Accessing the RPA regime – target thickness effects on ion acceleration mechanisms

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Abstract

The radiation pressure acceleration (RPA) regime for ions accelerated after irradiating thin targets with high intensity short pulse lasers has recently been given a lot of attention due to the inherent monoenergetic nature of the ion beam, with energy scaling predicted to be proportional to the intensity of the laser [1,2]. In this paper, 2D Osiris PIC simulations using a realistic Gemini pulse interacting with nanometer scale targets will be discussed. Results showing the importance of circular polarisation and target thickness in accessing the RPA regime will be presented.

Introduction

Ion acceleration from solid targets using high power lasers is an exciting field with a variety of applications in science, medicine, and industry. Developments in laser technology have allowed lasers to reach intensities of up to 10^{23} $\mathrm{Wcm^{-2}}$.

Sheath acceleration has been widely investigated, experimentally and theoretically, in recent years [3,4]. However, it characteristically produces ion and proton beams with maxwellian spectra energy spreads of up to 100%, making it inefficient and unsuitable for many potential applications, such as hadron therapy. Recently, there has been much interest in using thin foils with circularly polarised laser pulses to access the radiation pressure acceleration (RPA) regime [2]. In this regime, the main acceleration mechanism is the light pressure of the laser accelerating the material forward like a slab. Recent simulations have predicted energies up to 1 GeV from sub µm targets with circular polarisation at 10^{22} $\mathrm{Wcm^{-2}}$ [5]. Presented in this report are 2D PIC simulations that investigate the conditions in which the radiation pressure regime can be accessed using a realistic pulse modelled on the current Gemini laser system at Rutherford Appleton Laboratory. Circular and linear pulses were used, as well as a range of target thicknesses between 4 and 100 nm, to identify the range of applicability for the RPA regime, and to explore the crossover between different acceleration regimes. The simulations were run to tie in with the recent LIBRA run on Gemini (March-June 2009), in which similar targets were shot under similar conditions as presented in these simulations.

Theory

When interacting with a solid overdense target, it is possible to model the interaction by splitting the RPA regime into two phases – the hole-boring regime followed by the light-sail regime [5]. Initially, as the laser impinges on the target, electrons are pushed forward by light pressure, whereas the more massive ions remain effectively still. This sets up a depletion layer between the ions on the front surface and the accelerated electrons, and hence a strong electric field is created in this region. This field then accelerates the ions forward into the target. Assuming sufficient thickness in the target, the force from the electric field will eventually balance the light pressure, and the thickness of the depletion layer, l_d, will remain effectively constant. The laser hence passes through the target, pushing a shock front in front of it. In this regime, it has been shown that the speed at which this shock front travels is proportional to $I_L^{1/2}$.

The depletion layer thickness, l_d, can be estimated by balancing the light pressure from the laser with the force between two capacitor plates, giving

$$l_d = \sqrt{\frac{2(1+R)\varepsilon_0 I_L}{c n_e^2 e^2}} \qquad (1)$$

where R is the reflectivity of the laser, ε_0 is the permittivity of free space, I_L is the intensity of the laser, c is the speed of light, n_e is the electron density, and e is the electron charge/cite.

When the shock front reaches the back of the target, all the ions are moving at the shock front velocity. It can then be estimated that the laser accelerates the material in the shock front forward as a slab by radiation pressure, in what has been called the light-sail phase. At this point, the acceleration of the slab is proportional to I_L, offering a great potential advantage over hole-boring and sheath-acceleration. Furthermore, due to the inherent block-like nature of the acceleration, the ion beams from radiation pressure acceleration can in principle have an inherently small energy spread.

One of the requirements of making RPA the dominant acceleration mechanism at intensities $<10^{23}\mathrm{Wcm^{-2}}$ is that electron heating is kept to a minimum. By using circularly polarised beams, the electron heating is damped as the oscillating term of the longitudinal electron motion equation disappears [6]. If the electrons are heated to high energies, then they dominate the neutralisation mechanisms and the ions are not accelerated. Problems with accessing this regime arise due to deformation of the target during the hole boring phase and the characteristic gaussian shape of realistic pulses.

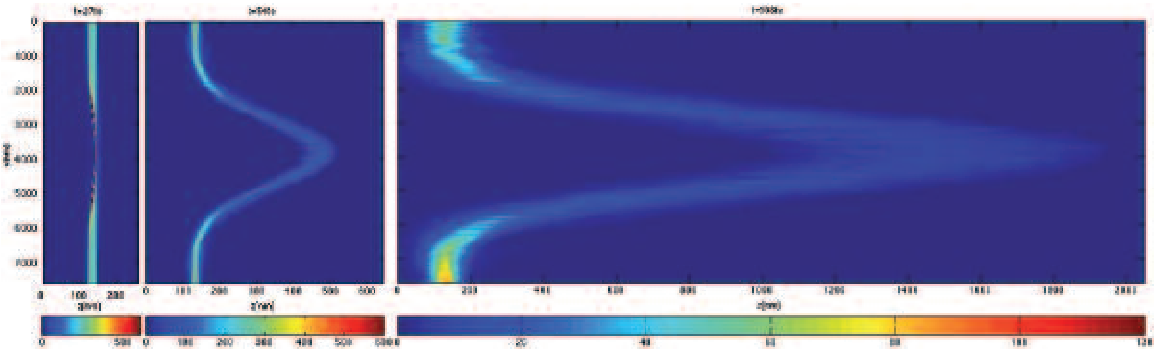

Figure 1. Results from 2D PIC simulation on a 25 nm target using a circularly polarised beam. The carbon density spectrum is given (units (n_c/Z)) at 27 fs (left), 54 fs (middle) and 108 fs (right) into the simulation.

The thickness of the targets is critical for efficient energy conversion to the ion species in the RPA regime. It has been shown in 1D simulations that ion energy is maximised near the point where depletion layer thickness is equal to the target thickness[7]. This minimises the time spent in the hole-boring phase of the interaction, hence maximising time in the light sail phase. However, if d becomes less than l_d, the electric field in the target is insufficient to balance the ponderomotive force of the laser and the structure of the accelerated slab is not maintained.

Simulation setup

The simulations were modelled using the 2D3V OSIRIS particle in cell code. The incident pulse was gaussian, a_0=10.6, pulse length = 50 fs, and a waist of 2 μm (these laser conditions were designed to mimic the Gemini laser with a diffraction limited spot and a wave-plate inserted in the beam). The polarisation of the laser was varied between circular and linear for these simulations. The targets varied in thickness from 4 to 100 nm, with an initial electron density of 259 n_c, where n_c is the critical density above which the laser cannot propagate through the plasma. The ions were fully ionised carbon (Z=6, A=12.01, charge to mass ratio of 1/3674.8). The targets were modelled using a step profile. Effects of the prepulse were not modelled for these runs.

Simulation results

For comparison between linear and circular polarisation, two simulations were done with identical conditions, apart from polarisation, with a 25 nm target. Figure 1 shows the ion density from the simulation with the circular polarised pulse after 27, 54, and 108 fs. This shows RPA dominating, due to the slab-like nature of the density profile. The transverse profile of the ion beam mirrors the gaussian shape of the laser intensity profile. There is much reduced heating of electrons with circular as compared to linear polarisation on the front surface, allowing the radiation pressure acceleration regime to dominate. The circularly polarised pulse hence results in an ion beam with a much lower energy spread as shown in figure 2 for 25 nm targets. The linearly polarised pulse results in a broader spectrum with higher maximum energies, but a very broad energy spread. This demonstrates the inherent advantage of circular polarization in accessing the RPA regime. It should be stressed that this is not a full spectrum of accelerated ions, but just the spectrum along the centre of the target where the intensity is maximum. This serves to replicate the narrow solid angle of any spectrometer that would be used to characterise this spectrum experimentally (usually a Thomson parabola spectrometer).

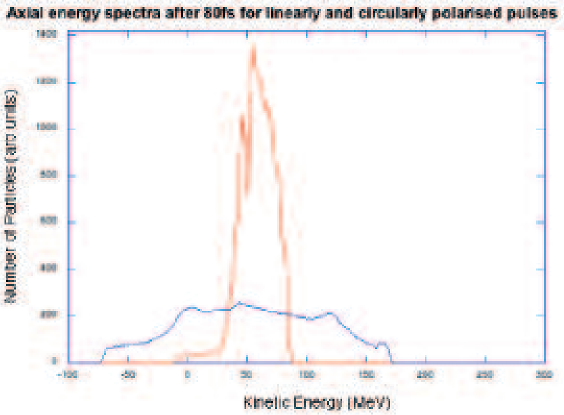

Figure 2. Longitudinal energy spectra through the central axis of the target after 80 fs for circular (red) and linear (blue) pulses. Line-out is taken over central 300 nm. The simulations are identical (25 nm carbon target, gaussian beam, etc) apart from the polarisation.

Figure 3 shows the results of the effect of varying the thickness on the axial energy spectrum. It was found that the peak energy is maximum around d = 10 nm. The energy spread, however, was found to be minimum for targets near 25 nm, where the regime can be clearly seen as RPA. As the targets became thicker, the maximum energy increases again, but the peak energy tends toward zero and the energy spread increases dramatically as sheath acceleration starts to dominate. As these are axial spectrum, the peak and FWHM measurement would not be expected to be seen experimentally using conventional techniques. The maximum energy would, however, be expected to follow the trend shown here, as the maximum energy ion is most likely to come from the region of highest laser intensity.

For an electron density of 259 n_c, and an a_0 = 10.6, as simulated here, the depletion layer thickness, calculated from (*1*), is 10.4 nm. For targets where $d < l_d$, the electrons were not completely contained by the electric field in the target and failed to set up the

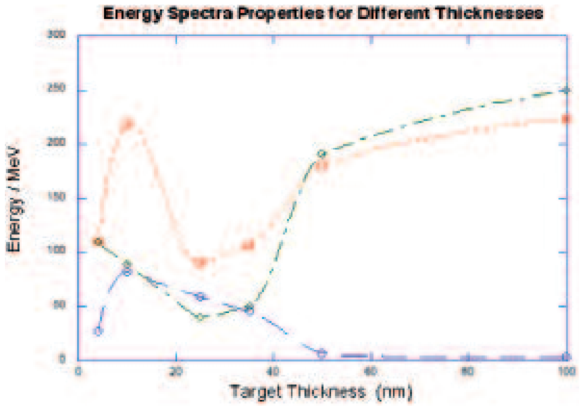

Figure 3. Comparison of axial ion energies 106 fs into simulation for varying target thickness: peak energy (blue long dash), maximum energy (red dots), and FWHM width (green dash dot) of the carbon 6+ spectrum for carbon targets with a density of 1.5 gcm^{-3}.

homogenous space charge which RPA relies on, giving a larger ion energy spread. This has been described before[7]. However, there appears to also be a transition region between structured RPA and this Coulomb explosion regime where high energies are achieved, but with higher energy spreads. The maximum energy was found in these simulations to be maximised where $d = l_d$, similar to what has been found previously. However, the simulations showed that at this limit the ion acceleration is still not completely coherent, and the effects of acceleration regimes other than RPA are still visible, broadening the spectrum.

The acceleration becomes fully pressure driven by $d = 2\text{-}3\ l_d$, where the energy spread is minimised, but the peak and maximum energies are also lower. This reduction in energies is due to greater time spent in the hole-boring phase compared to the light-sail phase.

Pressure driven acceleration then holds until around $d = 4\text{-}5\ l_d$, where the peak energy continues to drop, but the energy spread and maximum energy increases. Compared to the thinner targets, far more hot electrons are seen at the front surface, mostly due to recirculation effects. For this simulation, the skin depth is 8 nm. For the thinner targets, then, all of the electrons in the main width of the beam will feel an acceleration force due to the laser, and hence recirculation back towards the front surface is limited. As the targets become thicker, the electrons at the rear of the target become effectively isolated from the ponderomotive force of the laser and are hence able to recirculate to the front of the target. This method of heating will then cause thermal expansion of the target to become the dominant acceleration mechanism.

Conclusions

It has been shown that the RPA regime for ultrathin targets is easier to access using circular polarisation, which damps the vacuum heating term and hence suppresses heating mechanisms in the target. The RPA regime also seems accessible only for a small range of thicknesses when modelling a realistic Gemini pulse. For $d < l_d$, the foil is too thin and the electrons are ripped off, creating spectrum broadening and lower energies. For $d \approx l_d$ the foil energy is maximised, but there is still significant broadening of the spectrum. When $d > l_d$, the acceleration becomes dominated by RPA, until $d \approx 4\text{-}5\ l_d$ when the thickness of the target causes the dominant acceleration mechanism to change to thermal expansion. Here, the maximum energy of the ion beam increases, but the energy spread also increases considerably. Further extensions of this work would include a realistic simulation of the prepulse, to observe the effect of low contrast on the ability to access the regime. Furthermore, experimentally verifying the dip in maximum energies similar to those shown in figure 3, coupled with the generation of narrow energy spread features may indicate the action of radiation pressure acceleration mechanism, showing this regime can be accessed experimentally using current state-of-the-art laser systems.

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