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Enhanced proton beams from ultrathin targets driven by high contrast laser pulses

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The generation of proton beams from ultrathin targets, down to 20 nm in thickness, driven with ultrahigh contrast laser pulses is explored. The conversion efficiency from laser energy into protons increases as the foil thickness is decreased, with good beam quality and high efficiencies of 1% being achieved, for protons with kinetic energy exceeding 0.9 MeV, for 100 nm thick aluminum foils at intensities of $10^{19}$ W/cm$^2$ with 33 fs, 0.3 J pulses. To minimize amplified spontaneous emission (ASE) induced effects disrupting the acceleration mechanism, exceptional laser to ASE intensity contrasts of up to $10^{10}$ are achieved by introducing a plasma mirror to the high contrast 10 Hz multiterawatt laser at the Lund Laser Centre. It is shown that for a given laser energy on target, regimes of higher laser-to-proton energy conversion efficiency can be accessed with increasing contrast. The increasing efficiency as the target thickness decreases is closely correlated to an increasing proton temperature. © 2006 American Institute of Physics.

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Significant progress has recently been made in the production of low-divergence beams of MeV protons from the interaction between short pulse, high intensity laser radiation, and thin target foils. Such laser-driven ion beams will potentially find numerous uses in the fields of physics, materials science, and medicine. However, important work remains, for example, to increase the maximum proton energy and to optimize the laser-to-proton energy conversion efficiency. Studies along these lines are presently the focus of many research programs worldwide.

The main mechanism behind the highest energy protons is target normal sheath acceleration (TNSA) at the rear surface. In particular, with a hydrogen containing layer on the target surface, always present under the vacuum conditions normally available for laser-plasma experiments, the dominant accelerated ion species is proton, due to their high charge to mass ratio. The highest electron density at the rear surface, and consequently highest acceleration field, is expected for ultrathin targets of a conducting material. As the target thickness is decreased, transverse spreading of the hot electrons inside the target. Mackinnon et al. have demonstrated a gradual increase in maximum proton energy observed $E_{\text{max}}$ as the target thickness was decreased. For example, Kaluza et al. with a laser contrast of $10^7$ demonstrate an increase in proton energy with decreasing target thickness down to 2 μm. The increase was attributed to reduced transverse spreading of the hot electrons inside the target.4 An induced density gradient can drastically reduce the effectiveness of the TNSA mechanism. The thinner the target, the more sensitive it is to such prepulses. For a given peak laser intensity, the optimum target thickness is thus related to the laser temporal contrast, defined as the ratio between the intensity of the main pulse to that of the pedestal or prepulse. Most experiments reported in the literature are limited to targets with thickness in the range from a few micrometers to several tens of micrometers.

Previous investigations using medium contrast Ti:sapphire laser systems, have demonstrated a gradual increase in maximum proton energy observed $E_{\text{max}}$ as the target thickness was decreased. For example, Kaluza et al. with a laser contrast of $10^7$ demonstrate an increase in proton energy with decreasing target thickness down to 2 μm. The increase was attributed to reduced transverse spreading of the hot electrons inside the target. Mackinnon et al. using a laser with a contrast of $10^{10}$ demonstrated significant enhancement in $E_{\text{max}}$ as the target thickness was decreased below $\tau c/2$ (∼10 μm in their case). This increase was attributed to electron recirculation. In the studies by Kaluza et al., the same drastic enhancement was not observed, possibly because ASE induced density gradients of the target rear surface disrupted the proton acceleration before the recirculation mechanism became effective.

Motivated by these earlier studies we embark on a program of work examining proton acceleration from surface contamination layers on ultrathin target substrates. In particular, we study the influence of target thickness on the laser-to-proton energy conversion efficiency and energy distribution. In this letter we report results with Al targets and ultrahigh contrast laser pulses, allowing us to extend the in-

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The experiments employ the 10 Hz, 800 nm multiterawatt laser system at the Lund Laser Centre (LLC), which delivers 33 fs pulses with a 1 ns duration ASE, at an intensity contrast of \(2 \times 10^8\). When this laser is focused to an intensity of \(\sim 10^{19}\) W/cm\(^2\), the ASE pedestal typically launches an \(\sim 8\) \(\mu\)m/ns shock wave into Al target foils. Therefore, to drive targets thinner than \(1\) \(\mu\)m, contrasts \(>10^8\) (or pedestals of much shorter duration) are necessary to maintain an undisturbed target rear surface. To achieve such conditions in the present study we use a plasma mirror. The transition from low to high reflectivity of a plasma mirror can be set to occur as the main pulse rises out of the ASE background approximately a few tens of picosecond before the peak of the pulse. The ASE pedestal is thus transmitted, resulting in a significant increase in temporal contrast in the reflected part of the pulse. Previous plasma mirror studies have demonstrated that it is possible to obtain high contrast and high reflectivity without adding any phase errors by carefully selecting the appropriate irradiance conditions.

We operate our uncoated glass plasma mirror at 45° angle of incidence, in a \(P\)-polarized geometry, 3 mm from the laser focus. At this point the ASE intensity onto the plasma mirror is always below \(10^8\) W/cm\(^2\), while the peak laser pulse intensity exceeds \(10^{15}\) W/cm\(^2\). In this configuration we measure a reflectivity of \(41 \pm 3\%\). The contrast enhancement, calculated as the ratio of ASE reflectivity to main pulse reflectivity, is 45 under these conditions leading to an on-target contrast of \(10^{10}\). The laser pulse is focused onto thin Al foils at 30° angle of incidence by an \(f/3\), off-axis parabolic mirror, via the plasma mirror, as illustrated in Fig. 1. With a pulse energy, after the plasma mirror, of \(0.3\) J and a 1/e\(^2\) focal spot diameter of 10 \(\mu\)m, the peak intensity on target reaches \(10^{19}\) W/cm\(^2\). In this configuration, and with an ASE contrast of \(1 \times 10^{10}\), a data set comprising of over 50 shots is obtained for a wide range of target thickness, enabling trends to be clearly identified. The rear surface proton beam emission is sampled by three diagnostics, two magnetic spectrometers operating at deflection angles \(\phi=0°\) and 14° with respect to target normal, and a half-beam “spatial profile monitor” consisting of a CR-39 track detector covered with an array of Al filters.

Proton spectra from Al foils in the range of 20 nm–30 \(\mu\)m are recorded and a typical example of the 0° and 14° emissions is shown in the inset in Fig. 2. The maximum detectable proton energy \(E_{\text{max}}\) is plotted as a function of target thickness in Fig. 2. The average \(E_{\text{max}}\) for a given foil thickness increases from \(0.6\) MeV with \(30\) \(\mu\)m thick foils to \(4\) MeV with \(0.1\) \(\mu\)m and then decreases slightly to \(3\) MeV for \(0.02\) \(\mu\)m thickness targets. The shot-to-shot variations under nominally identical conditions at a given foil thickness have an average standard deviation of 12%. It is believed that this is partly due to variation within the proton contamination layer or intensity modulations within the focal spot and will be studied in future experiments.

Proton acceleration using the same incident energy on target but at a lower contrast of \(5 \times 10^7\) reveals that \(E_{\text{max}}\) is always lower when using the lower contrast pulse, although comparable for targets thicker than a few micrometers.

The proton spectra show an almost single temperature Boltzmann-like distribution (see inset in Fig. 2). The number of protons/MeV/Sr, \(N(E, \phi)\), can be fitted by a simple distribution of the form \(N(E, \phi) = N_0(\phi)\exp[-E/T(\phi)]\), where \(E\) is the proton energy in MeV, \(N_0(\phi) = N(0, \phi)\) extrapolated from the data to \(E=0\), and \(T(\phi)\) is the temperature in MeV of the distribution. A plot of the fitted temperatures as a function of target thickness is shown in Fig. 3. The data clearly show an increase in the effective temperature of the protons as the target thickness decreases, with the temperature rising from \(0.2\) MeV at 12 \(\mu\m\) to a maximum temperature of \(0.65\) MeV for targets of thickness of 0.1 \(\mu\m\) and then falling to \(0.4\) MeV for \(0.02\) \(\mu\m\) targets. \(N_0(\phi)\) is approximately independent of target thickness with an average value of \(10^{12}\) protons/MeV/Sr.

The 14° proton spectra follow similar trends to the target normal data in terms of temperature in the majority of shots. However, in a small number of shots (3 out of 50) an off-axis peaked energy spectrum was observed. The angular divergence of the proton beams generally decreases with increasing proton energy, with the ratio \(E_{\text{max}}(\phi)/E_{\text{max}}(14°)\) having an average of 1.5 and a standard deviation of 0.4. This ratio
does not show any correlation with target thickness. The energy of the energetic part of the proton beam is obtained by integrating the proton beam angular distribution spectrally and spatially for $E > 0.9$ MeV, corresponding to the detection threshold of the spatial profile monitor. The beam profile is obtained for each shot by combining the data from the two spectrometers and the spatial profile monitor using cubic spline interpolation. Dividing by the incident drive energy gives the efficiency of conversion into energetic protons, as shown in Fig. 3. The energy transferred into protons of energy above 0.9 MeV increases rapidly with decreasing target thickness and reaches an optimum of $\sim 100$ nm thickness.

In conclusion, a laser-to-proton beam energy conversion efficiency of 1%, for protons with $E > 0.9$ MeV, is obtained for the first time with a short pulse Ti:sapphire laser and pulse energy as low as 0.3 J on target. With a contrast of $10^{10}$, the optimum target thickness is found to be as thin as 100 nm. The results show a significant enhancement in proton beam scaling with a variation in target thickness and clearly demonstrate the benefits of using an ultrahigh contrast laser to drive thin targets.

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