Decreasing divergence and enhancing particle number of laser-driven ion beams by various target designs and laser parameters

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Abstract

The article demonstrates the results of 2D and 3D Particle-in-cell (PIC) simulations in enhancing charge and decreasing divergence of laser-accelerated ion beams by advanced target designs and by changeable laser features (e.g. laser beam width, two laser beams having the same on- target energy as a single one), which can be useful for various applications.

Introduction

The use of laser-driven ion beams is investigated in many research fields and is resulting in applications such as hadrontherapy, 'fast ignition' of ICF targets, material science, chemistry etc. [1]. In the last few years there has been a growing interest in improving ion beam quality, e.g. by decreasing beam divergence, by increasing maximum energy of protons/ions and by enhancing the number of accelerated particles. The low divergence and the high charge of accelerated protons are two main aims of 2D and 3D PIC simulations reported in this article.

Simulation methods and parameters

Various target designs (depicted in Fig. 1; the red elements represent changeable parameters) were simulated by the use of the 2D PIC code EPOCH [2]. In addition, we carried out the 3D EPOCH simulations for favorable targets as well (Fig. 1 (a), (b), (g)). The 2D simulations ((a)–(e)) were performed with the laser of wavelegth λ = 800 nm, duration of the Gaussian laser pulse (FWHM) 30 fs, the laser beam width (FWHM) 5 μm and intensity I=4.5e20 W/cm^2. The beam has 0° angle of incidence to the target and comes along the x-axis. For the 3D and the 2D (f) simulations, the parameters were slightly modified – beam width 3 μm (or both 3 μm and 5 μm in (f)), I=5e21 W/cm^2 (in (f) intensity was changed in order to get the same total energy of both laser pulses incident on a target), 15° incidence (ELIMAIA beamline) or ±45° in (f) case. In all simulations, three particle species were used (electrons, protons and carbon ions), while quasineutrality stays conserved. The maximum density of targets was 40 n_c (2D) and 200 n_c (the 3D cases and the case depicted in Fig. 1 (f)).

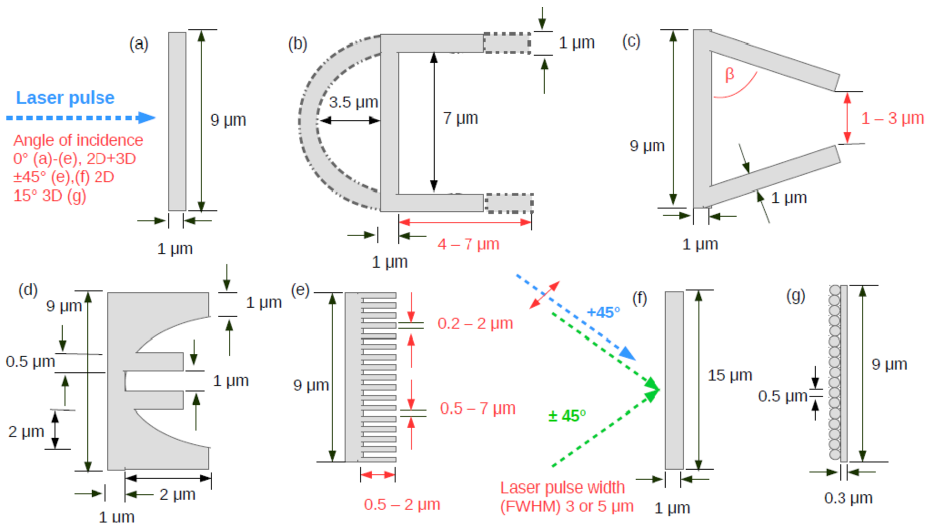

Fig. 1: Simulated targets: (a) – (f) with the aim to decrease the divergence, (a), (f) and (g) with the aim to enhance the total charge; all targets simulated by 2D PIC EPOCH, the cases (a), (b), (g) also simulated in 3D; the parameters of the simulations are described in the text; red color means changeable parameters; (color online)

Results and Discussion

(1) Decreasing the divergence of an accelerated proton beam: The comparison between angular distributions of the protons above 10 MeV accelerated from all target designs is listed in Tab. 1 (the maximum energy does not vary much and reaches ~ 33 MeV).

Target	flat	flat + channel (4 µm long)	flat + channel (7 µm long)	curved + channel (4 µm long)	flat + tappering channel (a 3-µm-hole)
div [°]	4.0	2.1	1.4	10.5	3.4
Target	(d)	flat + tappering channel (a 3-µm-hole; 2x bigger)	curved foil + channel (4 µm long)		flat + various µ-structures on the rear
div [°]	13.0	1.6	10.5		6.8 – 14.6

Tab. 1: Half-angle proton divergence (in FWHM) of various target types; the energy interval 10 MeV – E_{max} is taken into account; proton divergence was measured after the particles escape from the channels.

As seen in Tab. 1, the most effective design solution for divergence reduction was a flat target with a single channel (1.4° at FWHM), see proton density plot Fig. 2 (b). Furthermore, focusing and guiding were more efficient with a longer channel, because the additional electric field (~ 10^{13} V/m) from the sides of the channel operated at a longer distance, see Fig. 2 (d). Conversely, a shorter channel can better focus the protons with lower energy, because they remains in the channel eletric field for a longer time (having a lower velocity than the more energetic ones): $\mathrm{div}_{(0\mathrm{MeV}\text{-}E_{max})}$=3.2°, $\mathrm{div}_{(10\mathrm{MeV}\text{-}E_{max})}$=2.1°, $\mathrm{div}_{(30\mathrm{MeV}\text{-}E_{max})}$=4.6°; E_{max}=38 MeV. In fact, these results (Fig. 1 (b)) were confirmed by the 3D simulation; wherein divergence reaches 3.7°/1.2° (x-y/x-z plane). Although the curved foil focuses particles by its simple geometry [3], the additional electric field is not strong enough to keep all protons accelerated from such a foil with channel (Fig. 1 (b)) focused due to the strong defocusing tendency after the meeting point. The second favorable design seemed to be a flat target with a tappering channel, ideally twice bigger than a 'normal' size; Tab.1 and Fig. 2 (c). This foil, in principle, also acted as an energy selector, in that the 3-μm hole can reduce the number of particles having 0–5 MeV by 49%, a 1-μm hole by 58%. Since the less energetic protons have bigger divergence, the energy interval of the stopped ones naturaly depends on the size of the hole, i.e. a smaller hole retains more energetic particles. Targets with multiple μ- structures on their rear proved to be foils producing divergent beams, mainly because of the structures' gap dimensions being much smaller than the laser focal spot [4]. This results in severeal spheres micro-explosions continuing in small bunches creating the beam with final high divergence.

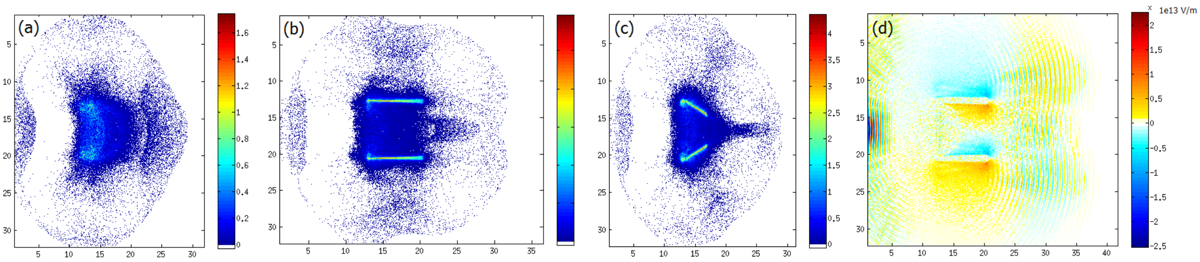

Fig. 2: Proton density plots at the end of the simulation of (a) flat foil, (b) flat foil with 7 μm long channel, (c) flat foil with tappering channel (a 3-μm-hole); (d) electric field (E_y ~ 1e13 V/m; the case (b)); (color online)

(2) Enhancing the total charge of a proton beam: For the application of proton pulsed radiolysis (PPR) of water [5], a ~10 MeV proton ns bunches of at least 1 nC charge are needed. Undoubtedly, we have to consider the particle number losess during beam transport (up to 90%), as well as energy losses. Thus, protons having 13.5–16.5 MeV, were analyzed. We have tested (in 2D) the dependence of laser parameters (Fig. 1 (f)) on the 13.5–16.5 MeV proton charge which reaches from 4 nC to12 nC (2D simulations overestimate the particle number, thus this will be investigated in 3D as well). In fact, preliminary 2D results show that two laser pulses having the same total energy on a target as a single pulse can enhance the proton charge (13.5–16.5 MeV) by ~ 60% (pulse width 5 μm). The reason is that the conversion into particles is enhanced and the temperature of hot electrons at the beginning of the interaction is doubled leading to the more effective acceleration. Nevertheless, the total charge of all accelerated protons remains ~ the same. Moreover the usage of two laser beams reduces the divergence of the 13.5–16.5 MeV protons by ~40% and ~55% for 3 μm and 5 μm laser spot size, respectively. The physical basis is connected to the significantly flatter space profile of accelerated protons and electrons, thus their trajectories are straighter and divergence lower. In addition, the 3D simulations of the most suitable targets (Fig. 1 (a) + (a) of the thicknesses of 800 and 300 nm, (f), (g)) were performed. The largest increase in proton

number (all energies) was expected and confirmed in the case of foil with spheres on its front, as reported in [6]. Nevertheless, the foil with spheres practically enhances only the number of high-energy protons (>16.5 MeV) and not the number of low energy ones (<16.5 MeV). In energy interval above 16.5 MeV the total proton charge at the source (just behind the target) was 26.4 nC in comparison to 11.2 nC obtained from a 800-nm flat foil. The proton number in the 'chemical' energy interval was the same for the foil with spheres as for the 800-nm flat foil (4 nC), while for a 300-nm flat foil the proton charge was 6.3 nC. Such target types can be used for PPR of water experiments at ELI- Beamlines assuming that no more than ~75% of protons will be lost during the transport.

Conclusions

The best target design in order to decrease divergence is a flat foil with a channel (either straight or tappering); also confirmed in 3D. Moreover, the foil with the tappering channel can, in principle, work as an energy selector. Two laser beams having the same laser energy can enhance the total beam charge and decrease its divergence, compared to a single laser beam having the same total energy. Furthermore, it was shown that a flat foil with spheres on its front enhances the number of >20 MeV protons efficiently, but in the energy interval required for PPR of water, the results are comparable with a 800-nm-thick plastic flat foil.

Acknowledgements

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