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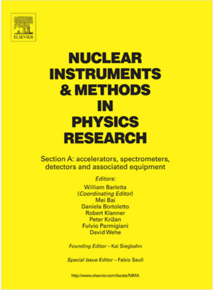

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Controlling laser driven proton acceleration using a deformable mirror at a high repetition rate

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Abstract

We present results from a proof-of-principle experiment to optimize energy spectrum of laser driven protons by directly feeding back its spectral information to a deformable mirror (DM) controlled by evolutionary algorithms (EAs). By irradiating a stable high-repetition rate tape driven target with ultra-intense pulses of $\sim 10^{20}$ W/cm^2, we optimize the maximum energy of the accelerated protons with a stability of less than ~5% fluctuations near optimum value. Moreover, due to spatio-temporal development of the sheath field, modulations in the spectrum are also observed. Particularly, a prominent narrow peak is observed with a spread of ~15% (FWHM) at low energy part of the spectrum. These results are helpful to develop high repetition rate optimization techniques required for future laser-driven ion accelerators.

Keywords: Laser driven protons, TNSA, Deformable mirror, Evolutionary algorithm, High rep. rate

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1. Introduction

The acceleration of ions beams using high power lasers emerges as a promising alternative to conventional accelerators and have attracted considerable interest over the last decade due to potential applications in science, industry and health care. Some of these applications are ion driven fast ignition, investigation of warm dense matter and high energy physics, generation of secondary radations, plasma radiography and hadron therapy [1]. In this context, the most investigated mechanism is the target normal-sheath acceleration (TNSA) [1]. In this mechanism, ions acceleration is due to the development of a large sheath electric field (TV/m) at the rear side of the target as the hot electrons, generated in the interaction, propagtes through the target. Protons, being lighter than other hydrocarbon contaminents present on the rear surface of the target, are accelerated most effectively in the normal direction to the target [1]. These proton beams exhibit unique properties, viz. short pulse duration, high brightness and low transverses emittance [1]. However, the characteristic broad energy spectrum and large angular spread poses significant challenges for their use in potential applications including proton therapy for cancer treatment and fast ignition [1, 2]. In order to use laser-driven protons for aforementioned applications, improvement in different parameters e.g, stability, maximum energy and broad energy spread are essential [3]. In addition to use the complex target designs or ultrathin targets [4, and references therein] for optimization of laser-driven proton beams, many publications [3–10] show the control of the spectrum by manipulating the laser beam profile. Control of the proton beams using optical methods are peferable [11]. Since this will be advantegeous for the development of next generation sources at a given high repeition rate [12, 13]. Use of deformable mirrors (DMs) is considered as a simple way of shaping a laser beam profile [5]. Recently, DMs have been

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used to optimize electrons beams from a high-repetition rate laser and gas jet target systems [14]. Based on spatio-temporal characteristics of DMs [15], a control over laser-plasma interaction and thus the optimization of proton spectrum may be possible.

In this paper, we present a proof-of-principle experiment of laser-driven protons from a tape-drive target [16], where, the proton energy spectrum information is supplied in the feedback loop to a DM controlled by evolutionary algorithms (EAs). A low-cost, stable and high repetition rate VHS (Video Home System) tape drive target system was used [16, 17]. This target system provides continuous and fresh supply at high repetition rate without extra efforts on the vacuum systems required for gas jets [18]. By employing this system for a large number of laser shots at a rate of 1 Hz and DM controlled by evolutionary algorithms (EAs), we demonstrate an enhancement in the maximum energy of the proton beams. The resutls show an improvement in the maximum enrgy with variations $\lesssim 5\%$ in stability and an error of ~10% as compared to the values obtained with optimized focal spot using EAs. In addition, influence of multi-parameter optimization is observed on spectral shape of the proton beams. For instance, a pronounced peak at ~1 MeV with ~15% spread is observed.

2. Tape drive target system, deformable mirror and evolutionary algorithms

A high repetition rate tape drive system used for this study has already been described in Ref. [16]. Mainly, it consists of a thin tape of 15 μm thickness driven by highly vacuum compatible DC motors with a computer control program in LabView [19]. The used bimorph deformable mirror (DM 2-80, AKA-Optics) consists of 31 piezo electrodes behind a clear reflective surface of 80 mm [20]. By controlling the voltages of the actuators (-200V to +300V), the surface of the mirror and thus shape of the reflected laser spatial profile can be altered. The geometry of the DM actuators is shown in Fig. 1 (a). Such type of DM can be used to optimize the laser wavefronts or an experimental measured quantity with a feedback loop using a reference wave front or an evolutionary algorithm [21–23]. The scheme of the EAs used is similar as described in Ref. [5]. In general, the voltages of DM actuators are taken as genes and a population is generated randomly with large number of individuals providing a search space to select the most fit parameters. For the optimization of laser focus using the focal spot information in the feedback loop the fitness function of the type $\text{Fitness}_{focus}=\text{A}/\text{B}^2$ is used, where A and B are the integrated intensities around the center. While for optimization of the proton energy, similar fitness function can be used with A and B being integrated counts for an energy range in the spectrum. To modify the spectral shape of proton beams, the fitness function of the type $\text{Fitness}_{protons}=(\text{A}+\text{C})/\text{B}^2$ can be used, where A, B and C are the counts correspond to specific energy intervals in the spectrum. Scheme of the fitness functions is shown in Fig. 1 (b). The flow chart of the optimization technique using EAs is shown in Fig. 1 (c). After having the energy spectrum, the fitness of all individuals are evaluated according to the fitness function described before and the best individuals are chosen for the creation of new generation of voltages values. The DM is set according to these new set of values before irradiating the fresh target surface.

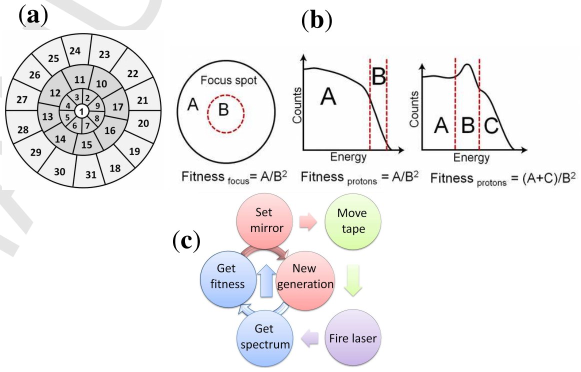

Figure 1: Schematics for deformable mirror and evolutionary algorithms implementation. (a) Geometry of the electrostatic piezo actuators of the DM, (b) scheme for fitness functions (left to right) for focal spot optimization, proton spectrum for maximum energy and spectral shape respectively, and (c) flow chart to implement EAs for optimization of proton spectral shape.

3. Experiment

The experiment was performed at Max-Born-Institute Berlin. A multi-TW (maxed spec 70 TW) Ti:sapphire based laser system was used which can deliver p-polarized pluses of 35 fs duration and energy ~2 J. The amplified spontaneous emission contrast (ASE) to the main peak was measured to be 10^{-8} at τ~10 ps and 10^{-11} at $\tau \gtrsim 30$ ps before the peak by a scanning third-order auto correlator [24]. Fig. 2 shows the schematic of the experimental setup. Laser pulses were focused down to ~4 μm spot (FWHM), using an $f/2.5$ off-axis parabolic mirror, containing ~30% of the energy inside the first order of diffraction. The resulting maximum intensity on the target was ~ 1×10^{20} W/cm^2. The tape

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drive system with VHS tape of 15 μm was placed in the laser normal direction. Such a tape drive system can provide fresh target supply at a high repetition rate for large number of laser shots with stable and reproducible proton spectrum [16]. To characterize the accelerated ions, a Thomson parabola spectrometer was placed along the target normal direction. Ion traces were detected by an imaging micro-channel plate (MCP) coupled with a phosphor screen and a CCD camera. The signal was sent to a computer controlled program in Labview for evaluation of the voltages according to the fitness functions described in section-2. For simplicity in the current experiment, after optimizing the laser focal spot with EAs using all 31 actuators of the DM, only actuator No. 1, mainly responsible for defocusing the laser beam, was selected for optimization of the maximum energy of proton beams. The voltage range was selected from -60 to 60 volts. The population size was 5 and evolutionary algorithm was run for almost 12 generations for about 60 shots.

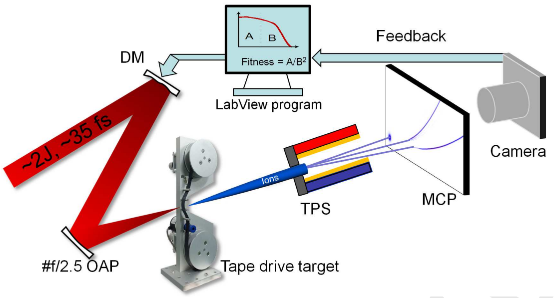

Figure 2: Schematic of the experimental setup for optimization of the maximum proton energy with deformable mirror controlled by EAs using VHS tape drive target system.

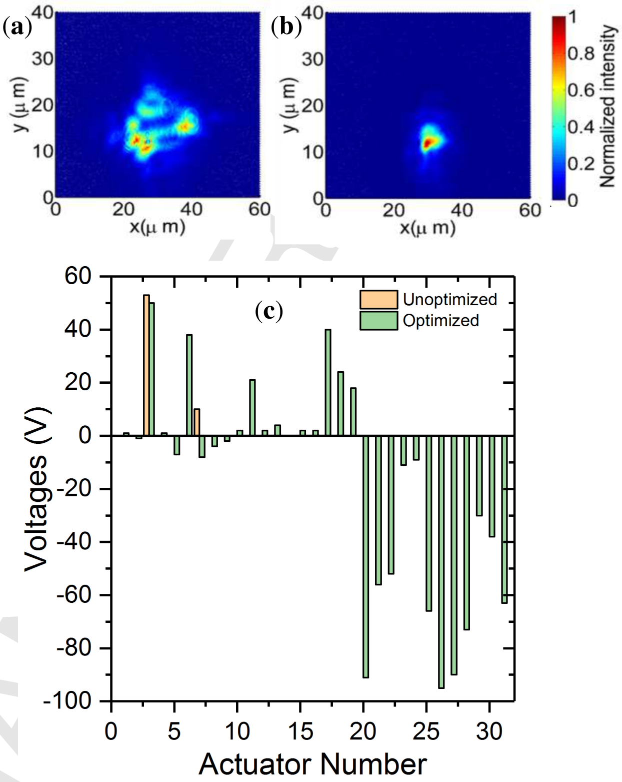

Figure 3: Optimization of the focal spot, (a) unoptimized focal spot for an arbitrary shape surface of the DM, (b) optimized focal spot using EAs and (c) corresponding voltages of the actuators of the DM.

4. Results and discussion

4.1. Enhancement in maximum energy

Before the optimization of the energy of the laser driven protons, the laser focal spot was optimized using EAs utilizing all actuators of the DM, hereafter, referred as an optimized focal spot state. Fig. 3 shows the result of the laser focal spot optimization using fitness functions as mentioned in section-2. This is also an indication that our EAs scheme fucntions properly. Fig. 3(a) shows initial large defocused beam spot $\gtrsim$30 μm for the un-optimized DM, whereas Fig. 3(b) shows the resulting optimized focal spot of ~4 μm (FWHM) incorporating all 31 actuators in the search space of EAs which took more than 1500 shots. Since at full laser energy it is difficult to record the wavefronts, information of the corresponding voltages can be used to reconstruct the shape of the DM surface as described in Refs. [25, 26]. Fig 3 (c) shows the corresponding voltages to the actuators. The proton energy spectrum for the optimized focal spot and alignment of the target system in real experimental situation with full laser energy is referred as a reference spectrum. For optimization of the maximum energy of the proton beam using DM with proton spectrum in the feedback loop, the optimum value of the selected actuator (actuaotr No. 1) was deliberately changed to an arbitrary value e.g. -30 Volts. This ultimately defocuses and deshapes the laser beam spot and produces a low energy proton beam which is considered as an initial spectrum. Maximum cut-off proton energy is obtained using EAs with the proton spectrum in the feedback loop to DM using the fitness function described in section-2. Fig. 4 shows the comparison of initial, optimized and the reference spectrum and evolution of maximum energy of the proton beams. The optimized spectrum is an average value of the last 10 shots and shows fluctuations of less than 4 %. The initial maximum energy is ~3 MeV and the value obtained by the optimization scheme is ~4.5 MeV similar to the reference spectrum with an error of about 10%. The difference is likely to be due to the complex nature of laser-plasma interaction which is affected by spatial profile of the laser beam [14, 23]. As mentioned earlier, the actuator used to control the maximum energy of proton beam affects the focus of laser. The focal position scan after optimization shows a further enhancement of the proton maximum energy(~ 6 MeV) in the range of 100 μm towards the OAP as shwon in the Fig 4(a). This indicates that consideration of more than one actuators of the DM to compensate likely effects of astigmatism and defocusing would be required [26]. This will be considered in future studies, however, our present results clearly shows a direct link of maximum energy of the proton beams to the laser beam profile which interacts with the plasma resulting in the energy enhancement. Fig. 4 (b) shows the variations of the maximum energies of the proton beam during EAs based optimizations. It shows high variations in the start which finally converges to ~4.5 MeV as the EAs scheme evolves. It is worth to mention here that using a VHS tape target (which is recently designed to investigate laser driven protons at a high repitition rate[16]) results in the maximum energy of the proton beam which is lower than the recently reported results [27–29]. This is due to relatively large thickness of the target compared to target thicknesses used in Ref. [27–29] and different target materials as the laser energy coupling to the target is better in case of metallic targets. Furthermore, maximum proton energy can be enhanced using a few micron thick (2-5 μm) tape drive targets.

As mentioned above, the DM is controlled by voltages to its actuators which shape reflecting surface of the mirror. To test the optimization of the maximum energy of the laser driven protons in the experiment, we selected acturator No. 1 only to minimize the search space and thus the shot numbers. The variation of voltages and the fitness function and their correlation is shown in Fig. 5. A similar trend is found for the fitness function and voltages and they start converging from the shot number 40. The converged value of the voltage is ~-1 volt closer to the case where laser focal spot information in the feedback loop to DM was used for its optimization. Fig. 4 (b) and Fig. 5 show a clear connection among them the variation of proton maximum energy, fitness function values and voltages.

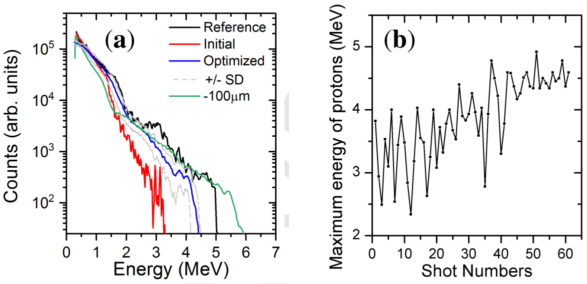

Figure 4: Optimized proton energy spectrum, (a) comparison of reference, initial and optimized spectra. SD stands for standard deviation. The focal spot scan towrds OAP shown by green line, and (b) variation of the maximum energy of protons with the laser shots during optimization.

4.2. *Modifying spectral shape*

Based on our above results, we used multiple actuators (5-15) of the DM for controlling the spectral shape the proton beams [15, 26, 30] in a specific energy range with the fitness function as described in section-2. Typical spectra with and without the effects on spectral shape are shown in Fig. 6. As can be seen in Fig. 6(a), for shot 1 and shot 2 modulations at both ends of the spectrum are observed. The pronounced peak has spectral width ~15% in low energy part of the spectrum at 0.8 MeV. As described above the spectral shape (kinematic distribution) of protons can be influenced by the spatial and temporal profile of the incident laser pulse. Spatio-temporal effects can also be introduced by the deformable mirror because of the non-flat reflecting sruface [26, 30]. Conesequently, the change in the laser pulse profile can influence the hot electrons distribution, which modifies the sheath field responsible for the proton acceleration [6, 14, 31]. Fig. 6 (shot 3) shows the typical proton spectral shape without any modulation. The difference is also clearly visible from the raw data shown in Fig. 6 (b) and (c). We observed a reduction of C^{4+} counts together with a sharp rise in the proton numbers which might indicate screening effects [32]. This possible multispecies behavior can be further investigated in future studies while considering the control of proton spectral shape using DM with the proton spectral information in the feedback loop. In the context of the effects shown in Fig 6 (a and b), our proof of concept study shows reproducibility of the modulated spectral features, however, the appearance on long intervals requires an improvement in our EAs scheme to control these feauters effectively. Another plausible reason for the spectral modulations in Fig. 6 could be the generation of multiple pulses with temporal delays due to refelction from non-flat surface of the DM [3]. These temporal delayed pulses can modify the contamination layer by changing hot electron distribution which results

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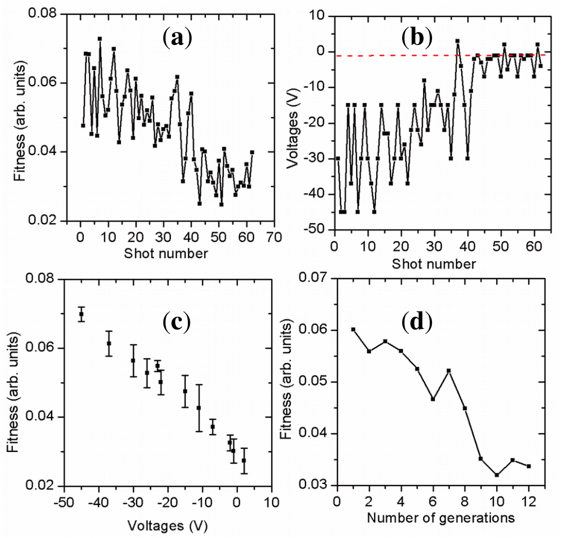

Figure 5: Variation of different parameters of evolutionary algorithm . (a-b) variation of fitness function and voltages with laser shot number respectively, where red line shows convergence ~-1 V, (c) evolution of fitness function with generations number, and (d) relation between fitness function and voltages.

in the spectral peaks [9, 10]. However, without additional simulation the pre-pulse effects and variation in the contamination layer [10, 33] are not easy to evaluate.

5. Summary

In summary, we have demonstrated the controlling scheme for laser driven protons from a tape driven target system using evolutionary algorithm controlled DM with proton spectal information in an active feedback loop. The maximum energy of the protons was optimized to ~5 MeV with about 10% error with reference to the proton spectrum obtained from the optimized focal spot. The fluctuation of the spectrum was found to be less than 5% near optimum value. While optimizing spectral shape with the scheme introduced, the modulations in the spectrum were also observed. Pronounced peaks at 0.8 MeV with a spread of ~15% (FWHM) were repeated on long intervals. Further work is required in future to control these features on short intervals. This study may be useful for establishing an efficient optimization system, at a high repeitition rate, linking a direct correlation between incident laser and the accelerated protons. This is important to overcome the daily variations in the starting parameters of highly complex systems by employing an automated and operator independent controlling scheme.

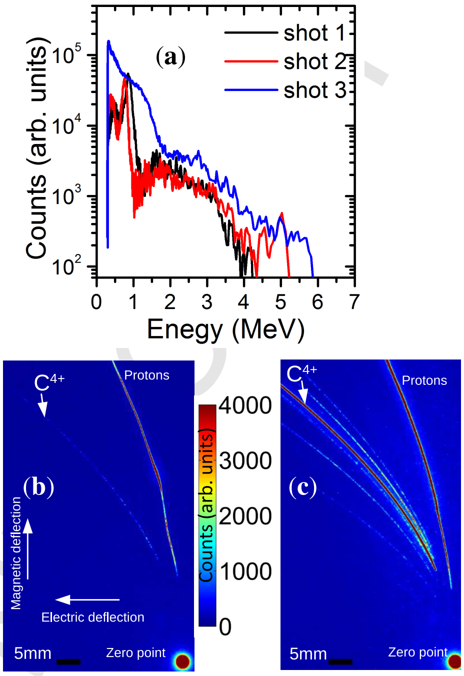

Figure 6: Effect on the spectral shape (a) shot 1 and shot 2 are showing effect on proton spectral shape, whereas shot 3 is showing no effect spectal shape by DM, (b-c) are corresponding raw traces for shot 1 and shot 3.

6. Acknowledgments

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