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Dover, N. P.; Nishiuchia, M.; Sakaki, H.; Kondo, K.; Lowe, H. F.; Alkhimova, M. A.; Ditter, E. J.; Ettlinger, O. C.; Faenov, A. Y.; Hata, M.; Hicks, G. S.; Iwata, N.; Kiriyama, H.; Koga, J. K.; Miyahara, T.; Najmudin, Z.; Pikuz, T. A.; Pirozhkov, A. S.; Sagisaka, A.; Schramm, U.; Sentoku, Y.; Watanabe, Y.; Ziegler, T.; Zeil, K.; Kando, M.; Kondo, K.;

Originally published:

June 2020

High Energy Density Physics 37(2020), 100847

DOI: https://doi.org/10.1016/j.hedp.2020.100847

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ARTICLE INFO

Keywords:
high intensity lasers
laser plasma accelerators
ion sources
proton acceleration

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 $\approx$ 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 with 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 $\approx$ 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, 3, 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, 10, 11] or for 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, 14, 15]. Upon exiting the rear surface, they generate a strong quasi-electrostatic space charge field, the sheath, which accelerates surface ions [16, 17, 18, 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, 24, 25, 26] and collisionless shockwave acceleration [27, 28, 29, 30]. Although these acceleration mechanisms are still being investigated and optimised, sheath acceleration is attractive due to its simple targetry, and relatively relaxed laser contrast requirements. 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 an attractive driver of laser driven ion sources. In the sheath acceleration regime this class of laser has been demonstrated to provide relatively high energy coupling [33], low divergence [34] with energies $\gg$ 10 MeV [35, 36, 37, 33], and also at $>$ 0.1 Hz repetition rates at slightly lower energies [38, 39, 40, 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 5×10^{21} Wcm^{-2} and 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 a. We investigate the shot-to-shot stability of the source, showing $\approx$ 25% fluctuation over 30 consecutive shots. We show the

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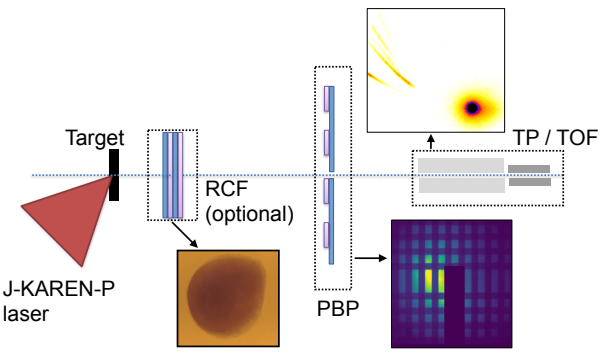

Figure 1: Simplified schematic of the experiment with inset examples of the raw data.

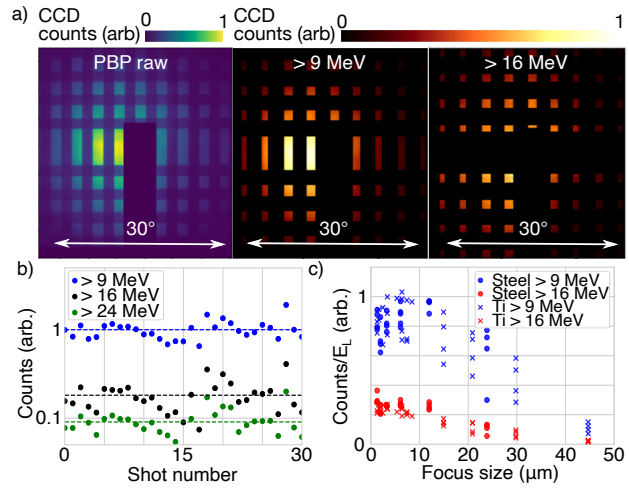

Figure 2: a) Example data from the PBP, including the raw camera image followed by separation into three different filtering levels. b) A series of 30 shots in nominally identical laser and target conditions. Dotted lines indicate the mean values over the shot series. c) The laser energy normalised flux 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.

proton flux is only weakly dependent on focal spot size at high intensities. We also demonstrate proton energies in excess of 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 energy $E_L \approx 10$ J on target with a 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 $r_L = 1.5\,\mu$m (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 E_L up to $\approx$ 15 J on target with a slightly larger focal spot resulting in approximately the same at-focus maximum intensity. The target was either a tape made of steel or titanium with thickness $d = 5\,\mu$m, which could be reeled between shots to be positioned within the Rayleigh range of the laser pulse, or an individual thin aluminium target placed on a raster mount moved and aligned at lower repetition.

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) [45] providing rough spectral and spatial information by differential filtering. Additionally, 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 [46]. 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 [47]). For more higher resolution proton spectra and maximum energy, we used either a time-of-flight (TOF) detector [48], 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

When running in high repetition rate operation, the proton beam profile and overall flux for different energy bands was measured using the PBP. Fig. 2a shows an example of the raw data from a single shot at best focus for 5 μm titanium. The grid pattern is the result of differential filtering, which provides different minimum cut-off energies that can contribute to the signal. A relatively thin 200 μm scintillator (EJ-212, Eljen Technology) was used in order to minimise the non-linearity of deposition above this cut-off [45]. Therefore, although the CCD signal is not strictly linear with proton number above this cut-off, it still gives a reasonable relative estimate of the flux.

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 $d = 5\,\mu$m steel target. The integrated scintillator signal for different energy bands is shown in fig. 2b. For example, in the 9 MeV band, the standard deviation of the signal fluctuation is $\approx 25\%$. 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.

This relatively stable system was then used to investigate the behaviour of the proton flux against laser focal spot size on the second experimental campaign ($E_L = 13 \pm 1$ J), shown in fig. 2c for both steel and titanium $d = 5\,\mu$m targets for two minimum cut-offs energies, 9 MeV (blue) and 16 MeV(red). The laser focal spot size was varied by dis-

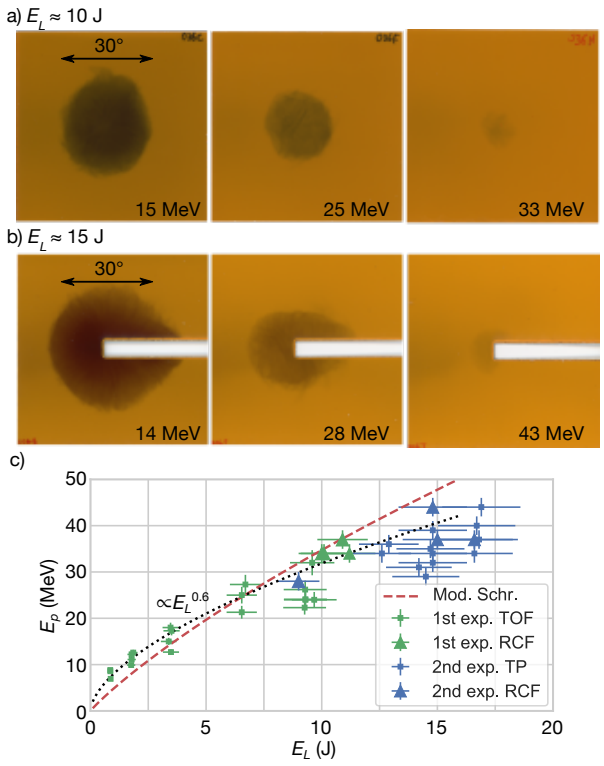

Figure 3: Selected RCF layers from a) $E_L \approx 10$ J from the first experimental campaign and b) $E_L \approx 15$ J from the second experimental campaign for 5 μm steel. Note that the same type of RCF was used in both experiments, but different scanners used, leading to slight colouration differences. 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 both experimental campaigns and 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.

placing 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 for $r_L < 10\,\mu$m, 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 been also observed previously and attributed to a larger acceleration area on the rear surface [49]. As described in [42], using a tight focal spot also only gives a limited boost in maximum energy scaling. Therefore, for ultrashort high power laser systems, using extremely small focal spots to maximise the intensity does not give a significant boost to sheath accelerated proton beams.

Recently, the maximum energy scaling of proton acceleration from 5 μm steel targets at ultra-high intensity was demonstrated with laser energies up to 10 J, using data taken during the first experimental campaign described here [42], and fit with a model based on the Schreiber sheath acceleration model [19], except adjusted for angle-of-incidence and with an acceleration time dependent on the focal spot size r_L, which becomes critical for extremely large spot sizes. In the 2nd experimental campaign, the increased laser energy available allowed us 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, using maximum laser energy, is shown in fig. 3a-b. Although both laser energy levels gives a round, relatively smooth beam profiles, increasing the energy to 15 J resulted in an increase in maximum proton energy from $E_p = 33$ MeV up to $E_p \approx 43$ MeV.

The maximum proton energies against laser energy are plotted in fig. 3c using data from both experimental campaigns, including TOF and TP measurements along target normal, and RCF. Also plotted is an arbitrary $E_L^{0.6}$ scaling along with the modified Schreiber scaling [42], using the same set of assumptions and model inputs. The modified Schreiber scaling agrees reasonably well with the peak performance of the system, but overestimates the average performance. We also note that according to the RCF, for large laser energies (> 10 J) the highest proton energies were consistently $\sim 5°$ away from target normal, towards laser axis [50], causing the target normal measurements (TOF, TP) to underestimate the maximum energy by $\approx 10\%$ on shots in which both diagnostics were used simultaneously.

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], 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 [51, 40, 52] or liquid sheet [41] 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 $d \approx 2\,\mu$m 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 prepulse.

The maximum proton energies for $d = 2\,\mu$m Al targets, as measured on the RCF, were typically between 40 and 50 MeV from shot-to-shot. Examples of background subtracted beam profiles are shown in fig. 4a. As typical for sheath accelerated beams, the full-angle divergence decreases with increasing energy, from $\theta \approx 40°$ at $E \approx 13$ MeV to $\theta \approx 10°$ at a maximum energy near $E = 50$ MeV. As can be seen in

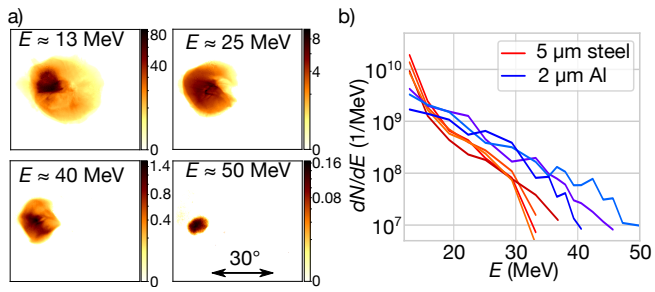

Figure 4: a) Spatial distribution of dose deposited in units Gy from selected RCF layers after background subtraction for $d = 2\,\mu$m Al and b) deconvolved spectrum from RCF of the whole beam for typical shots on $d = 2\,\mu$m Al (shades of blue) and $d = 5\,\mu$m steel target (shades of red) for $E_L \approx 10$ J during the first experimental campaign. RCF observing energies $E < 12$ MeV were beyond the calibrated range and not included.

fig. 4b, 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 tape target used was not optimal for maximising the proton flux each shot, it still could 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 both all protons > 12 MeV, and also a 1% energy band in 1 msr at 15 MeV, a figure of merit for acceptance into a collecting particle optic for transport to applications [4]. The peak currents available from the proton source are extremely high due to the ultra-short acceleration time (at least at the source, before debunching caused by energy spread). However, the average currents, particularly for a small energy band, are still relatively low for some applications, even when scaled to state-of-the-art laser repetition rates (e.g. 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. Although the use of different acceleration schemes may provide a higher conversion efficiency of laser energy into protons, particularly when considering a narrow energy band, the stability and beam quality still needs to be demonstrated. Whatever the acceleration scheme, achieving high beam currents will also quickly pose problems with debris, radioactivation, electromagnetic noise, and target replenishment, which are all major topics of research for future repetitive laser-driven ion sources.

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 only a weak dependence on beam flux for focal sizes $r_L < 10\,\mu$m 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.

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	$\sim 7\,\mu$J
I_{peak}	~ 30 kA	~ 5 A
I_{avg} (0.1 Hz)	~ 0.3 nA	~ 50 fA
I_{avg} (10 Hz)	~ 30 nA	~ 5 pA

6. Acknowledgements

We are grateful to the J-KAREN-P operations team for their support. This work was supported by a JSPS Postdoctoral Fellowship and Kakenhi project No. 15F15772, JST-MIRAI R&D Program #JPMJ17A1 and partially supported by JST PRESTO Grant Number JPMJPR16P9 and Kakenhi 10K05506.

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