High-flux high-energy ion beam production from stable collisionless shock acceleration by intense petawatt-picosecond laser pulses

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Abstract

A scheme to achieve stable collisionless shock acceleration (CSA) of ions from a near-critical plasma by intense petawatt-picosecond laser pulses is proposed, where the plasma is confined in a high-\(Z\) solid tube. The application of the tube, on the one hand, restrains the plasma from transverse thermal expansion, helping to sustain sufficient density steepening required for shock formation and maintenance; on the other hand, due to the induced sheath field along its wall, pinches hot electrons for recirculation near laser axis, aiding to reach efficient plasma heating that is crucial to have a strong shock velocity for ion reflection. Consequently, stable ion CSA can be maintained for picosecond time scales, resulting in production of high-flux high-energy ion beams. Two-dimensional PIC simulations show that proton beams with narrow energy spread between 50 and 80 MeV and high flux with particle number about \(10^{12}\) are produced by a laser pulse at intensity \(8.8 \times 10^{19}\) W cm\(^{-2}\) and duration 1 ps. By extending the pulse duration to 3 ps, over 100 MeV high-flux proton beams are obtained.

1. Introduction

Laser-driven ion acceleration \([1, 2]\) has attracted considerable interest due to its potential for production of compact energetic ion sources with unique characteristics such as short temporal duration and small emittance. The enabling sources have prospective applications in biomedicine \([3, 4]\), fusion energy \([5]\), nuclear physics \([6, 7]\) and high-energy-density science \([8, 9]\). However, many of these applications require high-quality ion beams with simultaneous high ion energies and high beam fluxes, in particular, for applications such as radiographic density diagnosis, probing highly transient electromagnetic fields in plasmas, and isochoric heating of matter.

Over the past decades, many acceleration mechanisms have been proposed, including the most-investigated target normal sheath acceleration (TNSA) \([10–12]\), and radiation pressure acceleration (RPA) \([13–18]\). Though numerous efforts have been done to optimize laser and target conditions, till very recently proton maximum energies of 85 MeV by TNSA \([19]\) and 94 MeV by a hybrid RPA-TNSA \([20]\) have been reported by using the petawatt-picosecond laser pulses. However, in both cases, the energy spectra still show exponentially-decaying features with particle number both at only \(10^9\)/MeV around the maximum energy and therefore the beam fluxes are rather low. One of the essential reasons is that their effective acceleration processes actually break/stop...
prematurely before the picosecond laser pulse ends. So far, high-flux high-energy ion beams have not been achieved yet, and, in fact, are extremely challenging with both TNSA and RPA schemes.

Collisionless electrostatic shocks, i.e. ion-acoustic shocks, are a consequence of non-linear wave steepening and wave breaking of ion-acoustic modes in plasma and are more relevant for laboratory experiments [21–25]. Different from TNSA and RPA, collisionless shock acceleration (CSA) [26–30] has been proposed as an alternative method for production of high-quality ion beams for comparatively long laser pulses. In CSA, the laser pulse launches a collisionless electrostatic shock wave in near-critical density plasmas, and the shock can continuously reflecting a fraction of the background ions as it propagates through the plasma due to the strong electrostatic field associated with the shock front. Ions with velocity \( |v| < \frac{2 m_e}{\varepsilon_1} \) are reflected/accelerated to the energy of \( \varepsilon_1 = \frac{1}{2} m_i |v| - 2 \varepsilon_{bh} \), where \( \varepsilon_{bh} \) is the shock velocity, \( m_i \) is the ion mass and \( \phi \) is the electrostatic potential of shock front. The reflected ion density is determined from energy and mass conservation, yielding \( n_i = \frac{N_0}{\sqrt{1 - 2 \varepsilon_i / M_i^2}} \) [28], where \( M = \varepsilon_{bh}/\varepsilon_i \) is the shock Mach number, \( \varepsilon_{bh} = (T_e/m_i)^{1/2} \) is the ion-acoustic velocity and \( T_e \) is the electron temperature. Such repeated reflection process of background ions results in increasing of the particle number with time, therefore, for petawatt-picosecond laser pulses, CSA has the great advantages for production of high-quality ion beams with not only high ion energies but also high beam fluxes. It is worth noting that CSA is different from hole-boring (HB) where ions are reflected by the charge-separation field that is built up due to purely piling-up of plasma electron density by the laser ponderomotive force (radiation pressure), where the plasma keeps opaque to the laser and the plasma temperature is rather low. As a result, both the HB velocity \( \varepsilon_{bh} = \sqrt{T_e/m_i} \) and the reflected ion energy \( (\varepsilon_1 \sim 1/m_i \varepsilon_f) \) are mainly determined by the laser intensity \( I \) (divided by the plasma density), where the plasma temperature has negligible contribution, and almost all ions are reflected to offset the charge-separation [14, 31–34]. However, CSA is based on the formation of an electrostatic shock that is typically associated with the excitation of ion acoustic waves in plasmas with cold ions and high electron temperatures, where the plasma is eventually transparent to the laser and an efficient plasma heating is the key factor. And the speed of electrostatic shock in the CSA process is directly determined by the plasma temperature.

In the one-dimensional CSA model [27, 29], to launch a collisionless shock capable of reflecting the upstream background ions in near-critical plasmas, both sufficient piling up of electrons by the laser ponderomotive force and efficient heating of plasmas by the hot electron recirculation are required. So a strong collisionless shock with the Mach number \( M > 1.6 \) and the large shock velocity \( \varepsilon_{bh} > \varepsilon_{bh} \) is formed. Based on this model, the required laser and target matching condition for production of high-quality ion beams by CSA has been given in [27, 28, 35], which, however, is under the assumption of the reduced one-dimensional geometry. The specific optimal tailored density profile required for launching the shock is proposed in order to both avoid strong TNSA field that broadens the energy spread and ensure uniform plasma heating [27, 28, 35]. Currently, CSA has been demonstrated experimentally by using CO₂ lasers [26, 36], where the wavelength is at 10.6 \( \mu \)m, the spot size is very large and the intensity is rather low. Experiments using femtosecond lasers also show evidences of CSA [37], where the shock propagation distance is only several microns due to the short time scale. However, to achieve and maintain a stable CSA in picosecond time scales driven by intense petawatt lasers with near-infrared (0.8–1 \( \mu \)m) wavelength, where the acceleration distance is significantly larger than the laser spot size, a couple of issues from the multi-dimensional effects still need to be resolved. First, during the shock propagation, the plasma in the piled-up density spike (downstream of the shock) undergoes significant transverse thermal expansion, which leads to heavy dropping of density steepening and eventually quenching of the shock. In previous works, the laser spot size required for the shock formation process is given as 16 \( \lambda_0 \) [27, 28], where \( \lambda_0 \) is the laser wavelength. However, it is not enough to maintain the stable propagation of shock in picoseconds. Second, similarly, a large number of hot electrons disperse transversely into a much broader area outside the laser focal spot without recirculation, which results in severe reduction of plasma temperature as well as shock velocity, and eventually inefficient reflection/acceleration of ions. Note that the near-critical plasma is now available via either using foams [38], cryogenic hydrogen microjet target [39], high-pressure gas jets [40] or exploding an ultrathin foil with nanosecond lasers [41]. We also notice that, very recently, a experiment using high-intensity 1 \( \mu \)m wavelength laser have successfully demonstrated the ability of CSA to efficiently accelerate ions with high yield and narrow distributions [42], where the ion energy (15–20 MeV) and particle number (3 \( \times \) 10⁸) in a 10 % energy width is comparable to the best results obtained experimentally by any other mechanism, including TNSA. However, we think it can be further improved by better resolving the above issues of upstream heating and transverse expansion.

In this paper, in order to overcome the above issues, we propose using a transversely-confined near-critical plasma filled in the high-Z solid tube (see figure 1) to achieve stable CSA of ions by intense petawatt-picosecond laser pulses. In our scheme, because of the confinement of tube, on the one hand, the plasma transverse thermal expansion is inhibited, where sufficient density steepening required for the shock formation and maintenance can be sustained for picosecond time scales; on the other hand, the hot electrons are pinched and recirculated.
A high electron density of 50 with narrow energy spread between 50 and 80 MeV and high energies but also high beam petawatt-picosecond laser pulses is more suitable for production of high-quality ion beams of not only high ion plasma heating that keeps a large shock velocity for ion reheat.

Two-dimensional PIC simulations are carried out with the PIC code *EPOCH* [48] to verify the idea. In the simulations, a linearly $\gamma$-polarized intense petawatt-picosecond laser pulses at intensity $I_0 = 8.8 \times 10^{19}$ W cm$^{-2}$ (the normalized amplitude $a_0 = eE_0/m_e\gamma c\omega = 8$) and wavelength $\lambda = 1 \mu m$ propagates from the left boundary at $x = -100 \mu m$ into the high-Z solid tube at $x = -50 \mu m$ and interacts with the confined near-critical plasmas. The laser pulse has a spatially super-Gaussian profile $I = I_0 \exp(-r^2/r_0^2)$ of radius $r_0 = 10 \mu m$ and a temporally Gaussian profile of duration $\tau = 1$ ps. The near-critical plasma targets with and without the confining high-Z solid tube are, respectively, considered for comparison, shown in figure 1. For simplicity, the near-critical plasma is assumed to be composed of only hydrogen ions $H^+$ and electrons both with the initial temperature of 1 keV. The plasma electron density has a tailored profile with a rapid 10 $\mu m$ linear rise starting at $x = -10 \mu m$ to the peak density $12n_e$ at $x = 0$ and then followed by an exponentially falling with 5 $\mu m$ scale length, which satisfies the optimized density profile of CSA [27, 28, 35]. The high-Z solid tube is assumed to have a high electron density of 50$n_e$, tube length of 300 $\mu m$ and wall thickness of 1 $\mu m$. The radius of the tube is chosen to be $r_{tube} = 10 \mu m$ here, being equal to the focal spot radius of the laser.

The simulations are conducted in two spatial dimensions, in a system domain of 500 $\mu m \times 100 \mu m$ longitudinal along the $x$-direction and transversely along the $y$-direction. We setup the size of each cell as $dx = 0.8c/\omega_{pe} = 0.037 \mu m$ where $\omega_{pe}$ is calculated with the peak density of the low-density target $12n_e$, and the simulation domain to be $13 \times 624 \times 2725$ cells. The open boundary conditions are used for both particles and fields on all sides apart from the left boundary from which the laser propagates into the simulation box. The large simulation box is used to avoid too much total charge imbalance. Each target cell is filled with 16 particles for both electrons and ions. To save the computational resources and for suppression of the numerical noise (heating), the ions of the high-Z solid tube are assumed to be immobile and the electron density of tube is assumed to be 50$n_e$. Since the tube only interacts with the wings of the laser where the laser intensity is rather low, the ionization of the tube is also low while the mass-to-charge ratio is rather large, which means ions are almost efficiently inside the tube due to the induced sheath electric field along the tube wall, which results in efficient plasma heating that keeps a large shock velocity for ion reflection and acceleration. Such stable CSA by intense petawatt-picosecond laser pulses is more suitable for production of high-quality ion beams of not only high ion energies but also high beam fluxes. Two-dimensional particle-in-cell (PIC) simulations show that proton beams with narrow energy spread between 50 and 80 MeV and high flux with particle number about $10^{12}$ are produced by an intense petawatt-picosecond laser pulse at intensity $8.8 \times 10^{19}$ W cm$^{-2}$ and duration 1 ps. By extending the laser pulse duration to 3 ps, over 100 MeV high-flux proton beams can be obtained. Note that though the shock tube has been discussed in gasdynamic shock experiments [43–45], the influence of the high-Z solid tube on CSA has seldom been considered. Besides, the near critical plasma combining with a high density tube is attracting more interests in other scenarios [46, 47].

The paper is organized as follows. In section 2, the target design and the basic PIC simulation setup with laser and target parameters are described. In section 3, the dynamics of CSA in the confined near-critical plasmas driven by intense petawatt-picosecond laser pulses are analyzed in details. The qualities of the produced high-flux high-proton beams, comparing with the case without the confining tube, are given in section 4. The robustness of the proposed scheme are discussed in section 5. Summary and discussion are given in the section 6.

2. Target design and PIC simulation setup

Two-dimensional PIC simulations are carried out with the PIC code *EPOCH* [48] to verify the idea. In the simulations, a linearly $\gamma$-polarized intense petawatt-picosecond laser pulses at intensity $I_0 = 8.8 \times 10^{19}$ W cm$^{-2}$ (the normalized amplitude $a_0 = eE_0/m_e\gamma c\omega = 8$) and wavelength $\lambda = 1 \mu m$ propagates from the left boundary at $x = -100 \mu m$ into the high-Z solid tube at $x = -50 \mu m$ and interacts with the confined near-critical plasmas. The laser pulse has a spatially super-Gaussian profile $I = I_0 \exp(-r^2/r_0^2)$ of radius $r_0 = 10 \mu m$ and a temporally Gaussian profile of duration $\tau = 1$ ps. The near-critical plasma targets with and without the confining high-Z solid tube are, respectively, considered for comparison, shown in figure 1. For simplicity, the near-critical plasma is assumed to be composed of only hydrogen ions $H^+$ and electrons both with the initial temperature of 1 keV. The plasma electron density has a tailored profile with a rapid 10 $\mu m$ linear rise starting at $x = -10 \mu m$ to the peak density $12n_e$ at $x = 0$ and then followed by an exponentially falling with 5 $\mu m$ scale length, which satisfies the optimized density profile of CSA [27, 28, 35]. The high-Z solid tube is assumed to have a high electron density of 50$n_e$, tube length of 300 $\mu m$ and wall thickness of 1 $\mu m$. The radius of the tube is chosen to be $r_{tube} = 10 \mu m$ here, being equal to the focal spot radius of the laser.

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immobile during the acceleration progress and the expansion of the tube does not influence the near-axis shock formation area. Such assumptions have also been widely used in former research works [49–51]. In order to check the simulation convergence, a high resolution (about twice higher) case is also conducted, where the results are almost the same as the results with relative low resolution, as shown in figure 7(c) the gray line.

3. Dynamics of stable CSA in transversely-confined near-critical plasmas

Now, let us analyze in details the dynamics of stable CSA of ions from the near-critical plasmas confined in a high-Z solid tube driven by intense petawatt-picosecond laser pulses, from the 2D PIC simulation results.

Figure 2 plots the plasma ion density distributions as well as their longitudinal profiles at times $t = 0.9$, $1.8$ and $3.0$ ps for respectively the cases with ((a)–(c)) and without ((d)–(f)) the confining tubes. The corresponding longitudinal electrostatic field distributions and profiles are also plotted in figure 3. And figure 4 shows the ($x$, $px$) distribution of ions at corresponding time steps. At early time $t = 0.9$ ps, because of the strong radiation pressure exerted on the plasma, in both cases, electrons and ions are piled up forward, forming a density spike with the similar maximum values of around $17n_c$ (see figure 2(g)), which means the density ratio between the spike and the undisturbed plasma is $N_2/N_1 \approx 4.2$, larger than the required downstream to upstream density ratio condition [30] for formation of a collisionless shock. Furthermore, a significant number of hot electrons are generated by the $J\times B$ heating of the laser, and recirculate through the whole target and heating the target efficiently to have the average electron temperature of $T_e \approx 4.3$ MeV, as seen in figure 5(a) for both cases. This ensures that the ion-acoustic velocity $v_{\text{ia}} \approx 0.07c$ is larger than the laser HB velocity $v_{\text{lb}} \approx 0.05c$. And it indicates that the acceleration mechanism here is CSA rather than HB. As a result, two distinct plasma regions with different densities and drifting velocities and similar temperatures are formed in both cases, leading to launching of a strong collisionless shock, shown in figures 2(a) and (d), where the corresponding electrostatic fields are also
as similar as $eE_y/m_c \omega \approx 0.6$ (figures 3(a) and (d)). From figure 3(g), we can also see that TNSA is efficiently suppressed due to a long low-density tail in our scheme, so the upstream ions are not accelerated by the TNSA before the shock arrives. In addition, it can be seen from figure 2(d) that, for the unconfined plasma case, the filamentation from transverse instabilities (such as laser filamentation etc.) and diffusion effect have already began to occur, which may destroy the electrostatic shock, causing the acceleration process to be unstable [25, 52]. For the confined plasma case, the transverse instabilities are substantially suppressed because of the more uniform plasma density distribution (figure 2(a)) and the much enhanced heating of the plasma.
(figure 5(a)) that significantly reduces the growth rate of the transverse instability. Therefore, in our scheme, the CSA can be kept rather stable and does not evolve into an electromagnetic shock.

At later time $t = 1.8$ ps, the plasma has been heated to $T_e > 4.3$ MeV so that $v_{th} > v_{hb}$. Because of the thermal expansion and the density drops of the plasma profile, the plasma becomes transparent to the laser, so the laser-plasma interaction surface actually disappears and the HB process terminates when the shock is formed. Here, in order to obtain large shock velocity and eventually high ion energy, the laser is allowed to partially penetrate to efficiently heat the upstream plasma through choosing a proper initial peak density. From the $(x, px)$ phase space, we can also see that the significant shock structure forms behind the density peak at $x = 60$ $\mu$m and $t = 1.8$ ps (figures 4(b) and (e)), while only ions from HB reflection is seen at earlier time $t = 0.9$ ps (figures 4(a) and (d)). On the other hand, ions are also heated to significant high temperature up to 400 keV (calculated from figure 4(c)), due to hot electron propagation and recirculation in the upstream plasma, which results in further increase of the number of the reflected ions. Due to the confining effects as analyzed above, a stable ion CSA is maintained in the case with the confining tube, shown in figures 2(b) and 3(b). As we expect, it can be clearly seen that the shock density front has a rather uniform distribution with the density ratio $N_f/N_i \approx 3.87$ (the maximum downstream density is about $1.2 n_i$), and the electrostatic field has a very sharp profile (also distributes uniformly in the transverse direction) with the large peak value of $eE_{max}/m_e \omega_c = 1.34$. Such sharp and strong electrostatic field at the shock front can reflect and accelerate ions to twice the shock velocity. Since the ion reflection causes potential oscillation at downstream, the typical bipolar structure of the electrostatic field appears at the shock front (figure 3(h)). However, for the case without the confining tube, from figures 2(e) and 3(e), we see clearly that the CSA becomes unstable due to the multi-dimensional effect, where the shock front becomes nonuniform and the density ratio drops to $N_f/N_i \approx 2.5$ (the maximum downstream density is only $0.6 n_i$) due to transverse plasma thermal expansion. Moreover, the electron temperature $T_e = 3.6$ MeV is also much lower than that (11.2 MeV) in the case with the confining tube, see figure 5(b), because hot electrons disperse outside the interaction region. As a result, the shock electrostatic field is also much lower as $eE_{max}/m_e \omega_c = 0.9$, see figures 3(e) and (h). The confining effects of the hot electrons by the tube can be also clearly seen from the particle trajectory tracking plots in figure 5(c). It clearly shows that the hot electrons are pinched and bent back by the induced sheath electric field along the tube wall so that they recirculate transversely and longitudinally inside the tube, eventually achieving efficient and uniform plasma heating. Note that the charge-separation field $E_y$ at the high-Z target surface is induced by the expansion of the heated electrons on the tube wall into the plasma. The $B_y$ field generated by a surface current along the tube wall also helps to confine the plasma. But, $E_y$ plays a dominant role in the confinement, since the major time of CSA occurs after the laser is over when the surface current vanishes. The exact value of $E_y$ may slightly change in the case with mobile wall ions, but does not affect its ability to confine the near critical density plasma.
When the time arrives at \( t = 3.0 \) ps (the laser is completely over), the CSA with the confining tube still exists and ions are continuously accelerated, see figures 2(c) and 3(c), while that without the confining tube already stops (figures 2(f) and 3(f)) due to the multi-dimensional detrimental effects mentioned above as well as significant energy transferred to ions.

The different CSA dynamics for two cases can also be clearly seen from the time evolution plots of respectively the on-axis ion density ((a) and (c)) and the longitudinal electrostatic field ((b) and (d)) in figure 6. The peak of \( E_z \), the density steepness and the ion reflection surface in the \((x, p_x)\) phase space appear at the same position indicating the shock front. Obviously, without the confining tube, the shock launches at about time \( t = 0.9 \) ps and position \( x = 30 \) \(\mu m\), and quenches at distance of \( x = 80 \) \(\mu m\) \((t = 2.4 \) ps\), while with the confining tube the shock can be maintained till a distance over 150 \(\mu m\) \((t > 3.0 \) ps\). Moreover, from the slopes of these time evolution plots, we can also estimate that the shock velocity in the case with the confining tube is about \( v_{sh} = 0.22c \), which is much higher than that \((0.18c)\) in the case without the confining tube. This also indicates CSA with the confining tube can accelerate ions to much higher energy.

4. Qualities of high-flux high-energy ion beams

In this section, we give the qualities of the produced high-flux high-energy ion beams in the stable CSA by petawatt picosecond laser pulses. Firstly, from the ion phase space distributions plotted in figures 4(c) and (f) at time \( t = 3.0 \) ps when the laser pulse is over, we see that, in both cases, the accelerations exhibit typical CSA phase space distribution feature, which includes the pronounced stationary upstream, supersonic downstream and reflected ion plateau structures. Moreover, the upstream ions are reflected by the electrostatic shock and cross the sheath region while preserving their narrow energy spread, thus indicating a configuration suitable for the generation of quasi-monoenergetic (narrow-hand) ion beams. Since the collisionless shock continuously reflects upstream background ions during its propagation, the particle number of the ion beam increases with time. Comparing figures 4(c) and (f), we can see clearly that, for the case with the confining tube, a much stronger shock is achieved, which has larger velocity and propagates for a longer distance. Therefore, much more protons are reflected and accelerated to significantly higher ion velocity up to \( v_{\text{ion}} > 0.4c \), while those in the unconfined case are only at about \(< 0.3c\).

Figure 7(c) plots the final ion energy spectra for respectively the cases with (the solid red line) and without (the solid black line) the confining tube. In the 2D EPOCH code, the non-simulated direction is regarded as one unit length \((h = 1 \) m\), therefore, the particle numbers are converted to realistic 3D case by multiplying the factor \( E_{3D}/E_{2D} = \pi h/2h \) consistent with the ratio between the laser energy injection to the box in 2D \((E_{2D})\) and

\[ \text{Figure 6. Time evolution of the ion density (a) and (c) and longitudinal electric field (b) and (d) for the PIC simulation of figure 2, where the upper row is for the case with the confining tube, and the lower row for the case without the tube.} \]
in 3D ($E_{3D}$). With the confining tube (the solid red line), we see that a high-energy proton beam with narrow energy spread between 50 and 80 MeV and high flux with particle number in an energy bin of $\sim 2 \times 10^{10}/$MeV is produced. This particle number is almost an order of magnitude larger than that in the case without the confining tube (the solid black line). The total particle number of this high-flux high-energy proton beam is around $10^{12}$ with the total charge about 170 nC. Correspondingly the energy conversion efficiency from laser to ions is about 4.1% with the total beam energy of 12 J. Furthermore, from figures 7(a) and (b), we also infer that the divergence of the obtained ion beam in the case with the confining tube is also significantly reduced, comparing to that without the confining tube. This is because, on the one hand, the more uniform shock front in the case with the confining tube, as shown above, helps to reduce the divergence of the reflected ions in CSA; on the other hand, the induced sheath electrostatic field along the tube wall also plays an important role in collimating the produced ion beams, as discussed in [54].

5. Robustness of the proposed scheme

In order to check the robustness of the proposed CSA scheme, a series of PIC simulations with different laser and target parameters are carried out. Firstly, when the laser pulse duration is extended to more than 1 ps, such as $\tau = 3$ ps, we see from the dashed green line in figure 7(d) that the stable CSA in our scheme can even produce high-flux high-energy proton beams with the peaked energy $> 100$ MeV and the particle number $> 10^{12}$, which have many applications in high-energy-density science, medicine as well as neutron production. This higher ion energy is achieved due to the significantly increase of laser accelerated/heated electron temperature with longer laser pulse duration, which has been found and identified in [55, 56]. In other words, even though at the same laser intensity $a_0$, with longer pulse duration, the ion acoustic velocity increases so that shock velocity becomes larger and eventually a higher ion energy is obtained, which has also been discussed in theory [27]. Secondly, when the laser intensity drops to around $10^{19}$ W cm$^{-2}$ ($a = 3$), through matching the near-critical plasma target with the maximum density of 6$n_i$, and the similar profile as above, stable CSA for picosecond time scales can also be achieved, which results in production of high-flux high-energy proton beams at peak energy of respectively 30 MeV for 1ps laser pulse duration (the purple dashed line) and 40 MeV for 3 ps (the yellow dashed line). Note that if the near-critical plasma is not confined with the solid tube, because of the multi-dimensional effects.
analyzed above, generally CSA breaks prematurely before the laser pulse ends. The produced ion beam quality may not be improved even if a multi-picosecond laser pulse is used. Lastly, if the radius of the high-Z solid tube becomes larger than the laser spot size, such as \( r_{\text{tube}} = 2r_0 = 20 \, \mu\text{m} \) twice of the laser focal radius, the solid blue line in figure 7(d) clearly shows that the proposed scheme is still valid and high-flux high-energy proton beam can be still obtained, though the particle number of the beam drops a bit due to the weaker confinement effect. For the case where Gaussian laser incidences into the tube, the results are quite similar (the cyan line in figure 7(c)), which explains from one aspect that the use of tube can relax the requirements for laser conditions. In order to test the effect of the wall expansion, we have also conducted the case where the tube wall consists of mobile \( \text{Au}^{2+} \) ions with electron density of 200\( \text{n}_0 \). The results preliminarily prove that the wall expansion effect is negligible and the energy spectrum of the produced ion beams is similar as here (see figure 7(c) the green dashed line), however, the effect of wall ionization and expansion may be more complex in the realistic case and needs to be addressed in more detail in future work. In addition, simulations also show that variations of the density or thickness of the tube have little effects on the stable CSA dynamics.

6. Summary and discussion

In this paper, we have proposed a new scheme to achieve stable CSA of ions from a near-critical plasma by intense petawatt-picosecond laser pulses, where a high-Z solid tube is used to confine the plasma. The application of the tube helps to solve two issues of maintaining CSA in picosecond time scales, the plasma transverse thermal expansion and the hot electron transverse dispersion, both of which may lead to quenching of the collisionless shock in a short time. Such stable CSA by intense petawatt-picosecond laser pulses results in production of high-quality ion beam of not only high ion energies but also high beam fluxes. Two-dimensional PIC simulations show that proton beams with narrow energy spread between 50 and 80 MeV and high flux with particle number about \( 10^{12} \) are produced by a laser pulse at intensity \( 8.8 \times 10^{19} \, \text{W/cm}^2 \) and duration 1ps. By extending the laser pulse duration to 3 ps, over 100 MeV high-flux proton beams can be obtained. Therefore, the confining tube can not only help the acceleration process but also make it more robust to a wider set of parameters.

There are some other practical considerations for our proposed scheme. The target combining the near critical plasmas and the high density tube is complicated. However, as the rapid and significant technological advances have been made in the target fabrication [57], the description in this paper can now or very soon be manufactured, where the tube can be filled with foams [38], cryogenic hydrogen microjet [39] or high-pressure gas jets [40]. In order to make the proposed scheme work properly without prematurely expansion of the tube wall, a laser contrast of \( 10^{10} \) is required, which is available by using the plasma mirrors [58, 59]. Moreover, though the energy spread has a certain broadening as shock propagates a long distance [33] in our scheme, we obtained proton beams with large particle numbers that are preferable for many applications that require high flux, such as laser-driven neutron sources [7] and isochoric heating of matter [8]. Even for the applications needing small energy spread, proton beams with satisfying energy spread can be chosen by using energy selection devices such as magnetic and/or electrostatic lenses [60, 61]. Because, the energy spectrum obtained by stable CSA in our scheme is still with a narrow-band feature in the high-energy range of 50–80 MeV and with a high conversion efficiency due to the relatively stable shock velocity, which is still much better than those obtained by TNSA.

To overcome the multi-dimensional detrimental effect and achieve stable CSA in the interaction of petawatt-picosecond laser pulses with near-critical plasmas, besides using the high-Z solid tube discussed above, there are also other potential ways. For example, strong external magnetic fields can be applied, where the required strength of the magnetic field is estimated as \( B \approx E_y/c \approx 300\, \text{MG} \) by the analogy from our simulation results where the confining field \( E_y \) reaches 1TV/m. The mass-limited target may also achieve self-confinement due to the induced sheath electric field along the target boundaries, however needs further careful investigations.

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