Divergence and direction control of laser-driven energetic proton beam using a disk-solenoid target

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Abstract

A scheme for controlling the divergence and direction of an energetic proton beam driven by intense laser pulse is proposed. Simulations show that a precisely directed and collimated proton bunch can be produced by a sub-picosecond laser pulse interacting with a target consisting of a thin solid-density disk foil with a solenoid coil attached to its back at the desired angle. It is found that two partially overlapping sheath fields are induced. As a result, the accelerated protons are directed parallel to the axis of the solenoid, and their spread angle is also reduced by the overlapping sheath fields. The proton properties can thus be controlled by manipulating the solenoid parameters. Such highly directional and collimated energetic protons are useful in the high-energy-density as well as medical sciences.

Keywords: laser-driven ion source, target-normal sheath acceleration, direction control, collimation, disk-solenoid target, helical target

(Some figures may appear in colour only in the online journal)

1. Introduction

Energetic laser-driven ion source with unique features, such as small device size and high brightness, is useful in radiography [1], warm dense matter generation [2], fast ignition of fusion core [3], isotope generation [4], tumor therapy [5], brightness enhancement for conventional accelerators [6], etc. The target-normal sheath acceleration (TNSA) mechanism [7] is widely investigated because of its undemanding laser and target parameter requirements [8–13]. In TNSA, an intense laser interacts with a target, generating hot relativistic electrons that penetrate through the latter and establish in the backside vacuum a TV/m sheath electric field, which accelerates the target-back ions to multi-MeV energies [14]. However, the intrinsic target-normal direction and divergence of the TNSA protons limit their applications.

Different methods have been proposed for collimation and manipulation of the TNSA protons, including the use of structured targets [15–26], electrostatic lens [27, 28], laser prepulse [29], oblique laser incidence [30–32], etc. In particular, the recently proposed scheme, by Kar et al [18, 33] and Ahmed et al [34–36], of using a solenoid attached to a disk target shows its versatility and simultaneous focusing, energy spectrum selection and post-acceleration of TNSA protons. The scheme is based on the laser-excited electromagnetic field pulse traveling along the coil. Nevertheless, simultaneously controlling the divergence angle and the direction of the TNSA protons remains a challenge.

In this paper, we propose to attach a solenoid to the back of a thin disk target at a certain angle to simultaneously collimate and guide the TNSA protons. Three-dimensional (3D) particle-in-cell (PIC) simulations show that a precisely
directed proton bunch with small divergence angle can be obtained. The result is attributed to a uniquely structured sheath field created by the hot electrons from the disk, and is therefore quite different from the electromagnetic-pulse-induced field usually observed in the laser-target interaction [18, 33-36]. The results agree quite well with that from an analytical model, which is also useful for tailoring the solenoidal parameters in order to produce well directed and collimated high-energy proton bunches under given laser and target conditions.

2. Simulation setups

The target configuration can be visualized in figure 1(a) for the electron and proton densities at $t = 420$ fs. The helical plasma-wire solenoid is attached to the back of the disk at, for definitiveness, a $\psi = 20^\circ$ angle. The radius, length, and number of turns of the solenoid are $r_s = 3.5 \mu m$, $h = 10 \mu m$, and $n = 6$, respectively. The coil wire is of diameter $0.6 \mu m$ and total length $l = n_s \sqrt{\left(2\pi r_s\right)^2 + (h/n)^2} = 132 \mu m$. The radius and thickness of the disk are $6 \mu m$ and $1 \mu m$, respectively. As proton source, a hydrogen dot of thickness $0.5 \mu m$ and diameter $1 \mu m$ is placed at the center of the rear disk surface. In the 3D PIC simulations with EPOCH [37], the disk and the solenoid are Cu$^{2+}$ plasma, at densities $n_{0B} = 20n_c$ and $n_{0B} = 40 n_c$, respectively. The density of the hydrogen dot is $1n_c$, where $n_c \sim 1.1 \times 10^{21} \text{ cm}^{-3}/\lambda^2_L$ is the critical density, and $\lambda_L = 1.06 \mu m$ is the incident laser wavelength. To account for the laser prepulse, a $5 \mu m$ long prepulse of density $n_s = n_{0B} \exp(x/h)$, where $\delta = 0.5 \mu m$, is placed in front of the disk. We note that due to limitation of our computing resource, the target density in the simulation is made much lower than that of bulk solid copper. Such targets can be potentially fabricated by ion-beam machining [38] of porous copper [39, 40]. Another possible route to access the density regime is to use the second harmonic of the laser to irradiate bulk copper targets [41]. A y polarized Gaussian laser pulse of $\lambda_L$, intensity $2 \times 10^{20} \text{ W cm}^{-2}$, waist radius $3 \mu m$, and duration $500$ fs is normally incident from the left boundary at $x = -8 \mu m$. The laser has a flat-top temporal profile, with $3.5$ fs rising time. The flat-top pulse is used for convenience, saving the simulation time and simplifying the analysis of the hot electron propagation in the solenoid (see section 3). Simulations with a Gaussian pulse have also been carried out and they gave similar results. The simulation box is $23 \times 16 \times 16 \mu m^3$, with $1143 \times 795 \times 795$ grids. There are $7$ macroparticles per cell for the solenoid target and $30$ for the hydrogen dot. As shown in figure 1(a), at $t = 420$ fs, a directed and well collimated proton bunch with cut-off energy $>20$ MeV is generated. The exit angle of protons with energy $>12$ MeV is around $26^\circ$ from the disk normal in the $(x, y)$ plane. In contrast, figure 1(b) shows that without the solenoid, the proton beam propagates nearly normal to the target-back with a considerably larger divergence angle and lower flux than the former.

3. Simulation results and theoretical analysis

As the intense laser pulse impinges on the target, hot electrons are generated at the front surface and directly accelerated by the laser to high speeds [42, 43]. They can easily penetrate through the disk and establish immediately behind it as well as around the surface of the solenoid wire an intense sheath electric field, roughly given by $E_{sh} \sim T_{eh}/(e\nu) \sim 0.86 \times 10^{12} \text{ V m}^{-1}$, where $T_{eh}$ is the temperature of hot electrons and $e$ is the elementary charge [7]. This value agrees well with
that from the simulation, as shown in figure 2(a). The time interval between the establishment of \( E_0 \) on the first and last coil of the solenoid can be roughly estimated as the time-of-flight of hot electrons through the solenoid as \( \hbar \cos(\psi)/e c = 31.3 \) fs. On the other hand, the electrons exiting the disk at where the solenoid is attached can propagate in the solenoid wire (a conductor) and create around its surface a local sheath field with magnitude \( E_t \sim T_{\text{es}}/(eK) \approx 2.4 \times 10^{12} \text{ V m}^{-1} \), where \( T_{\text{es}} \) is the temperature of these secondary electrons and \( K \) the spatial scale of their field. It takes much longer time for the establishing of \( E_t \) than \( E_0 \) as the distance of electrons propagating in the solenoid wire is much larger than that of electrons flying through the solenoid. The establishment of \( E_t \) on the last coil is roughly at \( 1/e = 440 \) fs after the laser pulse impinging on the target. Thus \( E_b \) and \( E_t \) partially overlap, and in the overlapped region the shear field on the solenoid surface can be as high as \( E_b = E_t \approx 3.3 \times 10^{12} \text{ V m}^{-1} \). Both \( E_b \) and \( E_t \) are roughly azimuthally symmetric with respect to the solenoid axis, the slight asymmetry is due to the tilted connection of the solenoid to the disk-back. The normal (to the solenoid axis) components of both \( E_b \) and \( E_t \) lead to a focusing force on the dot protons accelerated by the disk-back sheath field, as shown in figures 2(a) and (b), so that instead of propagating normal to the disk-back surface, the protons are directed and collimated by the solenoid, as can be seen in figure 2(b).

It is also necessary to consider the effect of the self-generated magnetic fields. The electron current in the solenoid wire is much larger than the Alfvén limit [44]. The return current induced on the wire surface gives rise to a strong longitudinal magnetic field in the solenoid [45, 46].

\[ \frac{d^2 L}{dt^2} = eE_b/L \]

Figures 2(c) and (d) show that the peak magnetic field (on the solenoid axis) is \( B_0 \approx 1 \times 10^4 \text{ T} \). The corresponding proton gyroradius is \( r_{pg} \approx (m_p v_p/\alpha eB_0) \approx 15.7 \mu \text{m} \), where \( m_p \) and \( v_p \approx 0.05c \) are the proton rest mass and transverse velocity component, respectively. Since \( \gamma_{pg} \gg r_p \), the magnetic field should have little effect on the protons as can be seen in figure 2(e) for three typical proton trajectories resulted from single-particle simulations based on the time-dependent fields obtained from PIC simulations. Thus, the direction and collimation of the proton bunch are mainly determined by the electric fields \( E_b \) and \( E_t \).

It is thus of interest to see how \( E_b \) and \( E_t \) affect the proton dynamics. Since the solenoid electrons propagate at near light speed, the distance between the field boundary (i.e. the rough boundary between \( E_b \) and \( E_t \)) and the disk-back surface at \( t > T_0 \) is \( L_{bb}(t) \approx c(t - t_0)/v_p \), where \( T_0 \) is the time when the electrons start to propagate in the solenoid wire.

The protons are first accelerated to a velocity \( v_p \) by the sheath field at the disk rear from \( T_0 \) to \( T_0 + \tau_{acc} \), after which they are no longer accelerated. The parallel and transverse proton velocities are then

\[ v_{p,\parallel} = v_{p,\perp} \cos(\phi + \psi) = \text{const. and } v_{p,\perp} = v_{p,\perp} \sin(\phi + \psi), \]

where \( \phi \) is the divergence angle of the protons and \( \psi \) is the angle between the solenoid and the disk. Since protons with \( v_{p,\parallel} \geq c/\sqrt{1 - c^2/\alpha^2} \) cannot cross the field boundary, the protons (hereafter referred to as proton 1) is thus mainly governed by \( E_b \) (or \( E_t \)) for those with small \( v_{p,\perp} \). On the other hand, protons (hereafter referred to as proton 2) with \( v_{p,\perp} > c/\sqrt{1 - c^2/\alpha^2} \) can cross the field boundary at \( t = T_0 + \tau_{acc} \). Type 1 protons satisfy

\[ L_{bb}(t) = \frac{v_{p,\perp}}{\omega_s} \sin[\omega_s(t - (T_0 + \tau_{acc}))], \]

and

\[ v_{p,\parallel}(t) = v_{p,\parallel} \cos[\omega_s(t - (T_0 + \tau_{acc}))]. \]
for proton 1, where \( \omega_{h} = \sqrt{eE_{h,\text{max}}/(m_{p}r_{f})} \). Therefore, the exit angle for proton 1 is centered along the \( \psi \) direction, with the divergence given by

\[
\frac{v_{p_{h}}}{v_{p_{l}}} \leq \tan(\phi + \psi).
\]

(3)

The dynamics of proton 2 for \( t \leq T_{1} \) is similar to that of proton 1. However, at \( t = T_{1} \), proton 2 can cross the field boundary. Therefore, their motion is governed by \( \frac{d^{2}L_{2}}{dt^{2}} = eE_{h}/m_{p} \). Assuming again that \( E_{h} \) depends linearly on \( L_{\perp} \), i.e. \( E_{h} = -E_{h,\text{max}}L_{\perp}/r_{f} \), one obtains for proton 2

\[
L_{2}(t) = c_{1}\cos[\omega_{h}(t - T_{1})] + c_{2}\sin[\omega_{h}(t - T_{1})],
\]

(4)

\[
v_{p_{l}}(t) = -c_{1}\omega_{h}\sin[\omega_{h}(t - T_{1})] + c_{2}\omega_{h}\cos[\omega_{h}(t - T_{1})],
\]

(5)

where \( c_{1} = v_{p_{l}}\sin(\omega_{f}\tau)/\omega_{h}, \quad c_{2} = v_{p_{l}}\cos(\omega_{f}\tau)/\omega_{h}, \quad \tau = \frac{c\omega}{(v_{p_{l}}^{2} - c^{2})}, \) and \( \omega_{h} = \sqrt{eE_{h,\text{max}}/(m_{p}r_{f})} \). Accordingly, the exit angle of the type 2 protons for \( t > T_{1} \) is centered at \( \psi \), with the divergence given by

\[
\frac{v_{p_{h}}}{v_{p_{l}}} \leq f(\eta)\tan(\phi + \psi),
\]

(6)

where \( f(\eta) = \sqrt{(E_{h,\text{max}}/E_{h,\text{max}})\sin^{2}\eta + \cos^{2}\eta} \) and \( \eta = \omega_{f}\tau \). Since \( f(\eta) \leq 1 \), the divergence of the type 2 protons is reduced after they cross the field boundary.

Figure 3(a) shows the trajectories of the two proton types. Although \( E_{\perp} \) also evolves with time, only its distribution at \( t = 259 \) fs is displayed in the background as a reference. Note that at this moment proton 2 is located at the field boundary, agreeing well with the boundary crossing time from the theory and shown in figure 3(b). We see that, except immediately behind the disk, proton 1 experiences negative \( E_{h} \) at all times. On the other hand, proton 2 is decelerated by \( E_{h} \) when it moves away from the solenoid center axis and accelerated by \( E_{h} \) when it moves toward it.

Figures 3(c) and 3(d) show the trajectories of proton 1 and proton 2 in the \( E_{\perp} \) versus \( L_{\perp} \) space. In (c) we can see that proton 1 experiences a larger \( E_{\perp} \) field on the way back to the solenoid axis than that when it moves away from the latter, resulting in an increase of its divergence angle. In contrast, in (d) we see that proton 2 experiences a smaller \( E_{\perp} \) on the way back to the axis than that when it moves away from it, so that its divergence angle decreases with time. Accordingly, the divergence angle of the TNSA proton bunch can be minimized by tailoring the solenoid parameters such that a large number of protons can cross the boundary between the two sheath fields.

The parameter \( f(\eta) \) depends strongly on the solenoid parameters \( h, n, r_{f} \). If two of them are fixed, one can find the value of the third one in order to obtain the highest proton energy density, as shown in figure 4. For example, \( n = 6 \) should be the optimal number of turns if \( h = 10 \) \( \mu \)m and \( r_{f} = 3.5 \) \( \mu \)m. Indeed, figure 5(a) from the simulation shows...
Here, $E_{b, \max} \approx 0.86 \times 10^{12} \, \text{V m}^{-1}$, $E_{\mu, \max} \approx 3.26 \times 10^{12} \, \text{V m}^{-1}$, $\phi = 5^\circ$, $\psi = 20^\circ$, and $t_{\text{acc}} = 100 \, \text{fs}$, respectively.

Figure 5. Angular distribution of the normalized proton energy density for (a) $\psi = 20^\circ$, $r_s = 3.5 \, \mu \text{m}$, $h = 10 \, \mu \text{m}$, and $n = 4, 6,$ and 8, (b) $\psi = 20^\circ$, $r_s = 3.5 \, \mu \text{m}$, $h = 10 \, \mu \text{m}$, and $n = 6$ (red curve); $\psi = 30^\circ$, $r_s = 3.5 \, \mu \text{m}$, $h = 10 \, \mu \text{m}$, and $n = 7$ (green curve); and $\psi = 50^\circ$, $r_s = 3.5 \, \mu \text{m}$, $h = 10 \, \mu \text{m}$, and $n = 9$ (blue curve). The solenoid parameters here have been optimized for each $\psi$.

In this section, comparison between our results and that of the earlier ones [18, 33–36] is considered. The major difference is that in simulations the electric field around the solenoid is induced by sheath electrons leaving the target-back as well as the electrons propagating along the coil, and in the above-mentioned works the electric field is from the electromagnetic field pulse traveling along the coil. The different mechanisms of the focusing field generation can be due to the following factors. Firstly, we are using $\mu$m-scaled target instead of mmscaled one, so that the fast laser-plasma interaction here are more important than the relatively slow charging and discharging in the capacitor-like model. Secondly, the target in our simulation is not grounded, so that compensation current is precluded. Thirdly, the solenoid in the simulation is ionized so that electrons can propagate almost freely in the coil, which is beneficial for the generation of the sheath field around the coil. Finally, the use of relatively low-density target can enhance the laser-to-electrons energy conversion efficiency, which is also beneficial for the generation of the sheath field around the solenoid. Although the mechanisms are different, they both provide effective control of the proton beam properties.

5. Summary

In summary, we have proposed an effective scheme for collimation and directional control of intense laser-driven protons using a disk-solenoid target. Our simulations show that two partially overlapping sheath fields are induced by the hot electrons and they result in an electric field distribution that collimates and focuses the energetic protons in the solenoid to its axis (instead of the target-normal direction). In fact, the divergence angle of the protons decreases when they cross the boundary region of the two sheath fields. The simulation results are in good agreement with that of an analytical model of the proton dynamics, which is also useful for tailoring the solenoid parameters for obtaining the desired proton energy and divergence angle. Highly collimated and precisely directed proton bunches are desirable for radiography, tumor therapy, warm dense matter generation, etc.

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