Transition to light sail acceleration using ultraintense femtosecond pulses

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Abstract

Presented are results from experimental campaigns undertaken on the Gemini laser system at the Central Laser Facility in the UK. In these experiments amorphous carbon targets ranging in thickness from 10nm to 100nm were irradiated with high contrast 40fs pulses with an intensity up to 10^{21} W/cm^2, for both circular and linear polarisations and the resulting proton and ion spectra compared. Examining the highest energies achieved for a given polarisation and target thickness, allows to identify the transition from TNSA to LS. Observations of the optimal target thickness for ion acceleration are compared to analytical predictions from LS theory, in addition to results from Particle in Cell modelling.

Introduction

There is a number of different known mechanisms that contribute to ion acceleration. Which mechanism is dominant depends on parameters such as laser intensity, polarisation, and target density. The simplest and earliest model of ion acceleration is known as target normal sheath acceleration (TNSA) [1]. It is the regime which dominates at moderate laser intensities (say < 10^{20} W/cm^2) and for relatively thick targets. When the laser interacts with the front surface of a solid target, it ionises the atoms, creating a hot electron cloud which travel to the rear surface, forming a sheath of negative charge. This sheath sets up a charge separation, and therefore a large electric field, attracting positively charged ions which remain in the bulk of the target. The easiest positive ions to accelerate are the lightest, e.g. protons, which are present in the form of contaminants on the surface of the target, or part of the material itself, for example in the case of plastic targets.

When increasing the intensity of the light further, radiation pressure acceleration (RPA) can also play an important role. This mode of acceleration is based on the fact that the photons of the light pulse carry momentum, and can transfer that momentum to matter. When RPA is applied to ultrathin targets, ideally accelerating the irradiated region of the target as a whole, the mechanism is known as light sail (LS) acceleration. This requires that the target to be accelerated must stay opaque (i.e. the plasma remains overdense) throughout the whole acceleration process, as momentum transfer cannot happen effectively if the light is able to pass through. The target can become transparent during the irradiation if the electron temperature increases so much to drive a fast decompression of the target, so that the plasma becomes relativistically underdense for the laser light, effectively terminating the RPA process.

A way to prevent the onset of transparency is to inhibit the heating of electrons via controlling the laser pulse polarisation. With intense laser pulses, hot electrons are mainly produced due to $\mathbf{j} \times \mathbf{B}$ heating, an effect associated to the oscillatory component of the ponderomotive force (PF), which results from the magnetic component of the electromagnetic radiation affecting the electron trajectories, for sufficiently intense laser radiation. When circularly polarised pulses are used at normal incidence, the oscillating component of the PF is equal to zero, strongly suppressing hot electron generation and allowing the target to stay opaque for longer [2]. With linear polarised pulses, the oscillating component of this term is generally nonzero and results in the production of energetic electrons, leading to transparency effects, and the failure of RPA. An effective LS acceleration at currently available intensities requires using ultrathin foils (10s of nm) in order to minimize the mass that needs to be displaced by the laser pressure. Therefore, it is important to achieve an ultrahigh contrast through the use of Plasma mirrors, which reduce on-target intensities of ASE pedestal and prepulses by orders of magnitude, preserving the integrity of the target until it is irradiated by the high intensity peak.

Experimental Setup

Figure 1 below shows a schematic of the experimental setup [3]. Pulses of ~6J and 45fs duration are delivered on target at normal incidence using an f/2 off-axis parabolic mirror (OAP). Polarisation of the pulses are varied by the use of a quarter wave plate which is rotated to change from linear (LP) to circular (CP) polarisations. A double plasma mirror (DPM) arrangement is also used, in order to increase the contrast of the pulses to as high as 10^{14}.

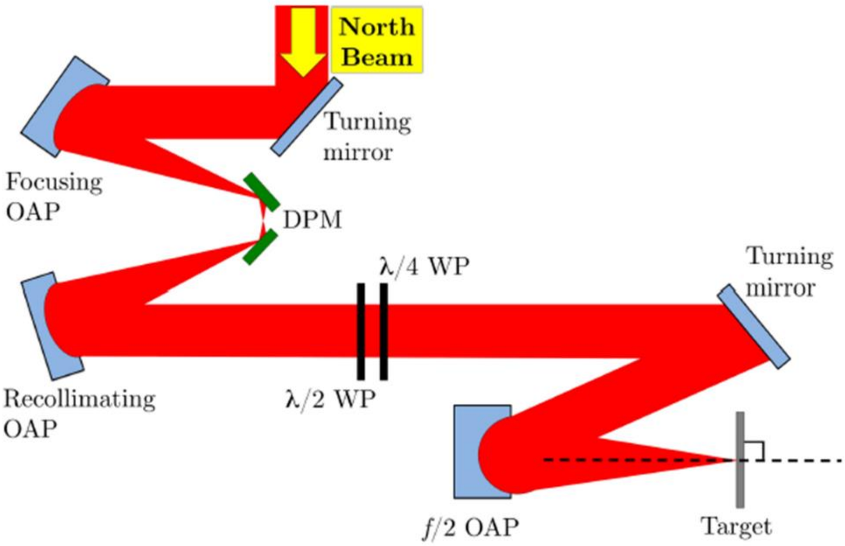

Figure 1: Experimental setup

Targets composed of amorphous carbon ranging in thickness from 10nm to 100nm were used. LS theory predicts that the optimal condition where LS acceleration is most effective occurs when $a_0 \approx \zeta$ [4]; a_0 is the laser strength parameter, defined as the normalised electron quiver momentum in the laser field, and ζ is the areal density of the target. For amorphous carbon targets and intensities in the range of 10^{20}–10^{21} W/cm^2, optimal acceleration should occur for the range 7-12nm.

Results and Analysis

Maximum energies of C^{6+} ions were determined for each target thickness and pulse polarisation, and the results are plotted in figure 2 below [3]. As can be seen, there is a clear point below 25nm where circularly polarised pulses generate higher energy ions than linear polarisations. This crossover region is the point at which light sail becomes the dominant acceleration mechanism. The peak of highest energy for CP 25 MeV/nucleon is seen at 10nm, in agreement with PIC simulations and the analytical predictions discussed above. These are the highest energy carbon ions accelerated with femtosecond pulses to date [5].

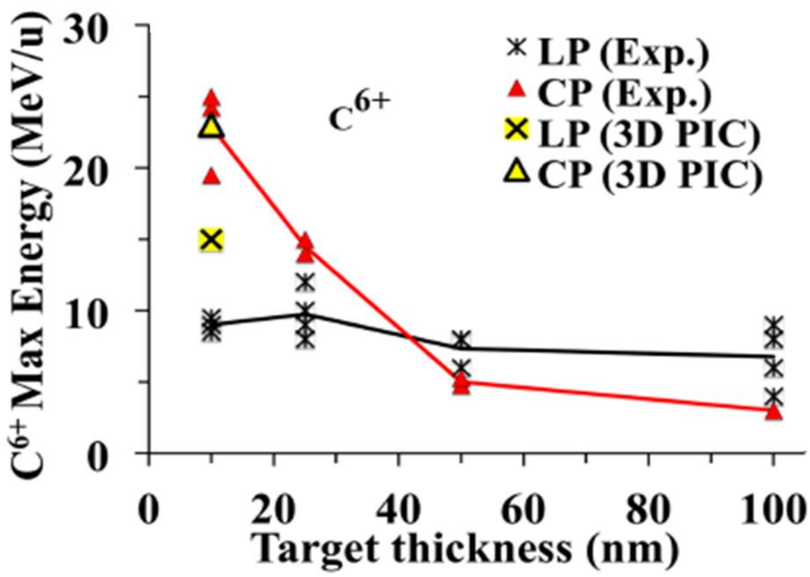

Figure 2: Experimental results, comparing circular (CP) and linear (LP) polarisations on ion energy for each thickness of amorphous carbon targets, alongside PIC simulation results

In conclusion, the results presented here highlight a strong dependence of ion energy on laser polarisation and target thickness, with a clear transition from TNSA to LS observed in targets below 25nm thickness when circular polarisation is employed. Linearly polarised pulses produced higher energies than circularly polarized pulses for thicker targets, but lower energies for the thinnest targets, providing evidence that electron heating and the onset of transparency playa strong role in diminishing RPA effects, and can be suppressed by the use of circular polarisation. The highest energies of 25 MeV/nucleon for carbon were found with 10nm thick targets and circular polarisation, in agreement with analytical predictions and PIC simulations.

References

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