Initial observations of the effect on the transverse acceleration of ions and production of neutrons from underdense plasma in controlled two pulse experiments with the Vulcan Petawatt laser

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Introduction

Contemporary laser systems are capable of producing ultra-high intensities of up to 10^{21} Wcm^{-2}, which, when interacting with underdense plasma, can produce relativistic electron beams[1)] and multi-MeV energy ions[2)]. Development in this branch of physics could lead to applications such as compact particle accelerators[3)] (mono-energetic electron beams have recently been achieved[4)]) and the fast ignition of inertial confinement fusion targets[5)]. During a laser-underdense plasma interaction, ions can be accelerated to multi-MeV energies by a 'Coulomb explosion'[6)] and also in collisionless shocks[7)].

Coulomb explosions occur when the ions are accelerated through the large space-charge field generated when the electrons are expelled from the central channel by the ponderomotive force of the laser. Measuring the ions accelerated in the transverse direction provides a method for estimating the peak intensity of the laser[2)]. Collisionless shock accelerated ions have been observed at energies beyond what is expected from the Coulomb explosion and form a plateau in the high-energy region of the ion spectra. Thermonuclear neutrons produced in laser interactions with underdense plasma have also been predicted and observed[8)]. If the neutron yield from this kind of interaction could be enhanced, applications such as a pulsed neutron source would be a possibility.

Investigating the interaction of collisionless shocks can be done in a more controlled manner by introducing a large pre-pulse, of about 10% of the main pulse energy, so that a small shock should be launched prior to the second pulse. The shock from the second pulse then should be stronger (shock strength being proportional to intensity) and faster than the first and would therefore overtake and interact with the first shock. This shock interaction should affect the acceleration of the transverse ions.

Presented in this report is an initial comparison of ion and neutron production resulting from the interaction of single and double laser pulses with a gas-jet plasma, which have electron densities of up to 5.9×10^{19} cm^{-3}. Laser intensities of up to 6×10^{20} Wcm^{-2} are investigated experimentally, which is well into the relativistic self-focusing regime. 2D particle-in-cell (PIC) simulations of similar single and double pulse situations are used to investigate the effect of the intensity ratio of first to second pulse in different electron density plasmas.

Experimental Set-up

The experiment was performed using the Vulcan Petawatt laser at the Rutherford Appleton Laboratory. The laser pulse had duration of (0.7 ± 0.3) ps and energy of up to 248 J on target with a wavelength of 1.054 μm. An f/3 off-axis parabolic mirror focused the laser onto the edge of a gas jet, which had a 2 mm diameter supersonic nozzle with a focal spot size of 7 μm in vacuum. The maximum vacuum intensity of the laser was therefore 6.0×10^{20} Wcm^{-2}, which corresponds to a normalised vector potential, a_0, of 21.9. The time delay between the double pulses was (5 ± 3) ps. Altering the backing pressure of the deuterium supply to the gas-jet allowed the electron density of the plasma to be varied between $(0.4 - 5.9) \times 10^{19}$ cm^{-3}. The satellite frequencies from the forward Raman scattered laser spectra provides a method to measure the electron plasma frequency of the interaction, $\omega_{pe} = (n_e e^2/m_e \varepsilon_0)^{1/2}$, where e is the charge on an electron, m_e is the mass of an electron and n_e is the electron density, which can then be calculated.

The ions were measured in the transverse direction at 90° to the laser propagation direction using a Thomson parabola spectrometer. A 250 μm diameter pinhole, which subtended an angle of 4.76×10^{-8} steradians, selected the ions to enter the spectrometer. The ions then pass through a magnetic field and the $\mathbf{v} \times \mathbf{B}$ force disperses the ions according to their energy. Additionally, an electric field separates different ion species, in the direction perpendicular to the magnetic deflection, according to their mass-to-charge ratio. The nuclear track detector CR39 recorded the ions as individual pits on the formed parabolic traces.

Neutrons were detected via the proton knock on technique with a scintillator coupled to a photomultiplier tube to provide a time-of-flight measurement. It was placed at a distance of 1.5 m directly above the interaction at 90° to the laser propagation direction.

Experimental Results

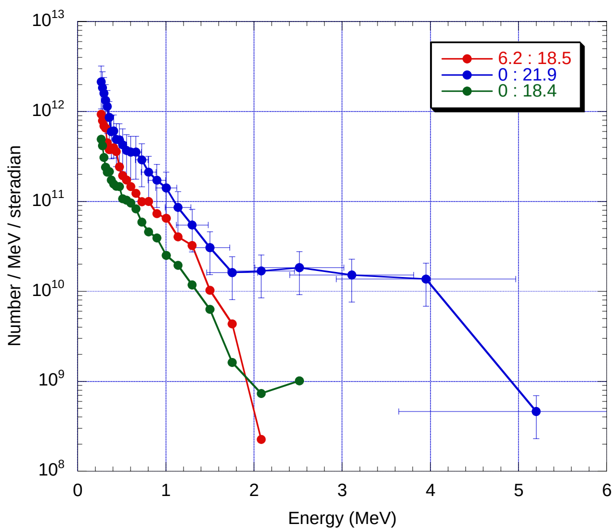

Figure 1. Transverse deuteron spectra of three shots labeled with the a_0 of the pulse ratios.

The deuteron spectra from three shots, all at a electron number density of $(5.8 \pm 0.1) \times 10^{19}$ cm^{-3}, are shown in Figure 1. The shot with no pre-pulse and an $a_0 \sim 21.9$ shows the characteristic plateau structure which is indicative of the shock acceleration mechanism. At the lower intensity ($a_0 \sim 18.4$) and also for the double pulse with a_0 ratio of 6.2: 18.5, there is no plateau feature. As the total amount of energy is increased so does the total number of ions, as expected. Therefore the neutron yield would be expected to show an increase in the yield similar to the ions, at constant density.

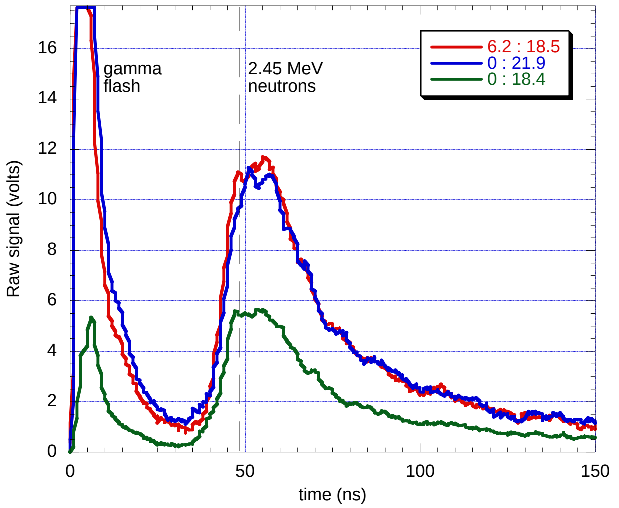

Figure 2. Neutron time-of-flight traces of three shots labeled with the a_0 of the pulse ratios.

For the same three shots, the neutron time-of-flight traces are shown in Figure 2. It shows that despite the total laser energy being less than a single pulse and a lower total number of measured deuterons (for the 6.2:18.5 shot, 196 J), the neutron yield for the pre-pulse shot is as high as that for the shot with $a_0 \sim 21.9$ (248 J). This could be due to multiple dense ion regions moving out from the interaction and the possible interaction of shock fronts moving through one another. It is also possible that the pre-pulse could form a channel, which may enable the second pulse to travel further through the gas jet before filamenting.

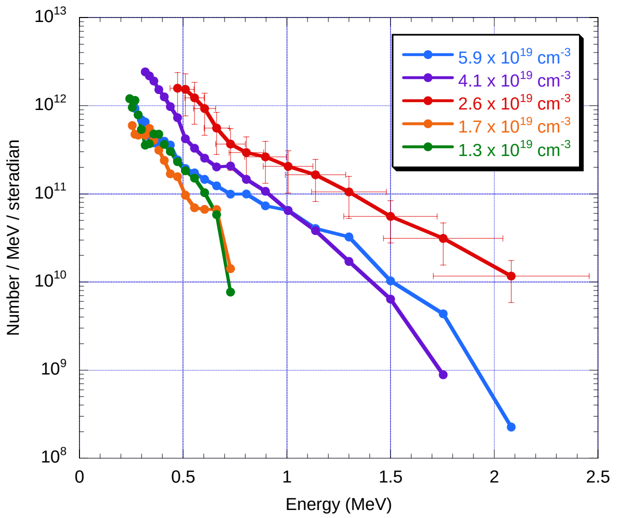

Figure 3. Transverse deuteron spectra at different electron number densities, all with a 10% pre-pulse.

The effect of the 10% pre-pulse for interactions at different electron number densities is considered in Figure 3, in which the transverse deuteron spectra for shots at different densities are shown. The a_0 ratios of the pulses are all (6.2 ± 0.2): (18.6 ± 0.4) within the error. Against intuition, the deuteron spectra does not increase in number and maximum energy smoothly with density as has been seen for the single pulse case, where the power law $E_{max} \propto n_e^{(0.7 \pm 0.05)}$ has been found[7]. This suggests that the effect of the pre-pulse is density dependant and can be more significant at a 'resonant' density for a particular a_0 ratio and time delay of the two pulses.

Further evidence for this complex relationship is seen in the neutron data for the same shots shown in Figure 4. The neutron yield is expected to increase with increasing background gas density. This is due to the fact that as the background density is increased there are more deuterons for the accelerated ions to interact with. The shot that produced the highest number of measured ions did not produce the highest neutron signal, which may be due to this shot having a lower background density. Although the signal for the 4.1×10^{19} cm^{-3} shot goes off the oscilloscope scale, it is clear that the neutron signal is larger than for the 5.9×10^{19} cm^{-3} shot.

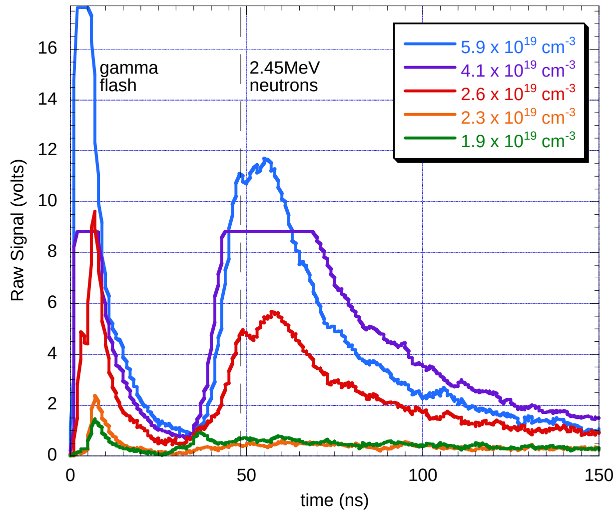

Figure 4. Transverse neutron time-of-flight traces at different electron number densities, all with a 10% pre-pulse.

PIC Simulations

The code OSIRIS[9] was implemented to perform two-spatial and three-momentum dimensions (2D3V) particle-in-cell simulations of these single and double pulse interactions. A stationary box allowed the ion dynamics to be observed to later times, even after the laser pulse had passed through the plasma. Two different resolutions were used. For the higher resolution simulations, in the longitudinal (x) direction, the box was 335 μm long with a resolution of 18.9 cells per λ and in the transverse (y) direction, the box was 134 μm wide with a resolution of 15.7 cells per λ. For the lower resolution, in the longitudinal (x) direction, the box was 587 μm long with a resolution of 12.6 cells per λ and in the transverse (y) direction, the box was 168 μm wide with a resolution of 9.4 cells per λ. There was one electron and one ion per cell for both resolutions.

Different energy ratios of the first to the second pulse and various electron densities were used to investigate the effectiveness of the double pulse increasing the ion acceleration. Proton plasma with a maximum density of $0.1n_c$ or $0.05n_c$, where n_c is the critical density, were used with a profile which had a 100 μm long linear density ramp from vacuum to the maximum density at the front of the plasma. Linearly polarized Gaussian-profile pulses were used with a duration of 0.5 ps which were focused to a spot with a waist diameter of 4 μm at the top of the density ramp. To compare the single and double pulse runs, the total laser energy was kept constant, so that the single pulse had an a_0 of 50 and can be thought of as having as first to second pulse ratio of 0:100. Three different first to second pulse ratios were considered, 1:99, 10:90 and 50:50 (only for $0.1n_c$) with an inter-pulse delay of 3 ps. The equivalent a_0 ratios for these are 5:49.7, 15.8:47.3 and 35.3:35.3. The a_0 values may seem significantly higher than the experimental a_0 values, but since the simulations are in 2D then the degree of self-focusing should be smaller than the 3D experiment.

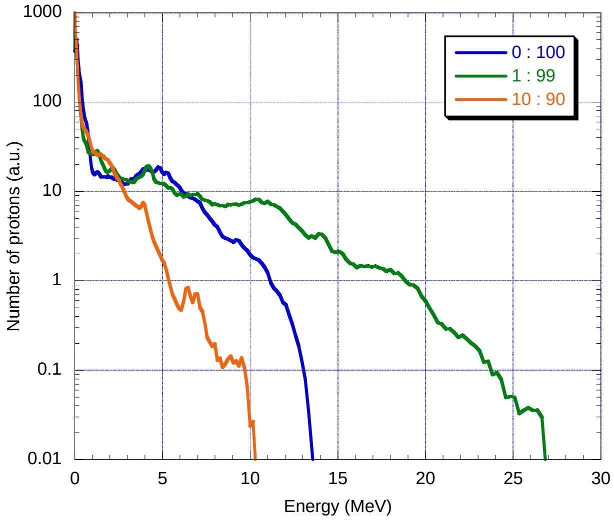

Figure 5. Simulated transverse ion spectra comparing different first to second pulse energy ratios all at an electron density of $0.05n_c$.

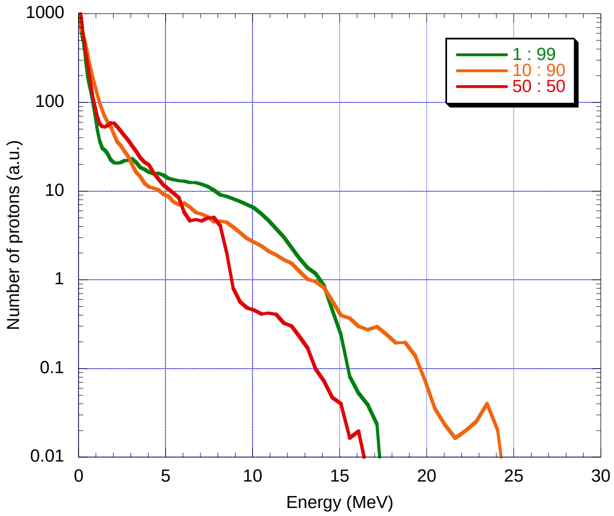

Figure 6. Simulated transverse ion spectra comparing different first to second pulse energy ratios all at an electron density of $0.1n_c$.

Figure 5 shows the transverse ion spectra 3.3 ps after the main pulse first enters the plasma for different pulse energy ratios all at a background electron density of $0.05n_c$. At low energies of less than 1 MeV the spectra are similar. However, the high-energy tails are very different. The 1:99 pulses gave a high energy tail up to 27 MeV. The single pulse (0:100) gave a maximum ion energy of 13.5 MeV. The 10: 90 ratio pulses on the other hand, produced maximum ion energy of only 10 MeV. Therefore, at $0.05n_c$, the most efficient ratio for the 3 ps inter-pulse time delay was the 1:99 ratio.

Figure 6 shows the transverse ion spectra of the lower resolution simulations 3.0 ps after the main pulse. These spectra indicate that at an electron density of $0.1n_c$, the most efficient ion acceleration is with the 10:90 pulse ratio. Therefore, again, the density seems important for the most efficient pulse ratios for maximising the ion acceleration.

Conclusions

In summary, the experimental and simulation results both demonstrate that the ion acceleration could possibly be enhanced by tuning the first to second pulse energy ratio. The maximised ratio seems strongly dependent upon the electron density of the plasma. In turn, if the ion acceleration at high electron densities can be maximised then this could provide a boost to the neutron yield. It is also likely that the inter-pulse delay provides a further parameter to optimise.

Acknowledgements

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