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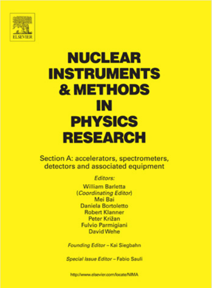

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Parametric scalings of laser driven protons using a high repetition rate tape drive target system

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Abstract

A series of experiments were carried out using the 200 TW laser facility at LLP SJTU aiming to explore parametric scalings of laser driven protons employing a low cost and stable high repetition rate tape drive target system. For numerous laser shots at a repetition rate of ~0.2 Hz with maximum laser intensity up to $\sim 5\times10^{19}$ W/cm^2, proton beams maximum energy were measured for variations in laser energy, focal spot and pulse duration. The data suggests that the proton maximum energy scales as $I^{\sim 0.6}$ while changing the incident laser energy. Scaling trends are in good agreement with the previously reported experimental results and theoretical models. This study may provide a platform to investigate the characteristics of proton beams, such as source size and angular dispersion at a repetition rate required for many potential applications.

Keywords: Laser driven protons, TNSA, Scaling laws, High repetition rate

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1. Introduction

Intense laser-driven ion acceleration has become an active area of research due to its potential applications in science and healthcare, such as fast ignition, proton imaging, high energy density physics, material processing and cancer therapy [1]. Typically, the research activities in this field are concentrated on exploration of diverse mechanisms and generation of sources of particles with unique properties [1]. For instance, laser-driven proton beams are of short duration (picoseconds scale at the source), have tens of MeV energy [2], high flux $\sim10^{13}$ protons/MeV/sr [3], low emittance and high laminarity [1]. Over the last decade, laser-driven proton based radiography have widely been used for the investigation of the electric and magnetic fields, dense objects and living organisms [4–6], proving it a unique diagnostic tool for diagnosing dynamic events with high temporal and spatial resolution.

The most robust mechanism responsible for protons acceleration in intense laser-solid interaction is target normal sheath acceleration (TNSA) [7]. In this mechanism hot electrons absorb energy from the incident laser and propagate through the target creating sheath of an electrostatic field of $\sim10^{12}$ V/m due to charge displacement. This field ionizes and accelerates the ions to multi-MeV energies from the contamination layer on the target rear surface [1], wherein, protons, having highest charge to mass ratio, are accelerated most efficiently.

In the context of the development of high power laser systems [8, 9] providing ultra-short laser pulses at a high repetition rate, target availability has become demanding to explore the laser systems, generated proton beams and relation among laser and proton beams parameters. Albeit laser acceleration of protons/ions is an indirect phenomenon, it is highly related to laser parameters, such as pulse energy, focal spot size, pulse duration. In this context, most of the investigations have been made

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in a single shot mode, yet require a systematic study to corroborate the existing scaling laws [10–17] and use the proton beams for potential applications in a single run for numerous laser shots at a high repetition rate.

In this paper, we present scalings of maximum energy of proton beams to the incident laser parameters at a shot rate of ~0.2Hz. For a systematic and precise observation, we used a stable and low-cost tape-drive target system [18]. The observed scalings show similar trends in comparison to the previously reported experimental results with different scaling exponents under our experimental conditions. This study will be helpful for optimization of laser and beam parameters for future proton radiography at a high repetition rate to investigate the spatial and temporal evolution of electromagnetic fields in a near critical dense plasmas [19].

2. Experimental setup

A series of the experiments were performed with 200 TW Ti:Sapphire laser system from Amplitude Technologies [20] at Laboratory for Laser Plasmas (LLP), Shanghai Jiao Tong University (SJTU). The system is based on chirped pulse amplification technology to deliver laser pulses having energy up to 5 J with a temporal duration of 25 fs and 10 Hz repetition rate. In this work, the experiments were performed one shot per 5 second (0.2 Hz) for large number of laser shots [18]. The schematic of the experimental setup has been reported in Ref. [18]. Briefly, it consists of intense *p*-polarized laser pulses of ~ 30 fs duration. These were focused down to ~ 6 μm spot (FWHM) onto the target at an incident angle of 54° containing 25% of energy using *f*/4 off axis parabolic (OAP) mirror. Laser energy was varied from ~0.3-1.5 J, resulting a peak intensity of ~5×10^{19} W/cm^2. The intensity contrast of the amplified spontaneous emission (ASE) to the main peak was measured to be 10^{-8} at 10 ps by a scanning third-order autocorrelator(Sequioa) [21]. A tape-drive target system based on commercially available Video Home System (VHS) tape of 15 μm thickness was used [18]. Such target systems are feasible for high repetition rate experiments and can provide fresh surface for large number of laser shots >1000 without frequent opening of the target chamber. The accelerated ions were characterized by a Thomson parabola spectrometer (TPS) which was placed along the target normal. The distance of the entrance pinhole of 100 μm diameter from the target was about 755 mm resulting in a solid angle of ~1.4×10^{-8}sr. The TPS was coupled with a multi-channel plate (MCP) detector with a phosphor screen and was equipped with 14-bit Grasshopper 2 CCD camera to image the ions traces. The observed ion traces were processed by a LabVIEW program to extract the energy spectrum.

In the current experiment, variations in the parameters of proton beams were recorded for changing laser intensity by varying laser energy (energy scan), focal spot (focus scan) and laser pulse duration (pulse duration scan) and at least 5 shots were carried out for each observation. While changing one parameter all other parameters were fixed except the unavoidable shot to shot fluctuations.

3. Results and discussion

As mentioned above, in TNSA regime the accelerated protons show a characteristic broad energy spectrum which has sharp cut-off at the maximum energy. This cut-off energy is an important parameter related to laser parameters for which scaling laws have been established [10–17]. The systematic study of the scalings of cut-off energy with laser parameters could be helpful for future experimental design and to upgrade the ultra-intense laser parameters. However, none of the scaling laws are universal, rather with laser intensity and experimental conditions different scalings are possible. Therefore, to utilize ion beams from any laser system it is appropriate to establish a relation among laser and beam parameters.

Fig. 1 shows main results of the parametric scalings of proton maximum energy in our experimental conditions. In Fig. 1 (a) proton maximum energy shows a power law scaling of $I^{\sim0.6}$ for the energy scan where laser intensity was varied by changing the laser energy. The scaling to laser intensity for focus scan in Fig. 1(b) shows a smooth variation with dependence as $I^{\sim0.3}$ by varying target position towards OAP side. In contrast, Fig. 1 (c) shows comparatively weaker dependence of the proton maximum energy on the laser intensity with a scaling of $I^{\sim0.05}$ for the stretched pulses in time with a fixed focal spot and the laser energy.

In comparison with previously reported results, the observed scalings in our work seems to be comparable and consistent. For instance, the scaling in Fig. 1 (a) lies in the range of ~ 0.5-0.9 which is presented for several experimental datum in Ref. [22]. However, it shows a significant variation from the typical linear scaling reported in [15, 23] for short pulses, instead it is comparable to the typical square root scaling for TNSA regime[15]. Also Fig. 1(a) compares the observed scaling laws with the theoretical calculations using Mora and Passoni models [12, 24] for our experimental parameters, in addition to the acceleration time discussed in Ref. [25]. A similar trend can be seen

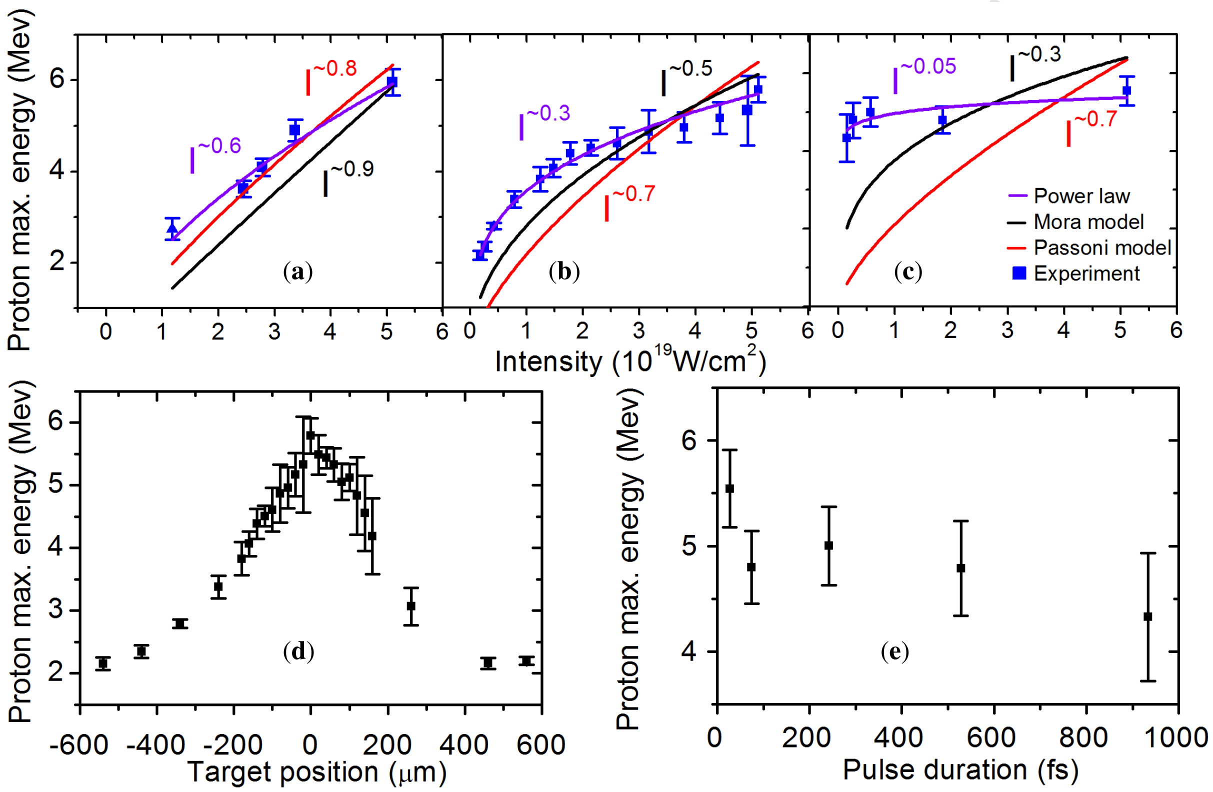

Figure 1: Parametric scalings of proton beams showing dependence of maximum proton energy on laser intensity for (a) changing laser energy (energy scan), (b) focal spot variation (focus scan), (c) stretching the pulse duration (pulse duration scan). (d) variation of proton maximum energy with target position (focal spot changes) where negative sign shows the movement towards OAP, and (e) proton maximum energy versus stretched laser pulses.

in Fig. 1 (a), however, due to limitations of theoretical calculations to model fully the complex nonlinear processes of ion acceleration, different scalings rates are not surprising.

In accordance with the results in Fig. 1(b), previous studies [17, 22] have demonstrated similar behavior wherein, for relatively thicker targets of a few microns, the maximum energy of protons decreases smoothly with decreasing laser intensity for the defocused laser pulses. As shown in Fig. 1(b) and Fig. 1(d), proton maximum energy decreases from ~ 6 MeV at the optimum focus position to ~ 4 MeV with an intensity drop in the range ~5-1.5×10^{19} W/cm^2 for varying the target position. Instead of some plateau region, in contrary to pure metal targets [17], we observed relatively small variation of ~ 0.5 MeV in the proton maximum energy in the range of ~1.5-4×10^{19} W/cm^2. Interestingly, as compared to the scaling reported in [17, 22] for a 2 μm Al target for focus scan, our experimental results shows more dependence on laser intensity using the VHS tape target (plastic) with the exponent twice the exponent of the Al foil target (metal). This is more likely to be attributed to different scale lengths of ASE produced pre-plasma in case of metals and plastic targets that can change interaction conditions [26]. Figure 1(b) also shows comparison with the scalings based on theoretical models where Mora model can be regarded as in good agreement to our results with the scaling as $I^{\sim 0.5}$. The dependence of proton maximum energy on laser intensity for the pulse duration scan for fixed laser energy and focal spot is shown in Fig. 1(c), which shows similar trend to the results reported in Refs. [23, 27, 28]. The proton maximum energy does not decrease significantly for decreasing the laser intensity while increasing the pulse duration. Also, Fig. 1 (e) shows the proton maximum energy variation with the stretched pulses. There is a small drop of 1 MeV in the proton maximum energy as the pulse duration is increased from ~30 fs to ~900 fs. For longer laser pulses, large plasma gradient on target front is reported in Ref. [23]. This limits the maximum energy deposit to hot electrons which results lower energy proton acceleration. However, in our study, with the long pulse duration of few hundred fs, we have not observed significant drop in the proton maximum energy. The weak dependence on laser intensity can be explained with the two competing processes one is the reduction of hot electron temperature for decreasing laser intensity and the other is increment in the acceleration time for increasing pulse duration [11, 13]. There seems a balance in these processes in our experimental conditions for which there is not a significant decrease in proton maximum energy for laser intensity variation for enhancing the pulse duration. In comparison to theoretical models from Fig. 1(c), there are significant deviations from the experimental results with the typical acceleration time used [25]. This would be further investigated with different values for parameters like hot electron propagation and acceleration times in the theoretical models.

4. Summary

In summary, we have demonstrated parametric scaling for proton beams using a low-cost high repetition rate tape drive target for the 200 TW laser system. For laser energy variations, proton maximum energy scales faster with laser intensity ($I^{\sim 0.6}$) whereas for focal spot variation it scales moderately as $I^{\sim 0.3}$. On the other hand, the data suggests weak dependence on laser pulse duration. For the three cases, the observations are broadly in agreement with previously reported results. This clearly indicates the suitability of the proton beams from the high repetition rate tape drive target used for future applications. Although, in this study, we took a large number of laser shots at the rate of ~0.2 Hz which is still lower as compared to the 10 Hz repetition rate of the laser system and required for many potential applications. This study provide platform to characterize the proton beams source size, angular and spectral properties for not only future applications but also for proton radiography to investigate electromagnetic fields and hot electron transport in near critical density targets/plasmas at a high repetition rate.

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