Light-sail acceleration from two moderate intensity pulses

Contact: `p.martin@qub.ac.uk`

P. Martin, S. Ferguson, A. McIlvenny,
M. Borghesi, S. Kar
Centre for Plasma Physics,
Queen's University Belfast,
United Kingdom

H. Ahmed, J. S. Green
Central Laser Facility,
Rutherford Appleton Laboratory,
United Kingdom

D. Doria
ELI NP,
Magurele, Ilfov,
Romania

S. Zhai
ELI Beamlines,
Dolní Břežany,
Czech Republic

J. Jarrett, P. McKenna
Department of Physics,
University of Strathclyde,
United Kingdom

Abstract

The acceleration of ions from ultrathin deuterated plastic foils is demonstrated by implementing two pulses with intensities on the order of 10^{19}W/cm^2, which could be spatio-temporally separated by varying degrees. At the optimal arrangement of the two pulses, maximum proton and deuteron energies of 45MeV and 33MeV/u, respectively, were accelerated from 85nm foils. This exceeded what was achieved from a single pulse irradiating the same target at $\sim 5\times 10^{20}$W/cm^2, despite the double pulse setup sacrificing a ~60% average reduction in total laser fluence on target.

1 Introduction

The field of laser driven ion acceleration has been an active area of research for some time and of interest for several multidisciplinary applications such as hadron therapy [1–3], nuclear fusion [4], neutron production [5–7], and particle radiography [8–10]. The most well-established mechanism of target normal sheath acceleration (TNSA) [11] deals with the irradiation of μm-thickness foils, and results in a broadband proton spectrum with a cutoff energy that scales with the peak laser intensity according to $E_{max} \propto I_0^{1/2}$.

For many of the applications listed above, a high energy, quasi-monoenergetic spectrum of ions is desired. This has lead, in recent years, to research investigating the acceleration of ions via the laser's radiation pressure (RPA) [12–15]. In the limit of ultrathin, nm-scale foils, the entire target bulk is accelerated at once by the laser pressure. This is known as the light sail (LS) mode of RPA [15–21], and has several advantages over TNSA, namely the monoenergetic acceleration, and more favourable scaing with the laser intensity. The ion's maximum energy predicted according to LS theory [17, 21] scales, in the non-relativistic limit, according to the relation:

$$\frac{E_{ion}}{Am_pc^2} \propto \left(\frac{a_0^2\tau}{\chi}\right)^2, \qquad (1)$$

where A is the ion mass number, m_pc^2 is the proton's rest mass-energy, and the terms $a_0 = 0.85\sqrt{I_0\lambda^2(\times 10^{18}\mathrm{W/cm^2}\cdot \mu m^2)}$, $\tau = ct_p/\lambda$, and $\chi = \rho l/\lambda m_p n_c$, are dimensionless parameters representing the laser intensity, pulse duration, and target areal density, respectively. Within these parameters, the terms t_p represents the pulse duration, λ the laser wavelength, ρ the target density, l the target thickness, and n_c the critical density for the laser. It can be seen from Eq. (1) that the ion maximum energy in this regime scales according to the laser pulse fluence, rather than the intensity.

An important caveat that comes with LS acceleration is that the target must remain opaque to the laser pulse in order for momentum transfer by the radiation pressure to occur. Therefore, the onset of relativistically induced transparency (RIT) that occurs in such high intensity interactions with ultrathin foils will effectively shut off RPA. By splitting the single high intensity pulse into two lower intensity pulses, one can achieve the same on target fluence, but greatly reduce the risk of RIT. This article reports on the first experimental demonstration of the use of two pulses of equal intensity incident on ultrathin foils to achieve a stable LS acceleration that accelerates ions to energies that surpassed what could be done when using a single, high intensity pulse incident on the same target.

2 Setup

The experiment was carried out on the petawatt arm of the VULCAN laser system, at the Central Laser Facility, UK. This delivers linearly polarised pulses of ~750fs FWHM duration and an average energy of 210J on tar-

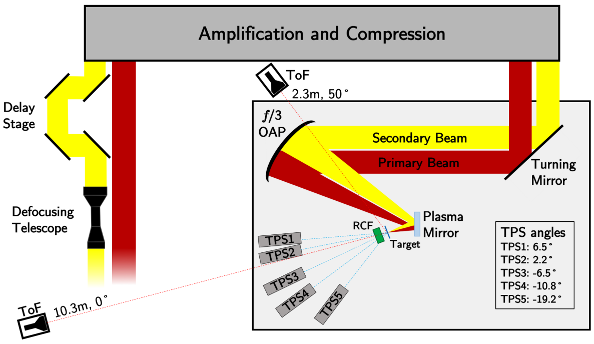

Figure 1: Schematic of the experimental setup when in the double pulse configuration. The delay stage and defocusing telescope in the secondary beamline are situated early in the laser chain, before the main amplification stages and compressor. The different colours of the beams are so they may be differentiated, and are not representative of their wavelength.

get, after reflection off a plasma mirror for temporal contrast enhancement. The laser was focused to a spot $\sim 5\mu$m FWHM in diameter, resulting in an on target intensity of $(3-5)\times 10^{20}$W/cm^2. In double pulse (DP) mode (see Fig. 1), the pulse is split early in the laser chain into two semicircular beams of equal area, known henceforth as the primary and secondary beams. The secondary beam was sent through a delay stage, and a defocusing telescope. The delay stage could be tailored to vary the arrival of the secondary pulse, relative to the primary, from 0ps to 20ps. The telescope introduced a small divergence into the beam, which meant the position of the secondary beams focal spot could be varied along the laser axis. The effect of the pulse splitting meant that the total energy on target from the two beams was on average 155J, ∼25% lower on average than what was reached when operating in single pulse mode, and the final focusing of the two spots was suboptimal, with ovular spots with major and minor diameters (FWHM) of (7-10)μm and (5-7)μm, respectively. These factors, and the more degraded spot from the secondary beam's passage through the telescope, resulted in on-target intensities of the primary and secondary beams of $(7-9)\times 10^{19}$ and $(5-7)\times 10^{19}$W/cm^2, respectively. The targets were aligned such that the laser was normally incident, and composed of deuterated plastic (CD) foils 60-1000nm in thickness. To diagnose the ion energy spectra, Thomson parabola spectrometers (TPS) were intstalled with image plate detectors using a differential filtering technique to distinguish the deuterons from the overlapping C^{6+} ions as described in Alejo *et al.* [22].

3 Results

A preliminary thickness scan of CD foils in single pulse (SP) mode was performed, and the optimum thickness, with highest ion energies, was found to be 143nm (see Fig. 2(c)). The next available thickness down, 85nm, was considered to be sub-optimal because the foil most likely undergoes RIT earlier in the rising edge of the pulse, leading to a less efficient LS stage. For this reason, 85nm was chosen as the thickness with which to perform the DP delay scan. The relative delay, ΔT, between the arrival of the primary and secondary pulses was varied from 0 to 20ps, and a peak in the ion maximum energy and central energy of the spectral bunch was observed for ΔT=2-6ps, seen in Figs. 2(a) and 2(b). A spectrum gained from irradiating 85nm with the primary pulse only is also shown in the figure, which exhibits energies of 15MeV protons and 6MeV/u deuterons. Preliminary particle-in-cell simulations indicate that this peak in energies at these time delays arises because the plasma, after the primary's irradiation, has expanded, reducing it's areal density. The areal density falls to a point where the light sail parameter, $a_0^2\tau/\chi$ (see Eq. 1), is at some optimal point - high enough to maximise the ion energies via LS, but not such a low density that RIT halts LS prematurely. For longer time delays, the ion energy decreases, as the now expanding plasma's density has decreased past the optimal, meaning the plasma will undergo RIT earlier in the secondary pulse's rising edge. The longer the plasma is allowed to expand, the earlier RIT will occur.

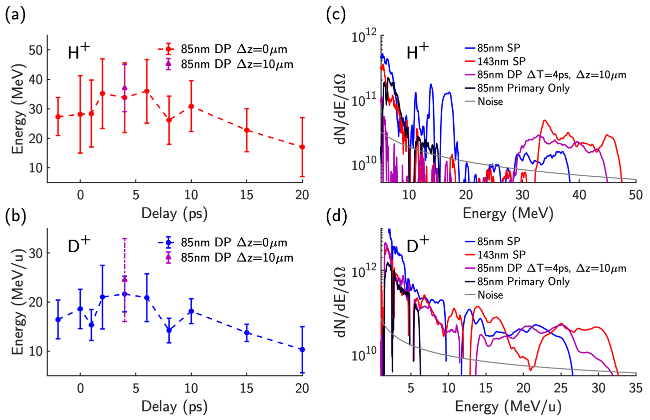

Figure 2: (a) Proton, and (b) deuteron central bunch energies along target normal direction vs time delay between the two beams in the double pulse setup. Also shown in purple is the highest energy reached when the secondary beam is focused 10μm further along the laser axis. The bars on each data point represent bunch widths of individual shots. The maximum limit of the bars correspond to the spectrum cutoff energies. (c) Proton and (d) deuteron TPS spectra, for selected SP and DP shots from the campaign, taken along the laser axis.

The relative focusing depth between the secondary pulse and the primary, Δz, was also varied, for delays of 4ps, i.e. around the optimal time delay for the DP setup. The highest proton and deuteron energies of 45MeV and 33MeV/u, respectively, was found for a setup with ΔT=4ps and Δz=10μm (the purple data point in shown in Figs. 2(a) and 2(b)). This matches what was achieved on SP at the optimal thickness of 143nm (see Figs. 2(c) and 2(d)), while sacrificing 25% of the total energy, and focused to degraded focal spots, which further lowered the total fluence significantly. This implies that the DP setup achieved similar ion energies while operating at an energy deficit of 40%. Taking the degraded DP focal spots to each have the average major and minor FWHM diameters of $(8 \pm 1)\mu$m and $(6 \pm 1)\mu$m, respectively, and the SP shot has the minimum spot diameter of $(5 \pm 0.5)\mu$m, this leads to an average fluence deficit across all shots of $F_{DP}/F_{SP} = 0.38 \pm 0.12$, equivalent to $(62 \pm 12)\%$ lower fluence when operating in the DP setup. Preliminary particle-in-cell simulations have been performed, showing a peak in ion energies at an optimal time delay. This arises due to the reduction of the target density to some optimal level for the secondary pulses radiation pressure to become significant.

4 Conclusion

In conclusion, we have demonstrated an enhancement in the light sail acceleration of ions by utilising a double pulse arrangement. Despite sacrificing 62% of the average total laser fluence on average, ion bunches were produced at energies and fluxes comparable to what was achieved with single pulses.

References

[1] S.V Bulanov, T.Zh Esirkepov, V.S Khoroshkov, A.V Kuznetsov, and F Pegoraro. Oncological hadrontherapy with laser ion accelerators. *Physics Letters A*, 299(2):240 – 247, 2002. ISSN 0375-9601. doi: https://doi.org/10.1016/S0375-9601(02)00521-2.

[2] D. Doria, K. F. Kakolee, S. Kar, S. K. Litt, F. Fiorini, H. Ahmed, S. Green, J. C G Jeynes, J. Kavanagh, D. Kirby, K. J. Kirkby, C. L. Lewis, M. J. Merchant, G. Nersisyan, R. Prasad, K. M. Prise, G. Schettino, M. Zepf, and M. Borghesi. Biological effectiveness on live cells of laser driven protons at dose rates exceeding 109 Gy/s. *AIP Adv.*, 2(1), 2012. ISSN 21583226. doi: 10.1063/1.3699063.

[3] F. Hanton, P. Chaudhary, D. Doria, D. Gwynne, C. Maiorino, C. Scullion, H. Ahmed, T. Marshall, K. Naughton, L. Romagnani, S. Kar, G. Schettino, P. McKenna, S. Botchway, D. R. Symes, P. P. Rajeev, K. M. Prise, and M. Borghesi. DNA DSB Repair Dynamics following Irradiation with Laser-Driven Protons at Ultra-High Dose Rates. *Sci. Rep.*, 9(1):1–10, 2019. ISSN 20452322. doi: 10.1038/s41598-019-40339-6.

[4] M. H. Key. Status of and prospects for the fast ignition inertial fusion concept. *Phys. Plasmas*, 14(5), 2007. ISSN 1070664X. doi: 10.1063/1.2719178.

[5] P Norreys, P Fews, F N Beg, R Bell, A E Dangor, P Lee, M B Nelson, H Schmidt, M Tatarakis, and M D Cable. Neutron production from picosecond laser irradiation of deuterated targets at intensities of 10^{19} W/cm2. *Plasma Phys. Control. Fussion*, 40:175–182, 1998. ISSN 0741-3335. doi: 10.1088/0741-3335/40/2/001.

[6] S. Kar, A. Green, H. Ahmed, A. Alejo, A. P.L. Robinson, M. Cerchez, R. Clarke, D. Doria, S. Dorkings, J. Fernandez, S. R. Mirfayzi, P. McKenna, K. Naughton, D. Neely, P. Norreys, C. Peth, H. Powell, J. A. Ruiz, J. Swain, O. Willi, and M. Borghesi. Beamed neutron emission driven by laser accelerated light ions. *New J. Phys.*, 18(5), 2016. ISSN 13672630. doi: 10.1088/1367-2630/18/5/053002.

[7] S. R. Mirfayzi, A. Alejo, H. Ahmed, D. Raspino, S. Ansell, L. A. Wilson, C. Armstrong, N. M.H. Butler, R. J. Clarke, A. Higginson, J. Kelleher, C. D. Murphy, M. Notley, D. R. Rusby, E. Schooneveld, M. Borghesi, P. McKenna, N. J. Rhodes, D. Neely, C. M. Brenner, and S. Kar. Experimental demonstration of a compact epithermal neutron source based on a high power laser. *Applied Physics Letters*, 111(4), 2017. ISSN 00036951. doi: 10.1063/1.4994161.

[8] M. Borghesi, A. J. Mackinnon, D. H. Campbell, D. G. Hicks, S. Kar, P. K. Patel, D. Price, L. Romagnani, A. Schiavi, and O. Willi. Multi-mev proton source investigations in ultraintense laser-foil interactions. *Phys. Rev. Lett.*, 92:055003, Feb 2004. doi: 10.1103/PhysRevLett.92.055003.

[9] M Borghesi, A Schiavi, D H Campbell, M G Haines, O Willi, A J MacKinnon, L A Gizzi, M Galimberti, R J Clarke, and H Ruhl. Proton imaging: a diagnostic for inertial confinement fusion/fast ignitor studies. *Plasma Physics and Controlled Fusion*, 43(12A):A267–A276, nov 2001. doi: 10.1088/0741-3335/43/12a/320.

[10] L. Romagnani, J. Fuchs, M. Borghesi, P. Antici, P. Audebert, F. Ceccherini, T. Cowan, T. Grismayer, S. Kar, A. Macchi, P. Mora, G. Pretzler, A. Schiavi, T. Toncian, and O. Willi. Dynamics of electric fields driving the laser acceleration of multi-MeV protons. *Phys. Rev. Lett.*, 95(19):4–7, 2005. ISSN 00319007. doi: 10.1103/PhysRevLett.95.195001.

[11] S. C. Wilks, A. B. Langdon, T. E. Cowan, M. Roth, M. Singh, S. Hatchett, M. H. Key, D. Pennington, A. MacKinnon, and R. A. Snavely. Energetic proton generation in ultra-intense laser-solid interactions. *Phys. Plasmas*, 8(2):542–549, 2001. ISSN 1070664X. doi: 10.1063/1.1333697.

[12] A. P.L. Robinson, P. Gibbon, M. Zepf, S. Kar, R. G. Evans, and C. Bellei. Relativistically correct hole-boring and ion acceleration by circularly polarized laser pulses. *Plasma Phys. Control. Fusion*, 51(2), 2009. ISSN 07413335. doi: 10.1088/0741-3335/51/2/024004.

[13] T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, and T. Tajima. Highly efficient relativistic-ion generation in the laser-piston regime. *Phys. Rev. Lett.*, 92(17):2–5, 2004. ISSN 00319007. doi: 10.1103/PhysRevLett.92.175003.

[14] Andrea Macchi, Federica Cattani, Tatiana V. Liseykina, and Fulvio Cornolti. Laser acceleration of ion bunches at the front surface of overdense plasmas. *Phys. Rev. Lett.*, 94(16):2–5, 2005. ISSN 00319007. doi: 10.1103/PhysRevLett.94.165003.

[15] Andrea Macchi and Carlo Benedetti. Ion acceleration by radiation pressure in thin and thick targets. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, 620(1):41–45, 2010. ISSN 01689002. doi: 10.1016/j.nima.2010.01.057.

[16] A. P L Robinson, M. Zepf, S. Kar, R. G. Evans, and C. Bellei. Radiation pressure acceleration of thin foils with circularly polarized laser pulses. *New J. Phys.*, 10, 2008. ISSN 13672630. doi: 10.1088/1367-2630/10/1/013021.

[17] Andrea Macchi, Silvia Veghini, and Francesco Pegoraro. ”Light Sail” Acceleration Reexamined. *Phys. Rev. Lett.*, 103 (8):1–4, 2009. ISSN 00319007. doi: 10.1103/PhysRevLett.103.085003.

[18] Andrea Macchi, Silvia Veghini, Tatyana V Liseykina, and Francesco Pegoraro. Radiation pressure acceleration of ultrathin foils. *New Journal of Physics*, 12(4):045013, apr 2010. doi: 10.1088/1367-2630/12/4/045013.

[19] B. Qiao, M. Zepf, M. Borghesi, and M. Geissler. Stable GeV ion-beam acceleration from thin foils by circularly polarized laser pulses. *Phys. Rev. Lett.*, 102(14):1–4, 2009. ISSN 00319007. doi: 10.1103/PhysRevLett.102.145002.

[20] B. Qiao, M. Zepf, M. Borghesi, B. Dromey, M. Geissler, A. Karmakar, and P. Gibbon. Radiation-pressure acceleration of ion beams from nanofoil targets: The leaky light-sail regime. *Phys. Rev. Lett.*, 105(15):8–11, 2010. ISSN 00319007. doi: 10.1103/PhysRevLett.105.155002.

[21] S. Kar, K. F. Kakolee, B. Qiao, A. Macchi, M. Cerchez, D. Doria, M. Geissler, P. McKenna, D. Neely, J. Osterholz, R. Prasad, K. Quinn, B. Ramakrishna, G. Sarri, O. Willi, X. Y. Yuan, M. Zepf, and M. Borghesi. Ion acceleration in multispecies targets driven by intense laser radiation pressure. *Phys. Rev. Lett.*, 109(18):1–5, nov 2012. ISSN 00319007. doi: 10.1103/PhysRevLett.109.185006.

[22] A. Alejo, S. Kar, H. Ahmed, A. G. Krygier, D. Doria, R. Clarke, J. Fernandez, R. R. Freeman, J. Fuchs, A. Green, J. S. Green, D. Jung, A. Kleinschmidt, C. L S Lewis, J. T. Morrison, Z. Najmudin, H. Nakamura, G. Nersisyan, P. Norreys, M. Notley, M. Oliver, M. Roth, J. A. Ruiz, L. Vassura, M. Zepf, and M. Borghesi. Characterisation of deuterium spectra from laser driven multi-species sources by employing differentially filtered image plate detectors in Thomson spectrometers. *Rev. Sci. Instrum.*, 85(9):0–7, 2014. ISSN 10897623. doi: 10.1063/1.4893780.

[23] S. R. Mirfayzi, S. Kar, H. Ahmed, A. G. Krygier, A. Green, A. Alejo, R. Clarke, R. R. Freeman, J. Fuchs, D. Jung, A. Kleinschmidt, J. T. Morrison, Z. Najmudin, H. Nakamura, P. Norreys, M. Oliver, M. Roth, L. Vassura, M. Zepf, and M. Borghesi. Calibration of time of flight detectors using laser-driven neutron source. *Rev. Sci. Instrum.*, 86(7), 2015. ISSN 10897623. doi: 10.1063/1.4923088.