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Polarization dependence of bulk ion acceleration from ultrathin foils irradiated by high intensity, ultrashort laser pulses

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The acceleration of ions from ultrathin (10-100 nm) carbon foils has been investigated using intense (∼6 × 10^20 Wcm⁻²), ultrashort (45 fs) laser pulses, highlighting a strong dependence of the ion beam parameters on the laser polarization, with circularly polarized (CP) pulses producing the highest energies for both protons and carbons (25-30 MeV/nucleon); carbon ion energies obtained employing CP pulses were significantly higher (∼2.5 times) than for irradiations employing linearly polarized (LP) pulses. Particle-in-cell simulations indicate that Radiation Pressure Acceleration (RPA) becomes the dominant mechanism for the thinnest targets and CP pulses.

Laser driven ion acceleration is an area of research attracting considerable interest [1, 2], due to a number of attractive features, such as the compactness of the approach compared to conventional accelerators, the excellent transverse [3] and longitudinal [4] emittance of the beams and the prospect of achieving high ion energies (100 s of MeV/nucleon) with next generation laser sources [5]. Research in this area is also motivated by applicative prospects in fields ranging from High Energy Density Physics [6–8] to biology and medicine [9–11], neutron production [12, 13] and nuclear physics [14, 15].

Until recently, most experimental research has been devoted to proton acceleration from laser irradiated foils of thickness in the μm-range with results interpreted in terms of the Target Normal Sheath Acceleration (TNSA) mechanism [16], where ions are accelerated by space charge fields generated at the rear surface of the target by relativistic electrons. Recently, the attention has shifted to a number of different, volumetric acceleration mechanisms displaying promising features in view of the aforementioned applications. Some of these novel mechanisms are ideally implemented employing low mass targets, which has motivated recent experimental research using ultrathin foils, with thickness in the nm-range [17–20]. In particular, ion acceleration harnessing the extreme radiation pressure exerted by intense lasers have been highlighted as a particularly promising approach to attain energies in the 100 s of MeV/u range and above, via the so-called Light Sail (LS) Radiation Pressure Acceleration (RPA) mechanism [21–26]. Controlling the polarization of the laser pulse was proposed as a means to preserve target opacity during the laser irradiation and to achieve an efficient radiation pressure drive on ultrathin foils. While a linearly polarized (LP) laser pulse incident normally on a flat foil drives, through the 2ω component of the J × B force, a sweeping oscillation of the density profile and causes strong absorption and hot electron generation, in the case of circular polarization (CP) the 2ω component vanishes. Using CP laser pulses, should therefore facilitate entering regimes where RPA is the dominant acceleration mechanism for ultrathin foils, since the reduced heating of the electrons of the foil delays the onset of target transparency during laser irradiation [22–26].

Accessing efficient RPA acceleration from ultrathin foils relies heavily on many critical parameters. In particular, while a quasi 1D drive is proven to be highly effective in numerical investigations, the finite spot size effects associated with tight focusing (unavoidable in current experiments due to pulse energy limitations, particularly with femtosecond systems) have been highlighted (e.g. in [27]) as a major obstacle to the implementation of LS acceleration. Nevertheless, some experiments employing tens of fs CP pulses, focused at mid 10^19 Wcm⁻² intensities on nm-scale foils [28, 29] reported features in the proton and C⁶⁺ spectra (at ∼ MeV energies) which could be interpreted in terms of LS-RPA acceleration. Henig et al. [28], in particular, showed the emergence of a broad peak feature in the carbon spectrum when using CP pulses, although at lower ion energies than that observed in LP shots. In recent experiments employing ultrashort pulses, a polarization-dependent enhancement in ion acceleration efficiency was induced by laser pulse self-focusing in low density media preceeding the foil [30]. In longer pulse (ps) regimes, Kar et al. [31] reported ion acceleration in an hybrid RPA-TNSA mode which displayed some of the characteristic features of LS RPA (e.g. the fast scaling), but did not highlight a significant polarization dependence, likely due to the effect of target deformation within the relatively long interaction duration.

This Letter reports on the first clear evidence of the polarization-dependent dominance of RPA-LS in accelerating ions during the interaction of ultrashort (45 fs) laser pulses with ultrathin carbon foils. The effect is evident from measuring the spectra of the carbon ions, where
significantly higher (more than twice) energies were obtained employing CP laser pulses compared to irradiations employing LP pulses. Multidimensional PIC simulations reproduce the salient features of the data and indicate that two different acceleration processes are dominant for CP and LP laser pulses at the thinnest targets employed. While an efficient LS drive is sustained for most of the pulse in CP, for LP an earlier transition to transparency and stronger electron heating leads to a less efficient acceleration.

The experiment was carried out on the GEMINI Ti:Sapphire laser system at the Rutherford Appleton Laboratory, STFC, UK. The laser delivered $\sim 6$ J energy on target in pulses of 800 nm wavelength ($\lambda$), and 45 fs full width at half maximum (FWHM) duration ($\tau$), after being reflected off a double plasma mirror [32] arrangement. The recollimated laser beam after the plasma mirrors was focused on the targets at normal incidence by an $f/2$ off-axis parabolic mirror, delivering peak intensities on target $\sim 6 \times 10^{20}$ W cm$^{-2}$. The laser polarization on the target was varied from LP to CP by employing a zero order quarter wave plate (WP), placed between the plasma mirror and the focusing parabola (see Figure 1). Amorphous carbon targets of thickness ($L$), in the range 10-100 nm were irradiated. The energy spectra of the ions accelerated from the interaction were diagnosed, by a Thomson Parabola Spectrometer (TPS) with BAS-TR image plate (IP) detectors [33, 34], along the laser axis (also target normal axis) with an acceptance angle of 1.1 $\mu$Sr. The energy-resolved spatial profiles of the ion beam were recorded by using stacks of radiochromic films (RCF) and CR-39. Representative $C^{6+}$ spectra obtained for different target thicknesses and CP are plotted in Fig. 3 (b). A sharp energy increase for decreasing target thickness is evident from the data, with a factor 5 increase in energies when decreasing the thickness from 100 to 10 nm.

For thick (50 and 100 nm) targets, the maximum ion energies were higher for LP pulses. The ion energies for LP pulses increase only slightly for thinner targets, remaining at around 10 MeV/nucleon for $C^{6+}$ across the whole range of target thicknesses deployed in the experiment. On the other hand, when employing CP laser pulses and decreasing the thickness below 25 nm targets, the situation changes dramatically, producing significantly higher energy carbon ions. An increase of maximum energies for protons at the thinnest targets and for CP is also observed - however, the effect is much less pronounced than for carbon ions. The highest $C^{6+}$ energies observed (for 10 nm targets) are of the order of 25 MeV/u (300 MeV), to our knowledge the highest carbon ion energies reported so far for tens of femtosecond pulses.

To confirm the scenario suggested by the data, 2D and 3D PIC simulations were carried out employing the AL-
aDyn code [35, 36]. The simulation box was a moving window of 51 μm along X (the laser-propagation direction) and 100 μm wide along both Y and Z. In the central region (51 × 21.8 × 21.8 μm), the cell size is Δx = 8.3 nm, Δy = Δz = 4Δx which is stretched towards the borders to reduce the computational cost. The grid size is 6144 × 2048 × 2048 cells and 100 particles per cell per species were used accounting for 4.8 × 10^9 particles. A large number of 2D simulations (across XY plane) were run for two configurations, with the exact same parameters as the 3D runs, but with an increased transverse resolution Δy = Δx, no stretched grid and 200 instead of 100 macro particles per cell. The laser pulse duration (FWHM of the intensity profile) was τ = 40 fs with a peak intensity I = 5.5 × 10^{20} W/cm^2 and a focal spot at waist w_0 = 3 μm. The target was composed of two layers. The first layer contained ions with charge to mass ratio Z/A = 1/2 (i.e. C^{6+}), thickness ℓ_i and initial electron density n_i = 100n_e. The following layer was a low density proton layer of thickness ℓ_p = 12.5 nm and electron density n_p = 10n_e. This configuration mimics the carbon foil with the contaminants on the rear side and allows to differentiate the dynamics of the different charge states. For computational feasibility, in the simulations the target density and thickness were respectively lower and larger than in the experiment while their product, i.e. the areal density covered the same range employed in the experimental run considering that the estimated electron density for solid carbon is n_e ≃ 350n_e. For the 3D simulations the areal density was chosen to correspond to the thinnest cases tested in the experiment, whereas in 2D mode, a large parameter scan was carried out considering different target thicknesses.

FIG. 3. (Color online). (a) Maximum energy of C^{6+} ions vs target thickness for LP (black stars) and CP (red triangles). Data points for 10 nm amorphous carbon 3D PIC simulations are also shown (yellow). Note solid red and black lines indicate average maximum energy for each thickness for CP and LP laser pulses respectively for clarity. (b) C^{6+} spectra from target thicknesses 10 nm (green), 25 nm (purple), 50 nm (blue) and 100 nm (red) with CP laser pulses (vertical axis units of particles/MeV/sr). (c) Spectra generated from PIC simulations: 2D (solid lines) and 3D (dotted line).

which is before the peak of the laser pulse reaches the foil) than for CP, explaining the lower proton energies observed in the former case. The pulse transmission is much stronger for LP than for CP and may lead to a polarization-dependent transverse shaping of the pulse [37].

For LP the proton layer is promptly accelerated and detaches from the ion bulk (see Fig. 4). The ion acceleration process is in this case essentially due to the sheath field. In CP the electron heating is strongly suppressed, but also in this case, due to the locally non-normal incidence due to the foil deformation, a small fraction of the electrons escape towards the rear side (see the two lobes of electrons above and below the laser axis at t = 83 fs) building a smaller TNSA field which initially accelerates the protons before RPA becomes the dominant process. The majority of the C^{6+} ions are bunched and accelerated as a whole by the radiation pressure until the target becomes transparent.

The strong dependence on target thickness and polarization reported in the data of Fig. 2 (and in particular the large increase in C^{6+} energies observed for the thinnest targets employed and CP) suggest that RPA is the dominant mechanism for the carbon ions. Proton spectra show a similar trend with thickness and polarization, but with less marked differences: at 10 nm, the proton energy for CP is marginally higher than for LP, and, while decreasing the target thickness from 100 nm to 10 nm, proton energies increase by a factor ∼3 compared to the factor ∼8 observed for the C^{9+} ions. Our explanation for the different behavior between the two charged species is related to the onset of significant transmission of the laser pulse through the foil. First we recall that the threshold condition for the onset of relativistic transparency is equivalent to the condition for which the radiation pressure on electrons equals the maximum possible value of the backholding electrostatic tension exerted by the ions [25]. Thus, the onset of transparency implies that some electrons are swept away from the transmitted laser pulse, creating an electrostatic field at the target
The density profiles, which may be related to the experimental data. Fig. 4 also shows the onset of transverse modulation in the density profiles. The plot shows the density and the magnetic field $B_z$ (corresponding to the laser field for LP) in the plane $x-y$, which corresponds to the polarization plane for LP.

The onset of transparency determines the thickness at which the highest ion energy is observed. This has been investigated with a set of parametric 2D simulations for different target thickness. As shown in Fig. 5 “the optimal thickness” is a consequence of the earlier onset of pulse transmission (or target transparency). The thickness dependence is in qualitative agreement with the experimental results shown in Fig. 3(a). The difference in the ion energies (higher for 2D simulations) may be ascribed to the transition to transparency being slower in 2D than in the more realistic 3D case, in which the target rarefaction is faster, with the acceleration phase continuing for a longer time in the 2D simulations [40].

In conclusion, in an interaction regime employing ultrashort (50 fs) laser pulses and ultrathin foils (10-100 nm carbon), we have observed a strong dependence of the characteristics of the accelerated ions on the thickness and the laser polarization. The effect is particularly pronounced for carbon ions, for which a 'crossover' in the maximum energy for the two different polarizations was evident in both experimental results and supporting PIC simulations; for the thicker targets, the maximum ion energies were higher for LP pulses, while below 25 nm, the situation changed producing significantly higher energies for CP laser pulses, providing evidence that a regime in which RPA is the dominant acceleration mechanism can be accessed at current intensities by careful control of the interaction parameters (pulse contrast, polarization and target thickness).

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