Laser-driven ion acceleration via target normal sheath acceleration in the relativistic transparency regime

P I. Poole\textsuperscript{1,} \textsuperscript{2,} \textsuperscript{4,} L Obst\textsuperscript{2,} \textsuperscript{4}, G E Cochran\textsuperscript{3,} J Metzkes\textsuperscript{4,} H-P Schlenvoigt\textsuperscript{4}, I Prencipe\textsuperscript{1,} T Kluge\textsuperscript{1,} T Cowan\textsuperscript{2,3,} U Schramm\textsuperscript{2,4} and K Zeil\textsuperscript{1,} \textsuperscript{2,}\textsuperscript{3,} \textsuperscript{4}

\begin{itemize}
\item \textsuperscript{1} Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94551, United States
\item \textsuperscript{2} Helmholtz-Zentrum Dresden-Rossendorf, Dresden D-01314, Germany
\item \textsuperscript{3} Technische Universität Dresden, Dresden D-01062, Germany
\item \textsuperscript{4} The Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210, United States
\end{itemize}

E-mail: poole11@llnl.gov

Keywords: plasma physics, ion acceleration, ultra-intense laser, liquid crystal

Abstract

We present an experimental study investigating laser-driven proton acceleration via target normal sheath acceleration (TNSA) over a target thickness range spanning the typical TNSA-dominant regime (∼1 \textmu m) down to below the onset of relativistic laser-transparency (<40 nm). This is done with a single target material in the form of freely adjustable films of liquid crystals along with high contrast (via plasma mirror) laser interaction (∼2.65 \textmu J, 30 fs, I > 1 \times 10^{21} \text{ W cm}^{-2}). Thickness dependent maximum proton energies scale well with TNSA models down to the thinnest targets, while those under ∼40 nm indicate the influence of relativistic transparency on TNSA, observed via differences in light transmission, maximum proton energy, and proton beam spatial profile. Oblique laser incidence (45°) allowed the fielding of numerous diagnostics to determine the interaction quality and details: ion energy and spatial distribution was measured along the laser axis and both front and rear target normal directions; these along with reflected and transmitted light measurements on-shot verify TNSA as dominant during high contrast interaction, even for ultra-thin targets. Additionally, 3D particle-in-cell simulations qualitatively support the experimental observations of target-normal-directed proton acceleration from ultra-thin films.

1. Introduction

A primary research endeavor of ultra-intense laser plasma interaction is efficient secondary radiation production. Selection of various laser and target parameters can cause transfer of laser energy into electron beams [1], x-rays or neutron beams for radiography or remote detection applications [2, 3], positron–electron plasmas for fundamental studies related to astrophysics [4], and ion beams, which relate to radiography [5], generation of warm dense matter [6], and cancer therapy [7–10]. Efforts towards ion beam applications are hastened due to high power, high repetition rate laser facilities currently under development [11–13].

The realization of ion beam application goals faces two critical challenges. From a practical perspective, one needs the ability to produce sufficient ion flux through efficient procedures-rapid target insertion, laser operation, and optimized on-line diagnostics. More fundamentally, a thorough understanding of the underlying processes that govern ion acceleration in order to better control aspects such as kinetic energy, particle number, and beam profile is required. For this, increases in laser energy and power have not yielded ion energies necessary to achieve applications like cancer therapy due in part to poor scaling with laser intensity and also to stringent requirements on laser parameters like pulse contrast, which measures the intensity of unwanted but often unavoidable ‘pre-pulse’ light preceding the main beam relative to that of the peak pulse. While several mechanisms have been identified for ion acceleration [14–18] and multiple reviews have been done to accumulate experiment, simulation, and model descriptions of these [19, 20], the optimization of a given mechanism for an application on any particular facility remains difficult.

© 2018 The Author(s). Published by IOP Publishing Ltd on behalf of Deutsche Physikalische Gesellschaft
Target normal sheath acceleration (TNSA) \([14, 15]\), involves rear surface layer particles accelerated in the target normal direction up to tens of MeV/nucleon energies by a space-charge electric field set up as fast electrons originating in the front-side pre-plasma are laser-accelerated through the target. TNSA can benefit from pre-pulses—the resulting target pre-plasma is abundant with electrons available for laser acceleration, yielding a larger rear-surface sheath field—but will suffer if the target is sufficiently deformed by these early pulses or if the pre-pulse scale length becomes too long \([20, 21]\). Because of this TNSA is typically maximized for targets robust enough to withstand initial interaction with the laser pre-pulse and main pulse rising edge, typically above several hundred nm. TNSA is nevertheless observed on both short and long pulse systems: current experimental benchmarks for TNSA include 40 MeV protons for ultra-short pulse interaction \([22]\) and 85 MeV for longer pulse lasers \([23]\), both achieved with \(\sim 1\) \(\mu\)m thick foils.

Other ion acceleration mechanisms can arise for thinner targets (below 100 nm), but therefore often require intensity contrasts superior to \(10^{-10}\):1 for times at least one ps before the main pulse arrives to preserve target integrity. Sufficiently thin targets can undergo light-sail radiation pressure acceleration \([16]\), where the target receives initial momentum from the laser and then travels along with the pulse to continually gain energy \([20]\). This process requires irradiation with high intensity, exceptionally spatially homogeneous pulses of circularly polarized light at normal incidence to minimize early target heating and expansion. Other mechanisms can be categorized as enhanced-TNSA \([17, 18]\) where an increase in laser penetration due to a relativistic reduction of the plasma frequency (an effect known as relativistic transparency) results a larger volume of electrons being accelerated to generate the sheath field. While these mechanisms may scale more favorably with laser intensity than TNSA \([20]\) they are also difficult to produce in experiments due in part to facility limits but also to interference from plasma instabilities and other complex interactions \([24-26]\).

What follows is the first experimental study of ultra-short pulse proton acceleration investigated with oblique laser incidence from the TNSA-dominant thickness regime down to that of relativistic transparency with a single target material. This is enabled first by high contrast (via a plasma mirror) interaction, as superior laser pulse quality is required for successful ion acceleration from ultra-thin targets, and secondly by an in situ target formation system using freely suspended liquid crystal films \([27]\). This material can be drawn across an aperture in a rigid frame with changes in wiping speed, temperature, and liquid crystal volume to form films several mm in diameter at repetition rates of 0.1 Hz and with thicknesses from 10 nm to several 10 s of \(\mu\)m \([28]\). Critically, the in situ target formation device forms films to within 2 \(\mu\)m of the same position each formation, removing the necessity for between-shot target alignment and thus allowing rapid data collection. While this on-demand thickness manipulation has been demonstrated as an avenue toward high formation rate plasma mirrors \([29]\), it is utilized here to enable a detailed investigation of the influence of target thickness on ion acceleration mechanisms, including the ultra-thin regime (<40 nm). Furthermore, the low density (~1 g/\(\mathrm{cm}^3\)) of liquid crystal used and thin target formation capabilities allowed easy access to the transparency regime.

Ultra-short (\(r = 30\) fs) pulses of \(\sim 2.65\) J were incident on targets at 45° in order to distinguish between laser-axis and target-normal directed acceleration. A single plasma mirror was optional to ascertain differences between moderate(\(10^{-6}:1\)) and ultra-high (\(10^{-10}:1\)) contrast. Oblique target incidence also allowed multiple secondary diagnostics to corroborate the target conditions during ultra-thin target proton beam production including ion spatial and energy diagnostics in the front normal, rear normal, and laser axis directions, as well as reflected and transmitted light diagnostics able to measure during laser interaction due to the optical quality of the liquid crystal film surface. The data show efficient acceleration yielding high quality proton beams (beam profile, divergence) in the target-normal direction and ion energy scaling with target thickness in agreement with TNSA models down to the ultra-thin region. Increased laser transparency is observed below the \(\sim 40\) nm relativistic skin depth, and the thinnest (~10 nm) targets exhibit higher average proton energy but larger shot-to-shot fluctuations along with changes in proton spatial characteristics including less homogeneity at large angles from target normal.

2. Experimental setup and apparatus

The experiment was performed on the Draco laser facility at HZDR, which is a 3.5 J, 30 fs, 10 Hz titanium: sapphire based system capable of intensities exceeding \(1 \times 10^{21}\) \(\text{W cm}^{-2}\) in a 3 \(\mu\)m diameter FWHM focal spot. Figure 1 (a) shows a simplified schematic of the primary diagnostic setup, which included an optional single plasma mirror for pulse contrast enhancement. Contrast measurements with and without a plasma mirror are shown in figure 1 (b). The optics design focused light onto and then recollected it from the plasma mirror with off-axis parabolas which allowed the setup to be bypassed if desired by moving an additional mirror into the beam-path. The entire plasma mirror optics path had an energy throughput of 80%, resulting in energies between 2.55 and 2.75 J on target. Near-field measurements after plasma mirror reflection were monitored on each shot and did not reveal modulations that would suggest a reduction in final focal spot quality. The plasma
mirror substrate had dimensions of 50 mm × 95 mm which allowed about 450 few mm spots to be used before it needed to be replaced.

The primary ion diagnostics were multi channel plate Thomson parabola spectrometers (TPS) situated along the laser axis (0°) and target normal (45°) axes, with energy resolution of 0.5–1 MeV from 0 to 30 MeV. Additionally, spatial information of accelerated protons was recorded for a number of shots on radiochromic film (RCF) packs, which could be moved into place on-demand at a distance of 55 mm from the target.

Additional diagnostics were implemented to investigate the reflected and transmitted light upon interaction with the optical quality target surface. This would not only reveal the onset of transparency effects and allow their interaction with ion acceleration to be observed, but also would allow target morphology conditions to be determined at the time of laser interaction. A piece of spectralon (Lambertian scatterer) was used to collect the transmitted beam mode, and a ceramic (MACOR) screen served the same purpose for the reflected light. Two cameras filtered for 1ω and 2ω observed scattered light imaged from the ceramic screen along the same line of sight by using a dichroic mirror. A final diagnostic was a sheet of LANEX, which fluoresces upon impact by energetic electrons, to reveal the spatial distribution of target front-surface electrons ejected in the reflection direction. On some shots a rough electron energy spectrum was obtained using transmission through a wedged aluminum piece in front of the screen.

Liquid crystal films were formed within a linear slide target inserter device (LSTI) [28], as shown in figure 1(c). The 4mm diameter circular aperture was oriented at 45° with respect to the incoming laser axis. 10 μl of the liquid crystal 4-cyano-4’-octylbiphenyl (8CB) was applied to the wiper, which allowed several dozen films to be formed before the chamber needed to be opened for new volume application. A cooled water line pumped by a small chiller unit was installed through the chamber wall to maintain the LSTI frame at the desired temperature for film control, typically around 28.0 °C. Film thicknesses were measured on-demand by white light interferometry, which was relayed in from outside the chamber. The LSTI design utilizes the same liquid crystal mesophase surface tension that enables freely suspended film formation to draw films at the front aperture edge within 2 μm of the same position each time, which eliminates the need for target alignment after it is performed on the first film. This alignment, performed with a scattered light imaging system, was verified by observing the accelerated proton energy with on-shot diagnostics as the target was shifted along the incoming laser axis. All data shown here was taken at best focus.

Figure 1. (a) Diagram of experimental setup including recollimating geometry plasma mirror, linear slide target inserter (LSTI) for in situ variable thickness target formation, Thomson parabola spectrometers (TPS) along the laser (0°) and target normal (45°) axes, scatter screens (spectralon) for reflected and transmitted light measurement, and a LANEX screen for measurement of specularly reflected electrons. (b) Measured ps intensity contrast without plasma mirror (blue line) and with plasma mirror (black dots); dashed line indicates ionization threshold. (c) Forming liquid crystal film with the 4 mm diameter aperture LSTI device.
3. Experimental data and analysis

3.1. TNSA behavior

The central experimental result is shown in figure 2(a): maximum proton cutoff energy recorded on the target normal TPS for film thicknesses ranging from >1 μm to 10 nm. Open blue circles indicate the maximum energy observed on the target normal Thomson parabola, and the filled circles are averages of these values with bin size indicated by shaded background region. Pink circles are from RCF stacks and serve to corroborate the Thomson parabola data. While shots without a plasma mirror (triangles) demonstrated predictably decreasing maximum proton energy as film thicknesses decreased below 1 μm, the high contrast data shown here exhibits an overall increase in proton cutoff energy along the target normal direction as thickness decreases down to 300 nm, at which point the cutoff energies plateau. This behavior is in agreement with TNSA scaling law predictions [30–32], where maximum proton energy depends on the electron density within the Debye sheath. Assuming that electron density depends on their divergence angle and path length to target rear (i.e. target thickness), a saturation for small thicknesses is expected. The fit shown is calculated using 1D TNSA model [30] with electron temperature scaling [32] and a best fit free parameter $a_0 \sim 17$; this vector potential corresponds to intensity $I = 6 \times 10^{20}$ W cm$^{-2}$, reasonably close to the estimated experimental peak intensity of $10^{21}$ W cm$^{-2}$.

Carbon ion (C$^+$) cutoff energies in the target normal direction exhibit the same target thickness dependence as the protons down to the thinnest targets, with a ratio of proton/carbon $6^+$ energies whose average remains near 3, shown in figure 2 with error bars. This behavior suggests that both protons and carbon ions gain energy in the same sheath field for each target as thickness is reduced, and in general is in agreement with predictions for TNSA [31].

The high proton energy achieved for ultra-thin targets suggests a high contrast laser interaction, where the target surfaces remain intact before the main pulse arrives. This is supported by observations of the specular-directed optical emission during laser interaction recorded with both $1\omega$ and $2\omega$ filters. Here we expand the measurement of previous target emission studies [33, 34] by always using peak laser intensity but with deliberate pulse contrast differences; figure 3 shows representative images of the moderate (no plasma mirror, left) and high contrast laser reflection (right). High contrast results in significantly enhanced reflected light levels and a better-defined spatial mode. Under this condition of unperturbed target surface at the initiation of high intensity laser interaction, $2\omega$ emission becomes visible, with expected spatial modulations due to the strongly intensity-dependent generation process. This improved reflection quality indicates a minimally expanded critical surface in the high contrast case [35] and was observed even for ultra-thin targets.

High contrast interaction is further corroborated by the LANEX diagnostic observing electrons ejected in the laser reflection direction during target interaction. Up to 30 nC sr$^{-1}$ was measured in electron distributions with energies exceeding 9 MeV, obtained by recording the calibrated [36] LANEX fluorescence behind different
thicknesses of the Al wedge. This is similar to recent results [37] where electrons ejected in this manner required laser interaction with a sharp density profile originating from high contrast pulse irradiation.

Figure 4 shows target normal ion energy traces for various thickness targets (blue lines) for comparison to an average of those laser axis ion spectra observed (red). While all targets have similar spectral shape at low proton energies, the thinnest targets also exhibit increased high energy component suggesting a greater hot electron population. The majority of shots (>90%) at high contrast showed no laser axis ion signal for any thickness, and when present the laser axis energy cutoff and yield were always significantly lower than that observed along target normal for the same shot.

The target normal spatial distribution of proton emission, shown for various thicknesses in figure 5, was of consistently small divergence (<10°) at low and high energy for all thicknesses. This was true even for ultra-thin targets near the transparency threshold with the exception of radial streaking in the low energy ion signal (as in the 4.7 MeV, 6 nm sheet in figure 5). For comparison, the rightmost film is one layer from a moderate contrast, 6500 nm target result, demonstrating significantly larger beam divergence.
The proton acceleration was also measured with RCF film from both the forward and backward target normals for a single target thickness of 36 nm, selected as near the relativistic transparency transition. Figure 6 shows that protons from these two directions are similar in maximum energy, yield, and beam divergence, indicating similarly strong accelerating fields on both surfaces. This is a hallmark of the TNSA mechanism and has been observed previously \cite{38, 39} in the case where the target front is sufficiently unperturbed by laser pre-pulse. A slight offset is observed in the proton emission centroid from exactly the target normal direction: toward the reflected laser in the backward direction and toward the transmitted laser in the forward direction (as indicated by the inset). This angular shift is attributed to an intra-pulse TNSA effect whereby the electron distribution accelerated in the direction of the reflected/transmitted beam will cause a sheath field asymmetry which likewise impacts the proton beam direction \cite{40}.

**Figure 5.** Radiochromic film (RCF) stacks demonstrating spatial distribution of accelerated protons for different target thicknesses (indicated along top) irradiated with high contrast pulses. Consistency in both beam divergence and overall shape is observed except for ultra-thin films. The rightmost sheet is a representative RCF layer for a moderate contrast shot, demonstrating a higher ion divergence under these conditions.

**Figure 6.** Representative RCF layers placed in the forward (within incoming laser, top images) and backward (bottom images) target normal axis. The maximum energies for these are 12 MeV and 10 MeV, respectively, for this 36 nm thick target. The inset shows the orientation of the target and RCF stacks, along with the direction protons are shifted with respect to the target normal axis (dark central hole).
3.2. Transition to transparency

While the energy spectra, spatial distribution, and directionality of the acceleration ions suggests TNSA as the dominant mechanism for low and high contrast shots for thicknesses from 40 nm and above, additional characteristics were observed for ultra-thin targets in the relativistic transparency regime. This state was verified in several ways, but most directly by measuring the laser pulse transmitted through the target. These values are shown in figure 7 as a function of film thickness. Thicknesses above 40 nm exhibit a nearly constant average of \( \approx 5\% \) transmission, but those below show both increased average transmission as well as greater shot-to-shot fluctuation.

There is a similar increase in maximum proton energy fluctuations for these ultra-thin targets. Near 10 nm target thickness proton energies ranged from 16 to 26 MeV (see figure 2(a))—despite this the average maximum energy was higher for these thinnest targets. A third observation from the transparency regime was a radial streak pattern outside the primary proton spatial structure visible in the lowest energy RCF layers, as in the top left stack of figure 5. These thinnest targets still showed a high quality reflection during laser interaction, so this burst proton pattern is suspected to originate not from target expansion via pre-pulse but rather from late-time TNSA fields still accelerating particles as the target volume expands after laser interaction.

Although fluctuations in the transmitted light, maximum proton energy, and low-energy spatial distribution were observed for ultra-thin target interaction, none of these effects are seen to correlate strongly with each other, nor with other measured values such as the quality of the reflected or transmitted modes. Additionally, the proton energy only weakly correlates with the \( \pm 2\% \) laser energy fluctuations on target. Critically, the ratio of proton to carbon \( 6^+ \) does not fluctuate largely at the thinnest targets (figure 2(b)), suggesting that rear surface acceleration and hence the target integrity is not affected. As such the source of these fluctuations is believed to be related to underlying laser plasma interaction in this relativistic regime, the details of which will be further studied with particle-in-cell simulations.

4. Simulations

Simulation efforts for comparison to experimental observations first focused on ion acceleration behavior with thickness: figure 8 shows snapshots in time of the Poynting vector magnitude \( S \), accelerated proton trajectory, and energy spectrum. These fully 3D particle-in-cell simulations were performed using the code large scale plasma (LSP) [41] with 8CB targets using an implicit field solver and particle advance as well particle tracking. A \( p \)-polarized laser pulse (\( \lambda = 800 \text{ nm, } \tau = 30 \text{ fs FWHM sin}^2 \) intensity temporal envelope) with a peak intensity of \( 1 \times 10^{21} \text{ W cm}^{-2} \) is incident at 45° on target, with \( x \) as the target normal direction. The target is composed of fully ionized carbon and hydrogen atoms in their stoichiometric ratio in the liquid crystal 8CB, with an electron density of 184 \( n_e \) and an initial electron temperature \( T_e = 10 \text{ keV} \). There were 125 particles per species per cell in the 300 nm target simulation, and 8 particles per species per cell in the 30 nm target simulation.

For the 300 nm target, the target normal cell size \( \Delta x = 15 \text{ nm and } \Delta y = \Delta z = 45 \text{ nm} \). In the case of the 30 nm target, \( \Delta x = 1.5 \text{ nm in the 150 nm directly around the target, expanding out to 12 nm; } \Delta y = \Delta z = 12 \text{ nm throughout the grid. In order to maximize vacuum acceleration length while limiting computational cost, the spot size used (1.2 \( \mu \text{m, Gaussian FWHM} \) was smaller than in the experiment to...
decrease transverse target extent. Additionally, the cells used do not resolve the Debye length (roughly 1 nm); as such, the energy-conserving force interpolation of LSP was employed to mitigate numerical heating. These simulations were conducted with a 0.75 Courant timestep.

Figures 8(a) and (b) show the strong dependence of laser penetration on target thickness. In figure 8(a) the magnitude of the Poynting vector is plotted at $t_0 + 20$ fs where $t_0$ is the time at which the peak of the laser pulse reaches the focus. The laser pulse is largely reflected from the still opaque 300 nm target. Plotting the same quantity at the same point in time in figure 8(b) shows the laser has penetrated through the 30 nm target. The total flux passing through simulation planes at $-1.8$ and $2.5 \mu m$ was recorded for both simulations, allowing measurement of total reflectivity and transmission. The 300 nm target showed 73% reflectivity and 2% transmission, while the 30 nm target showed a marked decrease in reflectivity (61%) and a slight increase in transmission (5%). This is consistent with the trend seen in experiment, where the amount of transmitted light increased substantially around a 30 nm target thickness (see figure 7).

Figure 8(c) shows the late-time angular distribution of accelerated protons for $t_0 + 300$ fs for two film thicknesses: the 300 nm target (blue) displays protons directed along target normal in a tight grouping, while the 30 nm target (orange) also shows general target normal acceleration although now with a somewhat broader distribution angle. Dominant proton acceleration in the target normal direction for both thick and relativistically transparent targets are observed, consistent with experimental results. This deviation from true target normal is in a consistent direction with that shown in figure 6, coming from a similar sheath field asymmetry [40].

Finally, figure 8(d) shows the experimental average proton cutoff energies from figure 2(a) in blue with the cutoff energy obtained from the two simulation thicknesses overlaid in red. The simulation cutoff energies fall reasonably close to experimental values and importantly reflect the general experimental trend of highest energies from thinnest targets. The discrepancy seen is most likely due to the simulation laser pulse not properly accounting for the small amount of laser pre-pulse remaining after plasma mirror reflection in the experiment, instead using an idealized pulse shape and beginning with a pre-ionized, initially hot target plasma. A full study of these pre-pulse related effects on the ultra-thin targets is planned to further investigate the ion acceleration fluctuations observed in this regime.
5. Comparison to literature

Figure 9 shows maximum proton energy thickness scans taken from numerous literature references, where those with $>3$ distinct thicknesses and linearly polarized pulses were selected. Here normal incidence data are indicated as triangles, non-normal as circles, and the data presented in this work as stars (also non-normal). Filled points are short pulses ($<50$ fs) and open are long ($>500$ fs). In general higher laser energies result in higher maximum proton energies, but the efficiency can vary strongly depending on other laser conditions.

Foremost, laser contrast plays an important role in the nature of proton acceleration as thickness is varied: maximized TNSA cutoff energy will occur at that thickness where electron divergence through the target and pre-pulse expansion from imperfect contrast are both minimized $[31, 52]$. Several previous thickness scans $[42, 45, 50, 51]$ therefore exhibit a peak of maximum proton cutoff energy at a certain thickness. If the laser pre-pulse can be sufficiently suppressed, proton cutoff energies tend to rise slightly or plateau as thickness decreases to 100 nm and below, as seen in $[23, 26, 47−50]$. Those datasets with thicknesses below the transparency regime ($<40$ nm) can exhibit a slight increase in proton energy here possibly due to a related enhancement effect. This is true as well of the averaged data presented in this work (black stars), which was also high contrast.

The uniqueness of the dataset presented here is then twofold: first, no other data spans the range from few nm to few $\mu$m with a single target material, enabling measurement of TNSA over the entire range of thicknesses previously seen as optimum with other laser conditions. The absence of a strong peak confirms the pre-pulse/electron divergence trade-off described previously. Secondly, this data is the only one to examine non-normal incidence below 100 nm, and the continued increase of cutoff energy in the target normal direction here suggests TNSA as a relevant acceleration mechanism for thicknesses down to the onset of laser transparency. Full characterization of the enhancement regime for targets near 10 nm requires further study with exceptional laser contrast and in particular with a quantity of shots capable of fully mapping the fluctuation regime observed in this experiment, which is only now possible due to laser and solid target technology advancements.

6. Conclusion

Presented here is a high granularity thickness scan of ultrashort pulse ion acceleration, the first to study oblique incidence interaction from the TNSA regime down below the onset of relativistic transparency, where proton energies are observed beyond 25 MeV with $\sim 2.65$ J, 30 fs pulses. Oblique laser incidence was used to discriminate between target normal and laser axis directed ion acceleration, which was verified with angularly separated ion and optical diagnostics that simultaneously ascertained high contrast laser-target interaction. In particular, the data set presented shows consistent TNSA energies for thicknesses down to $\sim 100$ nm if sufficient contrast can be achieved, providing an avenue toward repeatable, predictable ion acceleration from such targets.
Additionally, target normal acceleration in the transparency regime—below 40 nm for the conditions used here—reveal inconsistencies in laser transmission, maximum proton energy, and proton beam spatial profile, the origins of which warrant further simulation and experiment study. In particular, additional experimental control in the form of deliberate pre-pulses that tailor the critical surface and pre-plasma scale length could shed light on further acceleration dynamics.

The large data set allowing a credible statistical evaluation of the acceleration dynamics was able to be collected due to a combination of rapid shot-on-demand, ultra-high contrast laser, diagnostic, and target operation, and serves as an important step towards applications that will require optimized ion acceleration from high repetition rate laser plasma interaction. In particular, the observed proton energy stability in the regime below 100 nm but above the relativistic transparency threshold from consistent laser conditions in combination with the rapid target formation of the LSTI device has achieved the robustness necessary for progress toward applications. Additionally, the low mass of these targets and minimal, optimally directed plasma ejecta of liquid crystal compared to traditional metallic foils both present excellent prospects for low-debris, high rate laser-target interaction. In this setup, the last remaining cost-intensive consumable is the plasma mirror substrate, which can in principle be replaced with a liquid-crystal based setup [29]. This combination of liquid crystal plasma mirror and target film formation in the 40–100 nm range is hence a credible path toward future application-relevant laser-driven ion sources.

Acknowledgments

This work was supported by the DARPA PULSE program through AMRDEC, by the NNSA (DE-NA0003107), by EC Horizon 2020 LASERLAB-EUROPE/LEPP (654148), by the German Federal Ministry of Education and Research (BMBF, 03Z0S11), and by an allocation of computing time from the Ohio Supercomputer Center.

ORCID iDs

P L Poole @ https://orcid.org/0000-0002-6874-6664
L Obst @ https://orcid.org/0000-0001-9236-8037
G E Cochran @ https://orcid.org/0000-0001-8959-8341
U Schramm @ https://orcid.org/0000-0003-0390-7671

References

[1] Leemans W P et al 2014 Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime Phys. Rev. Lett. 113 245002
[2] Murnane M M, Kapteyn H C, Rosen M D and Falcone R W 1991 Ultrafast x-ray pulses from laser-produced plasmas Science 251 531–6
[3] Ledingham K W D, McKenna P and Singhal R P 2003 Applications for nuclear phenomena generated by ultra-intense lasers Science 300 1107–11
[4] Chen H et al 2009 Making relativistic positrons using ultraintense short pulse lasers Phys. Plasmas 16 122702
[5] Bartal T et al 2012 Focusing of short-pulse high-intensity laser-accelerated proton beams Nat. Phys. 8 139–42
[6] Roth M et al 2009 Proton acceleration experiments and warm dense matter research using high power lasers Plasma Phys. Control. Fusion 51 124039
[7] Bulanov S V, Daido H, Esirkepov T Z, Khoroshkov V S, Koga J, Nishihara K, Pegoraro F, Tajima T and Yamagiwa M 2004 Feasibility of using laser ion accelerators in proton therapy AAPM Conf. Proc. 740 414–29
[8] Kraft S D et al 2010 Dose-dependent biological damage of tumour cells by laser-accelerated proton beams New J. Phys. 12 085003
[9] Yogo A et al 2011 Measurement of relative biological effectiveness of protons in human cancer cells using a laser-driven quasimonoenergetic proton beamline Appl. Phys. Lett. 98 053701
[10] Zeil K et al 2013 Dose-controlled irradiation of cancer cells with laser-accelerated proton pulses Appl. Phys. B 110 437–44
[11] Galitski S 2013 Laser-driven nuclear science and applications: the need of high efficiency, high power and high repetition rate laser beams Eur. Phys. J. Spec. Top. 224 2631–7
[12] Schreiber J, Bolton P R and Parodi K 2016 Invited review article: ‘hands-on’ laser-driven ion acceleration: a primer for laser-driven source development and potential applications Rev. Sci. Instrum. 87 071101
[13] Irmam A et al 2017 First results with the novel peta-watt laser acceleration facility in Dresden IOP Conf. Proc. 874 012028
[14] Snively R A et al 2000 Intense high-energy proton beams from petawatt-laser irradiation of solids Phys. Rev. Lett. 85 2945–8
[15] Hatchett S P et al 2000 Electron, photon, and ion beams from the relativistic interaction of petawatt laser pulses with solid targets Phys. Plasmas 7 2076
[16] Esirkepov T, Borghesi M, Bulanov S V, Mouriou G and Tajima T 2004 Highly efficient relativistic-ion generation in the laser-piston regime Phys. Rev. Lett. 92 175003
[17] Dhurimes E, Lefebvre E, Grenillet L and Malka V 2005 Proton acceleration mechanisms in high-intensity laser interaction with thin foils Phys. Plasmas 12 062704
[18] Yin L, Albright B J, Hegelich B M and Fernandez J C 2006 GeV laser ion acceleration from ultrathin targets: the laser break-out afterburner Laser Part. Beams 24 291–8
[19] Daido H, Nishihara K and Pirozhkov A S 2012 Review of laser-driven ion sources and their applications Rep. Prog. Phys. 75 056401
[20] Macchi A, Borghesi M and Passoni M 2013 Ion acceleration by superintense laser-plasma interaction Rev. Mod. Phys. 85 751–93
Poole P L, Andereck C D, Schumacher D W, Daskalova R L, Feister S, George K M, Willis C, Akli K U and Chowdhury E A 2014 Liquid

Dover N P

Schreiber J

Mora P 2003 Plasma expansion into a vacuum

Kluge T, Cowan T, Debus A, Schramm U, Zeil K and Bussmann M 2011 Electron temperature scaling in laser interaction with solids

Poole P L, Willis C, Cochran G E, Hanna R T, Andereck C D and Schumacher D W 2016 Moderate repetition rate ultra-intense laser

Dollar F

Kaluza M, Schreiber J, Santala M I K, Tsakiris G D, Eidmann K, Meyer-ter Vehn J and Witte K J 2004 In

Kim I J

Jung D

Palmer C A J

Wagner F

Badziak J, Jaboski S, Parys P, Rosiski M, Wooskis J, Sznydowski A, Antici P, Fuchs J and Mancic A 2008 Ultraintense proton beams from laser-induced skin-layer ponderomotive acceleration J. Appl. Phys. 104 063310

Ogura K, Nishiuichi M, Pirozhkov A S, Tanimoto T, Sagasaka A, Esirkepov T Z, Kando M, Shizuma T, Hayakawa T and Kiriyama H 2012 Proton acceleration to 40 MeV using a high intensity, high contrast optical parametric chirped-pulse amplification/Tisapphire hybrid laser system Opt. Lett. 37 2868–70

Wagner F et al 2016 Maximum proton energy above 85 MeV from the relativistic interaction of laser pulses with micrometer thick CH2 targets Phys. Rev. Lett. 116 205002

Palmer C A J et al 2012 Rayleigh–Taylor instability of an ultrathin foil accelerated by the radiation pressure of an intense laser Phys. Rev. Lett. 225 090201

Powell H W et al 2015 Proton acceleration enhanced by a plasma jet in expanding foils undergoing relativistic transparency New J. Phys. 17 103033

Dover N P et al 2016 Buffered high charge spectrally-peaked proton beams in the relativistic-transparency regime New J. Phys. 18 013038

Poole P L, Andereck C D, Schumacher D W, Daskalova R L, Feister S, George K M, Willis C, Akli K U and Chowdhury E A 2014 Liquid crystal films as on-demand, variable thickness (50–5000nm) targets for intense lasers Phys. Plasmas 21 065109

Poole P L, Willis C, Cochran G E, Hanna R T, Andereck C D and Schumacher D W 2016 Moderate repetition rate ultra-intense laser targets and optics using variable thickness liquid crystal films Appl. Phys. Lett. 109 151109

Poole P L et al 2016 Experiment and simulation of novel liquid crystal plasma mirrors for high contrast, intense laser pulses Sci. Rep. 6 32041

Mora P 2003 Plasma expansion into a vacuum Phys. Rev. Lett. 90 185002

Schreiber J et al 2006 Analytical model for ion acceleration by high-intensity laser pulses Phys. Rev. Lett. 97 1–4

Klug T, Cowan T, Debus A, Schramm U, Zeil K and Bussmann M 2011 Electron temperature scaling in laser interaction with solids Phys. Rev. Lett. 107 205003

Pirozhkov A S et al 2009 Diagnostic of laser contrast using target reflectivity Appl. Phys. Lett. 94 241102

Streeter M J V et al 2011 Relativistic plasma surfaces as an efficient second harmonic generator New J. Phys. 13 023041

Schumacher D W, Kemp G E, Link A, Freeman R R and Van Woerkom L D 2011 The shaped critical surface in high intensity laser plasma interactions Phys. Plasmas 18 013102

Buck A et al 2010 Absolute charge calibration of scintillating screens for relativistic electron detection Rev. Sci. Instrum. 81 033301

Thévenet M, Leblanc A, Kahaly S, Vincienti H, Vernier A, Quere F and Faure J 2016 Vacuum laser acceleration of relativistic electrons using plasma mirror injectors Nat. Phys. 12 355–60

Ceccotti T, Levy A, Popescu H, Réau F, D’Oliveira P, Monot P, Geindre J P, Lefebvre E and Martin P 2007 Proton acceleration with high-intensity ultrahigh-contrast laser pulses Phys. Rev. Lett. 99 1–4

Steinke S et al 2011 Optimization of laser-generated ion beams Contrib. Plasma Phys. 51 444–50

Zeil K, Metzkes J, Bussmann M, Cowan T E, Kraft S D, Sauermann R and Schramm U 2012 Direct observation of prompt pre-thermal laser ion sheath acceleration Nat. Commun. 3 874

Welch D R, Rose D V, Cuneo M E, Campbell R B and Melihorn T A 2006 Integrated simulation of the generation and transport of proton beams from laser-target interaction Phys. Plasmas 13 063105

Neely D, Foster P, Robinson A, Lindau F, Lundh O, Persson A, Wahlstrm C-G and McKenna P 2006 Enhanced proton beams from ultrathin targets driven by high contrast laser pulses Appl. Phys. Lett. 89 021502

Carroll D C et al 2010 Carbon ion acceleration from thin foil targets irradiated by ultrahigh-contrast, ultraintense laser pulses New J. Phys. 12 045020

Zeil K, Kraft S D, Bock S, Bussmann M, Cowan T E, Kluge T, Metzkes J, Richter T, Sauermann R and Schramm U 2010 The scaling of proton energies in ultrashort pulse laser plasma acceleration New J. Phys. 12 045015

Green J S et al 2014 High efficiency proton beam generation through target thickness control in femtosecond laser-plasma interactions Appl. Phys. Lett. 104 214101

Mackinnon A J, Sentoku Y, Patel P K, Price D W, Hatchett S, Key M H, Andersen C, Sanvelly R and Freeman R R 2002 Enhancement of proton acceleration by hot-electron recirculation in thin foils irradiated by ultraintense laser pulses Phys. Rev. Lett. 88 215006

Henig A et al 2009 Radiation-pressure acceleration of ion beams driven by circularly polarized laser pulses Phys. Rev. Lett. 103 245003

Kim J I et al 2013 Transition of proton energy scaling using an ultrathin target irradiated by linearly polarized femtosecond laser pulses Phys. Rev. Lett. 111 165003

Dollar F et al 2013 High contrast ion acceleration at intensities exceeding 1021 w cm2 Phys. Plasmas 20 056703

Jung D et al 2013 Beam profiles of proton and carbon ions in the relativistic transparency regime New J. Phys. 15 123035

Kim J I et al 2016 Radiation pressure acceleration of protons to 93mev with circularly polarized petawatt laser pulses Phys. Plasmas 23 070701

Kaluza M, Schreiber J, Santala M I K, Tsakiris G D, Eidmann K, Meyer-ter Vehn J and Witte K J 2004 Influence of the laser prepulse on proton acceleration in thin-foil experiments Phys. Rev. Lett. 93 045003