Influence of micromachined targets on laser accelerated proton beam profiles

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Abstract

High intensity laser-driven proton acceleration from micromachined targets is studied experimentally in the target-normal-sheath-acceleration regime. Conical pits are created on the front surface of flat aluminium foils of initial thickness 12.5 and 3 μm using series of low energy pulses (0.5–2.5 μJ). Proton acceleration from such micromachined targets is compared with flat foils of equivalent thickness at a laser intensity of $7 \times 10^{19}$ W cm$^{-2}$. The maximum proton energy obtained from targets machined from 12.5 μm thick foils is found to be slightly lower than that of flat foils of equivalent remaining thickness, and the angular divergence of the proton beam is observed to increase as the depth of the pit approaches the foil thickness. Targets machined from 3 μm thick foils, on the other hand, show evidence of increasing the maximum proton energy when the depths of the structures are small. Furthermore, shallow pits on 3 μm thick foils are found to be efficient in reducing the proton beam divergence by a factor of up to three compared to that obtained from flat foils, while maintaining the maximum proton energy.

Keywords: laser-plasma based proton acceleration, laser micromachining, conical structures

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser-plasma based proton acceleration has become a widely studied research area due to its capability of accelerating ions over a very short distance [1, 2]. Typically protons are accelerated over a distance of up to tens of μm by a high amplitude transient electric field ($\sim$TV m$^{-1}$) produced in the interaction of high intensity laser interaction with thin foils. Compared to conventional accelerator beams, shorter bunch duration, lower transverse emittance, and smaller source size make laser accelerated protons potentially suitable for numerous applications in fundamental as well as applied science and medicine [3]. Although, the potential is enormous for viable applications, low repetition rate, broad energy spectra and large ion-divergence of laser-driven ion sources need to be overwhelmed.

The most robust mechanism for laser-driven ion acceleration is called target normal sheath acceleration (TNSA) [4–6]. In this scheme, typically, a high intensity ($>10^{18}$ W cm$^{-2}$), short (<1 ps) laser pulse is focused onto the front surface of a thin foil (few μm thick). Very often the laser pulse pedestal, originating from amplified spontaneous emission (ASE), and the rising edge of the pulse almost completely ionize the material in the focal area, resulting in hot dense plasma. The rest of the pulse cannot propagate through this plasma and transfers a fraction of its energy to the plasma electrons before being reflected. Depending on laser intensity and plasma density gradient, several processes (e.g. resonance absorption, $J \times B$ heating, Brunel heating, etc) lead to a copious production of energetic (hot) electrons [7, 8]. A large number of these hot electrons then penetrate the foil and generate a strong charge-separation sheath electric field at the rear side of the target. Atoms, present at the rear side of the target, usually as surface contamination, get field ionized and subsequently accelerated in this transient sheath.
field to multi-MeV energies according to their charge-to-mass ratio. The strength of the sheath field is proportional to the square root of the product of the hot electron density and temperature. Therefore, higher and hotter electron production can lead to enhanced proton acceleration. The use of thin targets reduces the effective area of hot electron emission from the rear side of the target and thereby increases the areal density of hot electrons which gives rise to improved proton acceleration [9–11]. However, the ultimate target thickness is limited by the intensity contrast between the pedestal and the peak of the laser pulse. In addition, structured targets, where the material distribution at the front surface is modified, can be more efficient in absorbing the laser pulse energy than flat targets leading to both larger number and increased temperature of hot electrons [12–15], resulting in enhanced proton acceleration [16–20].

Typically TNSA proton beams have a large and energy dependent angular divergence with the smallest divergence for the most energetic protons [21–23]. Focussing of the full proton beam down to a small spot has been demonstrated in the past using curved targets [24, 25]. Recently, Aurand et al have demonstrated that the spatial distribution of the hot electrons on the rear side of the target and the transverse expansion of the electric sheath field has a profound effect on the angular divergence of the accelerated protons; the proton beam divergence can be reduced if the transverse spatial distribution of the electron sheath on the rear surface of the target is increased [26]. One way to reduce it is to defocus the laser on the target [26]. The maximum proton energy in this case is found to be lower, as the laser intensity on the target becomes lower compared to the tight focus condition. In spite of obtaining enhanced hot electron production, Matsuoka et al have reported almost similar acceleration in terms of maximum proton energy from conical targets compared to flat targets [27]. The conical structures were created on the front surface of the thin foils of various initial thickness, in the range 25–100 μm using series of pulses of energy 7–70 μJ. The higher number of hot electrons produced in such interactions is argued to be balanced by a larger electron divergence which acts adversely to enhance the maximum proton energy. In the present study we extend that investigation with thinner target foils (3 and 12.5 μm) and also using lower energy pulses (0.5–2.5 μJ) for making structures. The questions we address here are, whether higher electron divergence produced in conical targets is effective in reducing the proton beam divergence, and if there are any effects of different aspect ratios (longitudinal versus radial dimension) of the conical structures on the proton acceleration.

To prepare our structured targets, we use laser micromachining on thin aluminium foils. Laser micromachining is the process in which micron sized features/structures are created by ablating material from a substrate using pulsed lasers. With femtosecond duration and low pulse energy, the laser energy is deposited very rapidly and the thermal diffusion to the ionic lattice is minimized, which results in sharp and reproducible structures [28]. This method has the advantage that it facilitates in situ target fabrication as the same beam and focusing geometry can be used for target preparation as well as proton acceleration without altering the experimental set-up. Laser micromachining is also very effective in generating controlled transient plasma structures on a plain solid surface, which can be used to study laser energy absorption, electron dynamics as well as proton acceleration from such structures [29–31]. In our experiment the pulse energy is adequately attenuated while micromachining such that only a very small amount of target material is removed from the focal area with each laser pulse, resulting in a pit on the front surface of the target. The depth of the pit is controlled by the number of machining pulses. Since the propagation axis for the machining pulse and the main pulse is identical, this method also relaxes the requirement of target alignment between target machining and proton acceleration. We found that micromachined targets, for a certain geometrical structure of the pit, can be effective in reducing the proton beam divergence by a factor of up to three compared to conventional flat targets.

2. Experimental set-up

The experiments are performed using the 10 Hz multi-terawatt Ti:sapphire laser system at Lund University, Sweden. It is a chirped pulse amplification based system delivering linearly polarized laser pulses of 35 fs temporal duration at a central wavelength of 800 nm. In the present experiments, the main pulse (accelerating pulse) energy on the target is kept fixed at 0.59(±0.05) J. The ASE to main pulse intensity contrast of the laser pulses, as measured by a third order autocorrelator, is 1–3 x 10^−9 up to 50 ps prior to the arrival of the peak of the pulse. After compression, a deformable mirror (DM) sends the laser beam to the experimental chamber. Figure 1 shows the schematics of the experimental setup. The p-polarized laser pulses are focused on the target by a f/3 off-axis parabolic mirror at an incidence angle of 45°. The DM, together with a wavefront sensor, corrects for wavefront aberrations and helps to achieve a circular focal spot of approximately 3.7 μm full-width-at-half-maximum (FWHM) in diameter, resulting in a peak intensity of 7 x 10^{19} W cm^{-2} in vacuum. The target foil is sandwiched between two rectangular metal frames, each having an identical array of circular openings (sites) that enables to have free standing target foils on every site. The whole target holder is mounted on a motorized x-y-z translation stage assembly allowing a new target foil to be positioned in the focal plane for each laser shot. A magnetic spectrometer, placed in the target normal direction on the rear side of the target, is used to record the proton energy spectra on a shot-to-shot basis. This spectrometer, which is based on a permanent dipole magnet, bends the proton trajectories downwards (y-direction) according to their energy. A rectangular slit is used at the entry of the spectrometer to sample the central part of the proton beam. After the magnet the protons impact on a plastic scintillator (Saint-Gobain, BC-408) and the resulting fluorescence is imaged onto a 16-bit EMCCD camera. The spatial profile of the proton beam is imaged by another scintillating screen (5 cm x 8 cm) placed within a light shielded box (footprint
monitor) at a distance of 8.3 cm from the rear surface of the target. The footprint monitor is mounted on a linear translational stage that allows it to be moved in and out of the proton beam path. It is positioned in a way that it can capture proton beams of transverse size up to approximately $32^{\circ}$ (full-angle). For a single laser shot either the spectrum or the spatial profile of the proton beam is recorded. Both scintillators are covered with a single layer of $13 \mu m$ thick Al foil to protect them from ambient light (radiation from resultant plasma as well as scattered laser radiation) and target debris. It also stops protons of energy less than 0.9 MeV and heavier ions compared to proton from reaching the detector. The whole experimental chamber is maintained at a pressure $\sim 10^{-5} \text{ mbar}$. More details about the target system and ion diagnostics can be found in [32].

3. Target preparation

We use Al foils of two different initial thicknesses (12.5 and $3 \mu m$) and the front side of each foil is laser machined to create conical pits. The laser pulse energy is selected by ensuring through a microscope objective that no surface deformation occurs on the rear surface of the foils. Approximately 2.5 $\mu J$/pulse and 0.5 $\mu J$/pulse are used respectively to machine the thicker foil and the thinner foil. Figure 2(a) shows the schematic of the micromachined targets. The impact of a large number of machining pulses eventually forms a tunnel through the foil. The transmission of a co-linear HeNe laser beam is used to confirm the tunnel making process. If $N_t$ is the minimum number of machining pulses required to make a tunnel through a foil of thickness $L$, then, the material removal rate is estimated as $L/N_t$. Therefore, the depth of the pit after $N (<N_t)$ machining pulses is estimated to be, $d = NL/N_t$; and the remaining foil thickness, $L_{\text{rem}} = L - d = L(1 - N/N_t)$. Figure 2(b) shows an microscope image of the front side of the foil after machining a 12.5 $\mu m$ foil with 25 pulses. The pit is slightly elliptical in shape as the laser pulse is incident obliquely onto the target. The width of the pit as a function of $N$ is shown in figure 2(c), and it is observed to remain below four times the diameter (FWHM) of the laser focal spot in vacuum.

4. Results and discussions

In the experiment, we first fix the initial foil thickness and send low energy machining pulses to create a pit on the front side of the foil. The full energy pulse is sent after micromachining, and proton energy spectra as well as proton beam profiles are recorded as a function of number of machining pulses ($N$). After each such measurement, we move to a new undamaged target site for the next measurement, and the whole process is repeated during the experiment. Results obtained from machined targets of different $L_{\text{rem}}$ are compared with flat foils of equivalent thickness under similar experimental conditions.

Prior to the experiment the laser focus is optimized in spatial domain using adaptive optics and in temporal domain by adjusting the compressor-grating to minimize any spatio-temporal coupling. The image of the focus of the accelerating pulse as well as the machining pulse are shown in figures 1(b) and (c), respectively. Other method of characterization can be...
found in [33]. We believe that ‘prethermal’ laser ion sheath acceleration [34] is absent in our experimental conditions. The Rayleigh length of the laser focus is much longer than the depth of the pits as well as the target thickness; therefore, the change in the main pulse intensity is negligible when it interacts with the micromachined targets.

4.1. Structures on 12.5 μm thick foils

Proton energy spectra (averaged over 5 shots), as derived from the magnetic spectrometer, from flat foils of different thickness and from laser machined targets with different \( l_{\text{rem}} \) are shown in figures 3(a) and (b), respectively. For flat targets, the maximum proton energy, \( E_{\text{max}}^p \) is observed to increase with decreasing foil thickness, which is consistent with the results of several previous experimental studies [9–11]. For micromachined targets, irrespective of \( l_{\text{rem}} \), \( E_{\text{max}}^p \) remains almost constant and equal to that obtained with 12.5 μm thick flat foils. This indicates that the ion front experiences almost equal accelerating sheath fields for the case of machined targets along the target normal direction. Figure 4 shows the spatial profile of the proton beam as detected by the footprint monitor from flat targets (figures 4(a)–(c)) as well as micromachined targets (figures 4(d)–(f)). We observe that the angular divergence of the proton beam from micromachined targets are comparable with that obtained from flat foils as long as \( l_{\text{rem}} \geq 6 \) μm. In this case the full-angle-at-half-maximum (FAHM) of the proton beam is found to be 6.1°(±0.6°). The beam divergence increases to 9°(±1°) (FAHM) when \( l_{\text{rem}} \) is reduced to 3 μm. The proton emission seems to lose beam-like properties and its spatial profile becomes larger than the footprint monitor detector window as \( l_{\text{rem}} \) becomes very small.

The results can be explained considering ballistic propagation of hot electrons through the target. The hot electrons leave the rear surface of the target from an effective area, \( w_{\text{eh}} = \frac{\pi}{2}D^2 \), where, \( D = s_{\text{eh}} + 2l_{\text{rem}}\tan \alpha_{\text{eh}} \) is the diameter of the area of hot electron emission from the rear side of the target, \( s_{\text{eh}} \) is the diameter of the laser interaction area on the front side and \( \alpha_{\text{eh}} \) is the half-divergence-angle of the hot electron beam [35]. For flat foils, \( E_{\text{max}}^p \) increases with decreasing foil thickness due to geometric effects as the hot electron density on the rear surface increases as \( n_{\text{eh}} \propto 1/w_{\text{eh}} \).
should not change, which can explain the beam pro-
remains at a constant value, the proton beam divergence
as the depth of the pit increases. However, if the product
higher hot electron production with a larger angular diver-
area around the tip including the wall surface, resulting in a
only from the tip of the conical structure but from a larger
\[\text{Table 1.} \]
**Figure 4.** (a)–(c) Show spatial profiles of proton beam obtained from flat foils of different thickness, \( L \) (top panel). Beam profiles acquired from micromachined targets of different \( l_{\text{rem}} \) are shown in (d)–(f) (bottom panel). \( L \) and \( l_{\text{rem}} \) for different targets are labelled accordingly.

Table 1. The diameter of the hot electron sheath on the rear side of the target \((D)\) as calculated using a simple model considering ballistic propagation of hot electrons for targets machined from an initial thickness of 12.5 \( \mu \text{m}. \)

| Targets                      | \( x_{\text{ch}} \) \( (\mu \text{m}) \) | \( l_{\text{rem}} \) \( (\mu \text{m}) \) | \( \alpha_{\text{ch}} \) \( (^\circ) \) | \( D \) \( (\mu \text{m}) \) |
|------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| Flat foil \((L = 12.5 \mu \text{m})\) | 3.7                                  | 12.5                                 | 40                                    | 24.7                                 |
| Machined (shallow pits)      | 3.7                                  | 11                                    | 40                                    | 22.2                                 |
| Machined (moderate pits)     | 3.7                                  | 6                                     | 50                                    | 18                                   |
| Machined (deep pits)         | 3.7                                  | 3                                     | 50                                    | 10.9                                 |

\[9, \, 10\]. In machined targets, the hot electrons originate not only from the tip of the conical structure but from a larger area around the tip including the wall surface, resulting in a higher hot electron production with a larger angular divergence [27]. Higher \( \alpha_{\text{ch}} \) acts adversely to increase \( \alpha_{\text{eh}} \) resulting in similar (slightly lower) maximum proton energy from micromachined targets compared to flat targets of equivalent thickness. These observations are consistent with earlier works of Matsuoka et al [27]. Previous studies have shown that the transverse spatial profile of the sheath field on the target-rear surface has a profound influence on the angular divergence of the accelerated proton beam. Using numerical simulations it has been shown that the diameter of the resultant proton beam at the detector can be reduced, if the transverse circular area of the sheath field on the rear side of the target is increased [26]. With micromachined targets, the laser interaction not only increases \( \alpha_{\text{eh}} \) but also decreases \( l_{\text{rem}} \) as the depth of the pit increases. However, if the product remains at a constant value, the proton beam divergence should not change, which can explain the beam profile obtained from micromachined targets for \( l_{\text{rem}} \geq 6 \mu \text{m}. \) For deeper pits \((l_{\text{rem}} \leq 3 \mu \text{m}), \) the hot electrons need to travel less distance to reach the rear side of the foil; therefore, the effective area of hot electron emission \((w_{\text{eh}})\) is reduced, resulting in more divergent proton beams. Table 1 shows the diameter of the hot electron sheath on the rear side of the target, \( D \) as calculated using our model. We assume that the half-divergence angle of the hot electron emission does not change due to shallow pits. The values for electron divergence for deeper pits are taken from [27]. It can be seen that \( D \) remains almost similar for shallow pits and the proton beam divergence does not show much change. For deep pits \((l_{\text{rem}} \leq 3 \mu \text{m}), \) \( D \) decreases significantly, that results in divergent proton beams.

### 4.2. Structures on 3 \( \mu \text{m} \) thick foils

The results of proton acceleration from targets machined from 3 \( \mu \text{m} \) thick Al foils are shown in figure 5. The proton energy spectra (averaged over 5 shots) from flat targets and micromachined targets are shown in figure 5(a) for various pit depths \((d)\) of the conical structure. Although \( E_{\text{max}}^p \) shows a slight increase for shallow pits \((d \sim 0.2 \mu \text{m}), \) this method does not seem to boost the proton acceleration significantly along the target normal direction (black triangles in figure 5(b)). However, for shallow pits \((d = 0.1 – 0.5 \mu \text{m}), \) the angular divergence of the proton beam is observed to be reduced by a factor of about 3 compared to flat foils (red circles in figure 5(b)). The error bars here represent the standard deviation of the data set as obtained from three
different targets and laser shots. The spatial profile of one such proton beam is shown in figure 5(c) measuring a beam divergence of only 2° (±0.3°) (FAHM), whereas the divergence is 5.9° (±1.1°) (FAHM) for 3 μm thick flat foils (figure 5(d)). Targets machined from thicker foils (12.5 μm) having similar pit depths are not very productive in reducing the beam divergence, indicating that a particular aspect ratio of the conical structure is needed for this effect. Deeper pits (d > 2 μm) machined in the 3 μm foils make the proton beam divergent, similar to the behaviour exhibited by machined targets from thicker foils. Table 2 shows the values of the extension of the sheath field, D as calculated using our model for different target parameters. For deep pits, D decreases slightly compared to that obtained with flat foils, which results in a small change in the proton beam divergence (see figure 5(b)). For shallow pits on 3 μm foils, D can increase by a factor of three compared to flat foils if αeh > 75°, which can results in a three fold reduction in proton beam divergence. However, the hot electron divergence as measured in [27] is well below this estimated value. Moreover, we have observed in section 4.1 that the results can be explained if αeh remains same to that of flat foils for shallow pits. Further investigations are needed to understand the effect of reduction of proton beam divergence as the hot electron recirculation may play an important role in shaping the transverse distribution of the sheath field for such target geometries.

To investigate the qualitative energy distribution of protons within the beam, we have used a stack made up with five layers of CR-39 (25 mm × 25 mm × 100 μm) plastic sheet. Energetic protons when is passed through CR-39, permanent tracks are formed and is used to detect protons. Proton deposits most of its energy at the Bragg peak; hence a stack of CR-39 provides energy resolved spatial profiles of the beam. The stack is placed on the rear side of the target foil, approximately 2 cm away from the target surface and is covered with a 13 μm thick Al-foil for shielding. For flat targets, protons are found to be distributed symmetrically where the most energetic protons are located at the central region around the target normal, which is consistent with several experimental studies. However, the distribution is skewed for machined targets and the most energetic protons are found to be shifted from the target normal towards the laser direction by about 20°. The findings are consistent with earlier works of Matsuoka et al [27]. The effect could be because of the combination of the denting of the target due to the J × B force [36, 37] and the geometry of the conical structure.

Table 2. The diameter of the hot electron sheath on the rear side of the target (D) as calculated using the simple model presented in section 4.1 for targets machined from an initial thickness of 3 μm.

| Targets                   | seh (μm) | lmax (μm) | αeh (°) | D (μm) |
|---------------------------|----------|-----------|---------|--------|
| Flat (L = 3 μm)           | 3.7      | 3         | 40      | 8.7    |
| Machined (shallow pits)   | 3.7      | 2.8       | 40      | 8.4    |
| Machined (deep pits)      | 3.7      | 0.8       | 50      | 5.6    |

Figure 5. (a) Average proton energy spectra as obtained from flat foils (3 μm thick) and machined (from 3 μm thick foils) targets of different pit depth. (b) Maximum proton energy (E_{p,max}) as derived from the spectrometer (black triangles) and angular divergence (FAHM) of the proton beams as detected in the footprint monitor (red circles) for different pit depth, d. The dotted lines correspond to the reference for flat targets (d = 0). (c) Shows the beam profile obtained from micromachined target when the pit depth, d ≈ 0.15 μm and (d) is a representative spatial profile of the proton beam from reference flat targets (3 μm thick).
5. Conclusion

We have carried out experimental investigations on proton acceleration from laser-machined structured targets. In order to exploit the inherent advantage of self-alignment of the target, the same focusing geometry is used for machining the target as well as for the accelerating laser pulse. Conical pits of different aspect ratios are micromachined at the front side of Al foils of initial thicknesses 12.5 and 3 μm. Even for the deepest pits, in the thicker foil, the width of the structure at the front surface is found to be within four times the diameter (FWHM) of the laser focal spot in vacuum. Proton acceleration results from micromachined targets of various remaining thicknesses are compared with flat targets of equivalent thickness. Micromachined targets from an initial thickness of 12.5 μm do not result in improved proton acceleration in terms of maximum energy compared to flat Al foils of equivalent thickness. Furthermore, the spatial profiles of the proton beams are observed to be similar to that obtained from flat foils for \( I_{\text{em}} \gtrsim L/2 \), but the beam becomes very divergent for \( I_{\text{em}} < L/2 \), which is attributed to the narrower transverse spatial distribution of the hot electrons on the rear-surface. On the other hand, shallow pits on the front side of a 3 μm thick Al foil are found to be effective in reducing the angular divergence of the proton beam by a factor of three, without affecting the maximum proton energy. In addition, a slight increase in the maximum proton energy is observed for these targets compared to unstructured flat foils. Targets machined from thicker foils with similar \( I_{\text{em}} (>L/2) \) do not result in such a reduction in proton beam divergence, indicating that the aspect ratio of the conical structure, \( d/2r_p \) (see figure 2(a)) also has a bearing on the angular divergence of the accelerated proton beam. A certain geometry of the pit structure (\( I_{\text{em}} \gtrsim L/2 \) and \( d/2r_p \sim 0.1 \)) on 3 μm foils is found to be effective in improving the proton beam quality.

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