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Demonstration of repetitive energetic proton generation by ultra-intense laser interaction with a tape target

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ABSTRACT

High power laser systems are an attractive driver for compact energetic ion sources. We demonstrate repetitive acceleration at 0.1 Hz of proton beams up to 40 MeV from a reeled tape target irradiated by ultra-high intensities up to 5×10^{21} Wcm^{-2} and laser energies ≈ 15 J using the J-KAREN-P laser system. We investigate the stability of the source and its behaviour with laser spot focal size. We compare the scaling of proton energy with laser energy to a recently developed analytical model, and also demonstrate that it is possible to reach energies up to 50 MeV on a single shot with a lower laser energy ≈ 10 J by using a thinner target, motivating development of high repetition targetry suitable for thinner targets.

1. Introduction

State-of-the-art high power laser systems ($>$ 100 TW) can be focused to intensities $> 10^{21}$ Wcm^{-2} [1]. When placing a thin foil at the laser focus, energetic ion beams can be generated with extremely high peak beam currents and low emittance [2–4]. These unique properties motivate a number of applications distinct from conventional ion sources, such as radiography of high energy density physics experiments [5], generation of warm dense matter [6], ultrafast material response studies [7], material processing [8], high dose radiobiology [9–11] and as high energy, high peak current injectors into a conventional accelerator [12]. These applications all have different requirements on the ion source, but typically they require high flux and energies.

There are a number of different techniques to accelerate ions using intense lasers. One of the most straightforward mechanisms is acceleration in a surface sheath, target normal sheath acceleration (TNSA). Electrons are rapidly heated to relativistic temperatures in the laser plasma interaction at the front side of the target [13–15]. Upon exiting the rear surface, they generate a strong quasi-electrostatic space charge field, the sheath, which accelerates surface ions [16–19]. Due to the predicted poor scaling of sheath acceleration with laser intensity [20,21], a number of other schemes have been developed, such as radiation pressure acceleration [22], acceleration during relativistic transparency [23–26] and collisionless shockwave acceleration [27–30]. Although these acceleration mechanisms are still being investigated and optimised, sheath acceleration is attractive due to its simple targetry, and relatively flexible laser contrast requirements compared to schemes requiring nanometer-scale targets. It generates smooth beams with low emittance [31,32] not yet demonstrated by other acceleration mechanisms. The simplicity and stability of the acceleration scheme is important when considering repetitive beam generation for applications.

Recently significant progress has been made in improving the repetition rate of femtosecond-class Petawatt laser systems, which can typically provide $>$ 10 J in $<$ 40 fs at repetition rates up to $\sim$ 1 Hz [1], making them attractive for laser driven ion sources. In the sheath acceleration regime, this class of laser has been demonstrated to

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provide relatively high energy coupling of the laser energy to the proton population [33], low divergence [34], and energies ≫ 10 MeV [33,35–37]. They have also been used to drive proton sources at > 0.1 Hz repetition rates at slightly lower energies [38–41].

Recently, proton beams with maximum energies up to 30 MeV were generated at 0.1 Hz repetition rate using a tape target irradiated at ultra-high intensities, $I_L \approx 5 \times 10^{21}$ Wcm^{-2}, with a laser energy $E_L \approx 10$ J [42]. In this article we further extend this scheme to higher laser energies, showing the repetitive generation of proton beams with energies around 40 MeV at 0.1 Hz by increasing the laser energy up to $E_L \approx 15$ J. We investigate the shot-to-shot stability of the source flux, showing ≈ 25% fluctuation over 30 consecutive shots. We show the proton flux is only weakly dependent on focal spot size at high intensities. We also demonstrate proton energies up to 50 MeV at lower repetition by reducing target thickness, and discuss the typical repetitive beam parameters and prospects for applications.

2. Experimental method

We used the J-KAREN-P laser [43,44] at Kansai Photon Science Institute, Japan, to investigate repetitive sheath acceleration of proton beams over two experimental campaigns. In the first campaign, also described in [42], the laser system delivered an $\lambda_L \approx 800$ nm wavelength pulse with energy $E_L \approx 10$ J (on target) and pulse length $\tau_L \approx 40$ fs, which was focused to a maximum intensity $I_L = 5 \times 10^{21}$ Wcm^{-2} with a focal spot size $r_L = 1.5$ μm (FWHM) onto a thin foil target at 45° in *p*-polarisation. The second campaign used the same set-up, but increased the maximum laser energy up to $E_L \approx 15$ J on target with a slightly larger focal spot, resulting in approximately the same at-focus maximum intensity. The laser can operate at full energy at 0.1 Hz, limited by the final amplifier. The target was either a tape made of steel or titanium with thickness $d = 5$ μm, or an individual thin aluminium target with thickness between 0.4 and 10 μm placed on a raster mount aligned at lower repetition in single shot mode. A photo of the tape target is shown in the inset of Fig. 1. The tape is reeled between two spools, with two support arms around the laser focus position to ensure positional accuracy within the Rayleigh length of the focused laser, ≈ 8 μm. The ASE contrast was around 10^{11} 150 ps before the main pulse. The rising edge contrast (around 10 to 100 ps before the main pulse [45]) was improved by an order of magnitude for the second experiment, although in both cases it was sufficiently high to not cause deformation of the rear surface and affect sheath formation.

The resultant accelerated protons were detected by a number of different diagnostics, as shown in Fig. 1. The proton beam divergence was measured at high repetition rate using a scintillator-based proton beam profiler (PBP) [46] providing rough spectral and spatial information by differential filtering. Fig. 2 shows an example of the raw

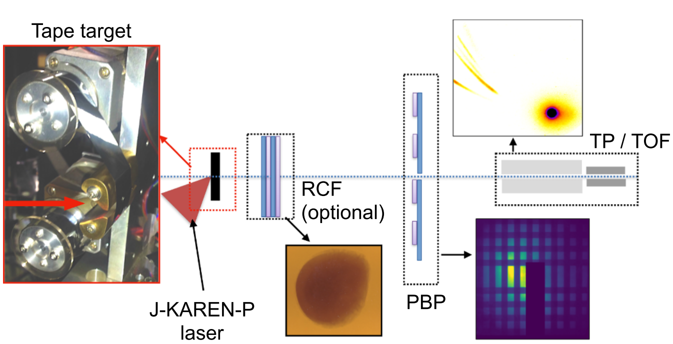

Fig. 1. Simplified schematic of the experiment with inset examples of the raw data. The red inset shows the tape target used in Section 3. The laser is incident from the left hand side of the image. A standard raster target was also used for individual target foils. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

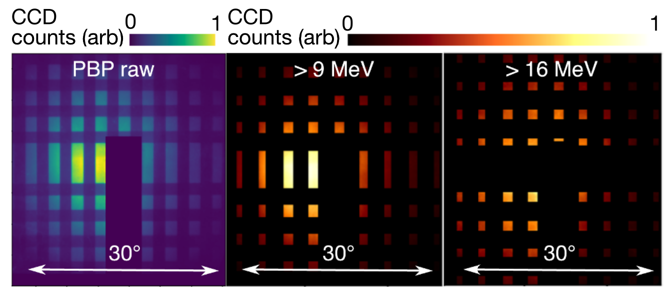

Fig. 2. Typical data from the PBP, including the raw camera image followed by separation into two examples of different filtering levels.

data from a shot at best focus for 5 μm titanium. The grid pattern is the result of the differential filtering with overlaid bars (5 × 100 × 1 mm) of different materials (titanium, aluminium), which provides different minimum cut-off energies that can contribute to the signal. A relatively thin 100 × 100 × 0.2 mm scintillator (EJ-212, Eljen Technology) was used in order to minimise the non-linearity of deposition above the minimum energy cut-off by reducing the number of protons with Bragg peaks in the scintillator. It was placed behind a full size 0.5 mm thick aluminium plate to ensure light tightness. Although the scintillator emission response depends on incident proton energy [46], it can still give a reasonable relative estimate of the flux. Absolute measurements of the flux require full calibration of the response and non-linearity of the scintillator, which is still on-going. However, stacks of GafChromic XR-RV3 radiochromic film (RCF) were also occasionally inserted for individual shots to provide full high dynamic range spectral and spatial beam properties [47], and were used to provide a benchmark for the absolute beam flux. Calibration was performed with a conventional proton accelerator at Hyogo Ion Beam Medical Center (HIBMC), and spectra were retrieved with an iterative fitting technique using proton stopping calculations from a series of Monte Carlo simulations (TRIM [48]). For higher resolution proton spectra and maximum energy, we used either a time-of-flight (TOF) detector [49], in the first experimental campaign, or a multi channel plate (MCP) based Thomson Parabola (TP) spectrometer in the second campaign.

3. Repetitive proton acceleration from tape targets

To test the stability of the source, a series of 30 shots was taken in nominally identical conditions for $E_L = 10.3 \pm 0.3$ J, using a $d = 5$ μm steel target. For such high repetition rate measurements, the proton beam profile and overall flux for different energy bands were measured using the PBP. The integrated scintillator signal for different energy bands is shown in Fig. 3 a. For example, in the 9 MeV band, the standard deviation of the signal fluctuation is ≈ 25%. Improving the stability of the source further will require continued development of on-shot characterisation of both the target and laser parameters to investigate the cause of fluctuation. For example, a remote target surface high magnification imaging and position sensor will monitor issues with the target surface quality and off-set from laser focus position. Although on-shot laser far field imaging, near field imaging, spectral monitoring and calorimetry are already implemented to monitor laser stability, these will be further complemented with single-shot measurement of the temporal profile including the picosecond rising edge [50] which impacts the relativistic laser plasma interaction and therefore the subsequent acceleration dynamics.

This relatively stable system was then used to investigate the behaviour of the proton flux against laser focal spot size for a series of shots with $E_L = 13 \pm 1$ J, shown in Fig. 3 b for both steel and titanium $d = 5$ μm targets for two minimum cut-off energies, 9 MeV (blue) and 16 MeV (red). The laser focal spot size was varied by displacing the target with respect to focus. Although there is a clear reduction at very large focus sizes and therefore low intensities, it is relatively insensitive

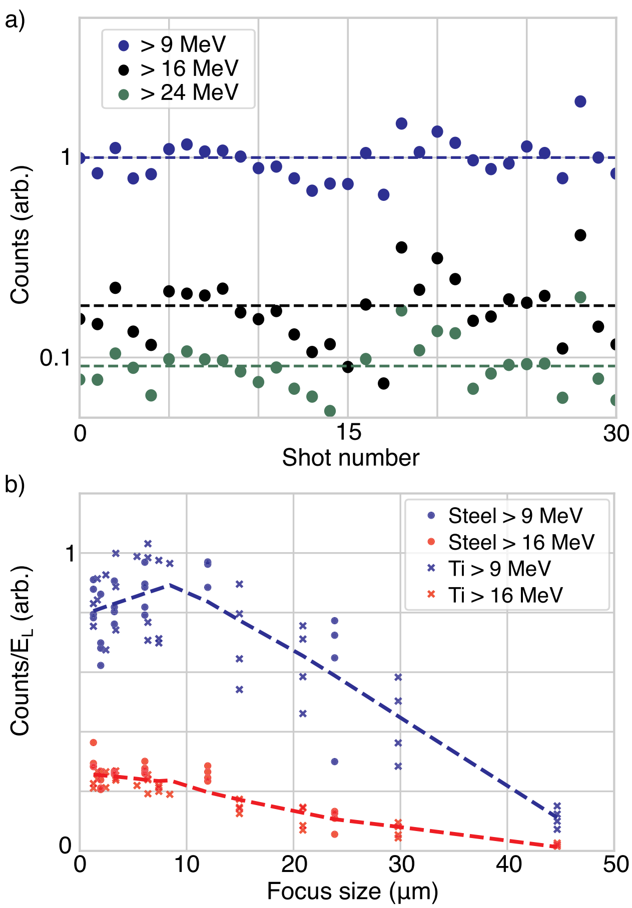

Fig. 3. a) Series of 30 shots in nominally identical laser and target conditions. Dotted lines indicate the mean values over the shot series. b) The laser energy normalised flux of protons against focal spot size r_L for 5 μm steel and titanium targets at two different filtering levels for $E_L = 13 \pm 1$ J on target. Dashed lines were calculated by combining the data from the two target types and performing locally-weighted scatterplot smoothing (LOWESS), to guide the eye.

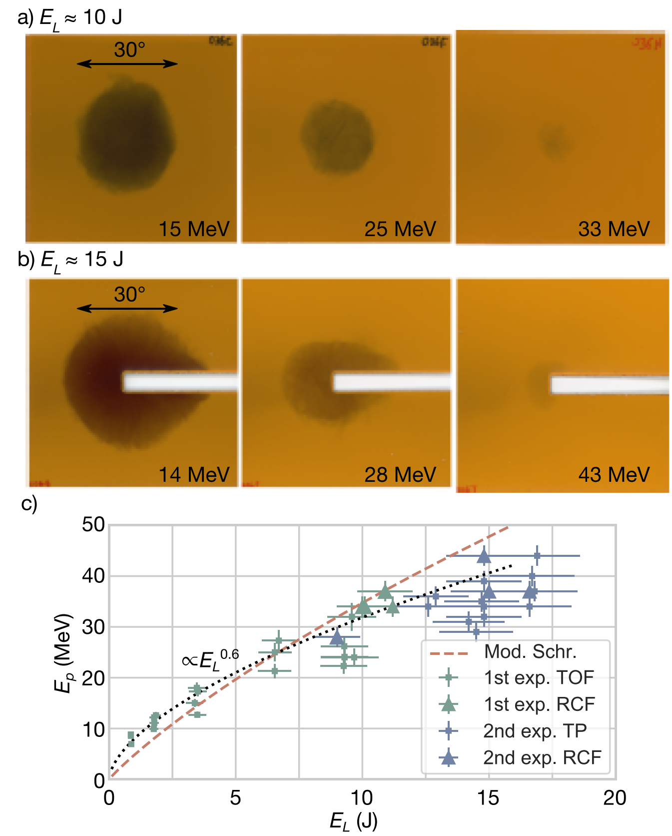

Fig. 4. Selected RCF layers from a) $E_L \approx 10$ J and b) $E_L \approx 15$ J for 5 μm steel. Note that the same type of RCF was used in both experiments, but different scanners used, leading to slight colouration differences. In (b), a slit was included to allow concurrent measurement on the TP. c) Scaling of maximum proton energy E_p against laser energy E_L from different diagnostics. The green circles (1st Exp. TOF) are taken from [42]. The error bar in laser energy is given by the accuracy of the calorimeter used to measure it, the error in the RCF proton energy is given by the stack resolution, and in TOF is the rise time of the signal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for $r_L < 10$ μm, despite a variation in laser intensity exceeding an order of magnitude. Indeed, the lower energy proton flux is highest slightly away from best focus, as has also observed previously and attributed to a larger acceleration area on the rear surface [51].

Recently, the maximum energy scaling of proton acceleration with focal spot size up to ultra-high intensity was investigated with $E_L \approx 10$ J, using data taken during the first experimental campaign described here [42]. The data was fitted with a model based on the Schreiber sheath acceleration model [19] with adjustments for angle-of-incidence and an acceleration time dependent on the focal spot size r_L, which becomes critical for extremely large spot sizes. This reduction in acceleration time when reducing focal spot size limits the increase in maximum proton energy, resulting in a relatively weak scaling falling far below previous theoretical predictions. There was only a limited improvement from $E_p \approx 20 \pm 3$ MeV at $r_L \approx 10$ μm to to $E_p \approx 26 \pm 4$ MeV at $r_L \approx 1.5$ μm. Therefore, for ultrashort high power laser systems, using extremely small focal spots to maximise the intensity does not give a significant boost to either the flux or maximum energy of sheath accelerated proton beams. Instead, increasing the laser energy was shown to be a more effective technique to increase the proton energy.

Therefore, we used the increased laser energy in the 2nd experimental campaign to extend this scaling up to 15 J, albeit with a similar maximum intensity due to a slightly larger focal spot. Example RCF data showing the difference in the beams between the two campaigns is shown in Fig. 4 a and b. Although both laser energy levels give a round and relatively smooth beam profile, increasing the energy to 15 J resulted in an increase in maximum proton energy from $E_p \approx 33$ MeV up to $E_p \approx 43$ MeV.

The maximum proton energy dependence with laser energy is plotted in Fig. 4 c, including TOF and TP measurements along target normal, and RCF. A shot was taken at lower energy, $E_L \approx 9$ J, during the second experiment, showing good agreement with the first experiment, indicating that the change in contrast between the experiments was not significant to the acceleration performance for such thick targets. Also plotted is an arbitrary $E_L^{0.6}$ scaling along with the modified Schreiber scaling, using the same set of assumptions and model inputs as [42]. The modified Schreiber scaling agrees reasonably well with the peak performance of the system, but slightly overestimates the average performance. We also note that according to the RCF, for large laser energies (> 10 J) the highest proton energies were consistently recorded ∼ 5° away from target normal, towards laser axis, causing the target normal measurements (TOF, TP) to underestimate the maximum energy by ≈ 10% on shots in which both diagnostics were used simultaneously. This is due to the sweeping of the sheath field along the rear target surface [52], and will be described in more detail in a future publication.

4. Increased acceleration efficiency with thinner targets

It is well known that for a given laser pulse, proton energies and flux can typically be increased by using thinner targets [19,53], with a minimum thickness depending on the laser contrast. However, using very thin targets is challenging for a simple tape-driven target system as they are susceptible to tearing, particularly when reeling after a laser shot. We were unable to reliably shoot targets thinner than 5 µm using our tape target system. However, future optimisation by, for example, using a wider target tape, mounting thinner targets from a thicker tape substrate, or other innovative approaches such as recently developed cryogenic [40,54,55], liquid sheet [41] or liquid crystal [53] targets may provide the opportunity to use thinner targets at higher repetition.

Therefore, during the first experimental campaign, we tested our system using thinner aluminium (Al) targets to optimise proton energy and flux to guide development of future high repetition targetry designs. We found an optimum target thickness of $d \approx 2$ µm for high energy proton generation. Below this, the proton beam pattern degraded and eventually a significant fraction of the laser was transmitted through the targets, with a lower observed proton beam energy, indicating significant expansion due to the laser prepulse, the details of which are given in Supplemental Material of [42] for this campaign.

The maximum proton energies for $d = 2$ µm Al targets, as measured on the RCF, typically varied between 40 and 50 MeV. Examples of background subtracted beam profiles are shown in Fig. 5 a. As typical for sheath accelerated beams, the full-angle divergence decreases with increasing energy, from $\theta \approx 40^{\circ}$ at $E \approx 13$ MeV to $\theta \approx 10^{\circ}$ at a maximum energy near $E = 50$ MeV. The centre of the beam of 50 MeV protons shown in Fig. 5 a is $(23 \pm 2)^{\circ}$ away from target normal, towards the laser axis direction. Indeed, as the target thickness decreases, the beam was typically observed to be directed increasingly towards laser axis [52]. As can be seen in Fig. 5 b, not only is the maximum energy higher, but the total particle number flux is higher throughout the higher energy end of the spectrum. Therefore, it is attractive to develop repetitive target systems capable of mounting thinner targets to optimise the source parameters.

5. Conclusion and future prospects

Although the target thickness of the tape target used was not optimal for maximising the proton flux and energy, it could still be used to provide a repetitive supply of $\gg 10$ MeV protons at 0.1 Hz. The typical performance of the source is summarised in Table 1 for all protons > 12 MeV, and a 1% energy band in 1 msr at 15 MeV. The latter is chosen as a figure of merit for acceptance into a collecting particle optic for transport to applications [4], although not all transport systems and

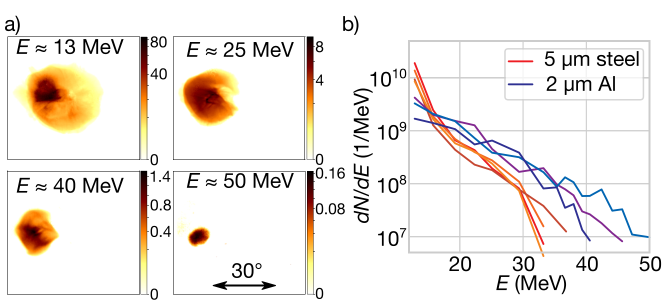

Fig. 5. a) Spatial distribution of dose deposited in units Gy from selected RCF layers after background subtraction for $d = 2$ µm Al and b) deconvolved spectrum from RCF of the whole beam for typical shots on $d = 2$ µm Al (shades of blue) and $d = 5$ µm steel target (shades of red) for $E_L \approx 10$ J. RCF observing energies $E < 12$ MeV were beyond the calibrated range and not included. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Typical parameters of the beam accelerated from a 5 µm steel target for all protons with energy $E > 12$ MeV, and protons in 1 msr at the beam centre in a 1% energy spread at $E = 15$ MeV. N_p is the total number of protons, Q_p the total charge, E_{beam} is the total beam energy, I_{peak} the peak beam current at source, estimated using a generation time 100 fs, and I_{avg} the time averaged current for our laser system (0.1 Hz) and for the highest repetition rate at upcoming petawatt-class laser systems (10 Hz).

	> 12 MeV	15 MeV, $\Delta E = 1\%E$, 1 msr
N_p	$\sim 2 \times 10^{10}$	$\sim 3 \times 10^{6}$
Q_p	~ 3 nC	~ 0.5 pC
E_{beam}	~ 50 mJ	~ 7 µJ
I_{peak}	~ 30 kA	~ 5 A
I_{avg} (0.1 Hz)	~ 0.3 nA	~ 50 fA
I_{avg} (10 Hz)	~ 30 nA	~ 5 pA

subsequent applications will require such small energy spread or small angular acceptance. For example, for a 10% energy spread [56] the values can be multiplied by 10 due to the spectra being approximately flat over the energy bin width. Each shot produces ~ 3 nC of charge with energies > 12 MeV, resulting in extremely high peak currents, ~ 30 kA, at source before debunching caused by the inherent energy spread. However, the average currents are still relatively low for some applications, even when scaled to state-of-the-art laser repetition rates (e.g. ~ 30 nA for the entire beam > 12 MeV at ~ 10 Hz).

As we have shown that the proton flux and energies are only marginally boosted by tight focusing and high intensities, it follows that improving these parameters for a sheath acceleration source can best be achieved by increasing the laser energy and/or increasing the laser repetition rate. The tape target used here has already been demonstrated in 1 Hz operation at lower laser power [38], near the state-of-the-art in repetition rate for this class of laser [1]. The use of different acceleration schemes may provide a higher conversion efficiency of laser energy into protons, particularly when considering a narrow energy band [22,25,28]. However, the stability and beam quality of such acceleration methods still needs to be demonstrated. Regardless of the acceleration scheme used, achieving higher beam currents with long-term operation will also pose problems with debris, radioactivation, electromagnetic noise and target replenishment, which are all major topics of research for future repetitive laser-driven ion sources. We mitigate these issues in our experiments by only running the source for short bursts before stopping to change laser or target parameters, although we still achieve in excess of 50 shots per hour. Indeed, our finding that using an extremely small focal spot size is not necessary for high flux proton generation motivates the use of a longer focal length focusing optic for repetitive laser driven proton sources. This could reduce the impact of debris and increase the Rayleigh range, resulting in a less stringent requirement for repetitive target positioning.

In conclusion, we have demonstrated a repetitive proton source with maximum energies $E_p \approx 40$ MeV using a state-of-the-art high power laser operating at 0.1 Hz irradiating a tape target. We investigated the beam stability and showed a weak dependence of proton beam flux on focal sizes $r_L < 10$ µm and fixed laser energy. We showed the beam parameters could be boosted even further by developing a repetitive design for a thinner target. Our demonstration of a repetitive intense laser driven proton source is therefore an important step towards the development of future laser driven ion sources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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