectra, with $\Delta E/E$ in the low percentage range. Remarkable progress has been achieved by methods based on TNSA – most effectively by using confined target of limited mass [5,6], micro-structured targets [7] and layered or staged foils [8–10]. Another approach is the use of a different acceleration mechanism. During recent years radiation-pressure acceleration (RPA) has been intensively discussed for quasi-monoenergetic acceleration of ions. Here the acceleration is driven by the light pressure $p=(1+R)I_L/c$, R being the reflectivity of the target and I_L the laser intensity . Laser intensities in the range of 10^{19} W/cm^2 result in pressures of a few tens of Gbar, leading to a homogeneous acceleration of the particles across the focal spot cross-section and ending up with a mono-energetic and overcritical bunch of particles. First descriptions of this process date back to the 1950s [11]. For current laser systems, RPA has been investigated theoretically by various groups during the last ten years [12–14]. It has been shown that RPA requires nanometer thin foil targets in order to fulfil the balance condition between light pressure and electrostatic pressure of the target [15]. First experimental studies have been preformed by different groups on solid [16,17] or gaseous targets [18].

We recently reported on monoenergetic features in different charge states of carbon even at rather low laser intensities of a few 10^{19} W/cm^2 [1]. By comparing the experimental results and PIC-simulations, we revealed a two step mechanism; as long as the laser is interacting with the foil, there is an accelerating force by the radiation-pressure leading to a small percentage of ions being collectively accelerated. In the second step, beginning immediately after the interaction, a post-acceleration induced by the

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accelerating field due to the displaced electron sheath sets in. From this additional force the protons gain most energy, due to their highest charge-to-mass ratio, ending up with an energy three to four times higher than the heavier carbon ions.

Nevertheless, RPA at these intensities is just at the onset of being driven efficiently and is not occurring in an isolated fashion. The acceleration process is a superimposed mixture of collective (RPA) and field induced (TNSA) acceleration. In this paper, we report on results, showing an improvement of the collective acceleration by RPA while suppressing TNSA. Originally designed to investigate the Doppler upshifted radiation from a relativistically moving mirror [19], we added a second, counter-propagating pulse and studied the influence of this second pulse on the foil expansion at different times with respect to the main pulse. This enabled the observation of different effects influencing the main acceleration process.

2. Setup

For the experiment we used the Ti:Sapphire laser system (JETI) at the University of Jena. The system delivers pulses of a maximum energy of $E_L = 0.8$ J and a pulse duration of $\tau_L = 27$ fs on target. These pulses are preceded by a ns-pedestal generated by amplified spontaneous emission (ASE) with a relative intensity contrast of 10^{-9}, and several short pre-pulses on the order of 10^{-6}, which arrive on a time scale of a few 10 ps. The observation of a decrease of the maximal achievable proton energy during a scan of the focal plane with respect to the foil surface using foils of a few nm-thickness indicated that in the position of the best focus the pre-pulses were already intense enough to partially destroy the target and deteriorate the ion acceleration. In order to circumvent this, the pre-pulse contrast was improved by three orders of magnitude using a single-pass plasma mirror system (PM) [20]. However, the resulting laser pulse energy on target was then reduced to $E_L = 0.6$ J owing to the plasma mirror. Note that all measurements were performed by using the PM, leading to a contrast ratio below 10^{-8} until 10 ps before the peak intensity which means that the laser pulses were interacting with a dense foil target. As target foils we used (15 ± 1) nm thick polymer foils made of parylene $(C_8H_6F_2)_n$ [21].

The experimental setup is shown in Fig. 1. The initial pulse was split into a main and a prepulse by means of a 4 mm-thick beam-splitter which is movable along the direction of the incident/transmitted beam. The intense part – in the following called *main pulse* – is reflected under 45°. In order to make the main pulse circularly polarized ($\varepsilon = 0.87$) we used a quarter-wave plate [22]. The main pulses were focussed by an $f/2$ off-axis-parabolic mirror onto the front side of the target foil under normal incidence. Ions which are accelerated in target normal direction were detected by a Thomson parabola covering a solid angle of 2.9×10^{-6} sr behind the target. The pulses transmitted through the beam splitter, containing 10% of the initial pulse energy – in the following called *back pulse* – were focussed by a second $f/2$ off-axis-parabolic mirror onto the rear side of the target. This second parabolic-mirror had a 3 mm hole in the center allowing accelerated particles to pass through. The spatial overlap of the two pulses was optimized using cameras observing the two focal spots from different directions. By moving the beam-splitter back and forth, the temporal delay of main- and back pulse could be varied without changing the spatial overlap. A third pulse – acting as a *diagnostic pulse* – with a separate delay-line was extracted from the main-beam right after compression. This beam probed the interaction zone perpendicularly, which allowed to adjust the temporal overlap of main- and back pulse by shadowgraphy of the generated plasma with an accuracy given by the laser pulse duration. By moving the beamsplitter, as can be seen in Fig. 1, we changed the delay of the main pulse with respect to the (fixed) back pulse. In the following, we set the main pulse as constant and instead recalculate all values so that the arrival time of the back pulse changes. A positive delay hereby refers to the case when the back pulse reaches the foil before the main pulse.

For a maximum intensity of 4×10^{19} W/cm^2 in the main pulse, we measured cutoff-energies of protons of up to $E_{cutoff} = 4.7$ MeV. The target was positioned at the best focus position by optimizing the proton signal towards the highest cutoff-energy, which depends on the intensity, as $E_{cutoff} \propto \sqrt{I_{laser}}$ [23–25]. Fig. 2 shows two thermal spectra with a typical modulation of about 20% which have been attributed to the aforementioned RPA-assisted acceleration process when both pulses interact with the foil. For two different delay times of -350 fs and $+690$ fs, a significant difference in the energy of the modulation can be observed. A delay scan in the range of -9 ps to 9 ps was performed, whilst the interaction parameters were kept constant. Fig. 3 shows the measured (a) cutoff and (b) peak energies in this scan based on a series of 102 shots.

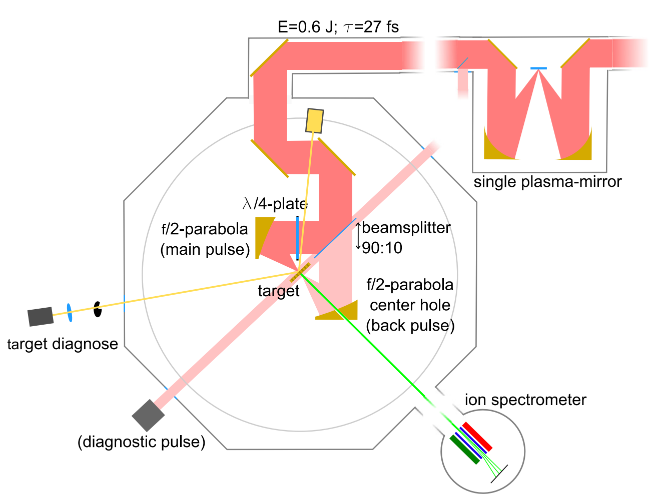

Fig. 1. Experimental setup: a high intensity laser pulse with enhanced contrast was separated by a beam-splitter with an energy ratio of 90:10. One beam could be temporally shifted with respect to the other. Both were focused with f/2 off-axis parabolic mirrors onto the front- and rear-side of a nm-thick foil target. The ion spectra were recorded using a Thomson parabola ion spectrometer.

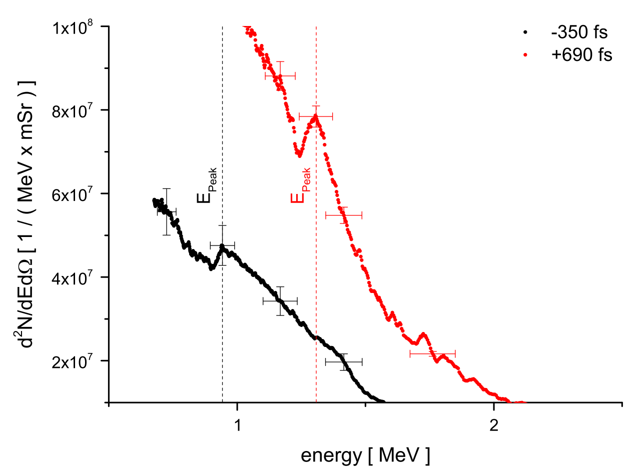

Fig. 2. Proton spectra obtained from a 15 nm thick polymer foil for a back pulse delay of -350 fs (main pulse reaches target before back pulse) and $+690$ fs (back pulse reaches target before main pulse) each. Beside the quasi-monoenergetic signature indicating a collective acceleration a clear energy increase by 40% is visible.