ENHANCED LASER-DRIVEN ION ACCELERATION VIA FORWARD RAMAN SCATTERING IN A RAMPED GAS TARGET

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Abstract

CO_2 laser-plasma interactions provide a unique parameter space for using a gas jet for Target Normal Sheath Acceleration (TNSA) of ions instead of a thin foil target. The generation of 1-5 MeV protons from the interaction of a 3 ps TW CO_2 laser pulse with a gas target with a peak density around the critical plasma density (10^{19} cm^{-3}) has been studied by 2D particle-in-cell simulations. The proton acceleration in the preformed plasma, having similar to the gas jet symmetric, linearly ramped density distribution, occurs via formation of sheath of the hot electrons on the back surface of the target. The maximum energy of the hot electrons and, hence net acceleration of protons is mainly defined by Forward Raman scattering instability in the underdense part of the plasma. This mechanism of an additional heating of electrons is strongly affected by nonlinear laser-plasma interactions and results in the proton energy enhancement by more than an order of magnitude in comparison with the regular ponderomotive force scaling of TNSA. Forward directed ion beams from a gaseous target can find an application as a high-brightness ion source-injector.

INTRODUCTION

Over the last decade, forward directed beams of energetic protons have been observed in numerous experiments by interacting intense sub-picosecond laser pulses with the foil targets [1]. High-current, and forward directed MeV beam of protons is the most common feature of these experiments irrespective of the target composition. These protons are thought to originate from either hydrogenated impurities [1] or specially deposited hydrocarbon layer [2] on the surface of the target. Such beams have attracted a lot of attention owing to their very high brightness resulting from a large number of particles (>10^{10}) tightly confined in time (~1ps) and space (source radius ~10 μm). The protons are accelerated by the large space-charge fields, on the order of MV/μm, set up at the rear surface of the target. At the rear surface, the accelerating field is set up by the expulsion of a hot electron cloud into vacuum producing a negatively charged sheath irrespective of the angle of incidence of the laser beam. The electric field of this thin sheath ionizes and accelerates ions from a thin layer normal to the target. This so-called target normal sheath acceleration (TNSA) mechanism has been extensively studied numerically [3] and its scalings are well established experimentally for solid foils. Such a solid foil based proton source has drawbacks limiting its practical use, since it susceptible to any prepulse, which leads to plasma formation at the target surface before the arrival of the main pulse, produces debris and its repetition rate is limited. If these problems can be overcome and ions can be accelerated to 1-10 MeV/u at a high-repetition rate, such a laser-driven source of ions could find application as a picosecond injector for a conventional accelerator or a compact ion source for high-energy-density physics and material science.

CO_2 laser driven LDIA in a gas jet could represent a promising alternative to using solid foils to obtain a high-energy proton beam. For a 10 μm laser pulse, the gas jet target with a peak plasma density greater than 10^{19} cm^{-3} can be opaque (since the critical plasma density n_c for 10 μm CO_2 laser light is 10^{19} cm^{-3}) . Compared to solid foils, using a gas jet is potentially very attractive as it produces no debris and can be run at a high-repetition rate. However, LDIA and CO_2 laser coupling into a gas plasma in the range of densities 0.5-5 n_c is practically unexplored at relativistic intensities either numerically or experimentally.

In this paper we present full scale particle-in-cell (PIC) simulations of ion acceleration in laser-plasma interactions of a relativistic CO_2 laser pulse with gas targets around critical plasma density. The main goal of the study is to determine whether a picosecond 10μm laser pulse incident on a symmetrically ramped preformed plasma slab, that is tens of wavelength wide, is suitable for production of a forward directed multi-MeV proton beam and to study the physical mechanisms that generate such a beam.

PARAMETER SPACE FOR MODELING

We use a 2D, particle-in-cell (PIC) code OSIRIS for full scale numerical studies of LDIA. In the simulations that we analyze below, the incident ~1 TW laser pulse has a 3 ps (full width at half maximum) duration and a transverse spot size $2w_0$=100 μm. The linearly polarized laser beam interacts with the target at normal incidence, and its electric field is in the simulation plane. The gas jet is modeled as a triangular preformed plasma slab, that is symmetrically ramped from 0 to 0.75 n_c over a distance of 20λ resulting in a 400 μm thick target. It should be noted that both the plasma density and its profile in simulations represent parameters routinely achieved in the experiments with a supersonic gas jet operating in the 10^{18}-10^{20} cm^{-3} plasma density range. In the simulations we consider the laser pulse without any prepulse.

RESULTS AND DISCUSSION

In Fig. 1a we show the ion density at t=3.6 ps when the peak of the laser pulse reaches the center of the gas target. When the TW power laser pulse with a power significantly larger than P_{cr} critical power for relativistic self-focusing interacts with an underdense plasma, the plasma dynamics is strongly nonlinear and self-focusing results in laser filamentation. Here $P_{cr} \simeq 17(\omega_0/\omega_p)^2$[GW], where ω_0 is the laser angular frequency and $\omega_p=(4\pi n_e e^2/m)^{1/2}$ is the plasma frequency. This filamentation causes partial evacuation of electrons in the filaments under the action of the transverse ponderomotive force. Later in time (t=6.6 ps), as is apparent in Fig1b, the hydrogen ions are pulled transversely by the electrostatic fields induced by expelled electrons and two channels can clearly be seen. The formation of such multiple filaments can be attributed to an "inverted corona" mechanism in which hot plasma particles from the channel walls heated by the laser pulse are expanded towards the channel [4]. After the laser pulse has passed (t>12 ps), the ion filament dissipates and only at this time hydrodynamic expansion of the the entire plasma slab is noticable. Therefore during the time required for the laser pulse to cross the plasma slab a sharp plasma-vacuum boundary important for the TNSA mechanism [3] is in place. At the end of the computations at t=21 ps the target's width has expanded by a factor of 4.

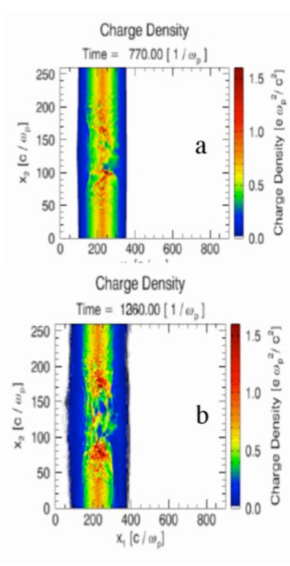

Figure 1: Proton density distribution at t=3.6 ps when the peak of the 3 ps CO_2 laser pulse reaches the center of the $0.75n_c$ target (a), and t=6.6 ps (b).

Since the laser power P reaches $58P_{cr}$, at the peak density the threshold of relativistic self-focusing is reached very early during the pulse. As seen in Fig. 2a, as a result of strong relativistic self-focusing, the peak laser field is enhanced significantly and the pulse has a characteristic steepening at the front. The finite rise time of the pulse creates a low-amplitude wakefield within the laser pulse and causes a low-amplitude modulation of the laser pulse at λ_p [5]. The modulated laser pulse can resonantly pump the wakefield and the process continues in an unstable way. This instability resembles a highly nonlinear two-dimensional form of usual FRS instability [5]. Indeed Fig. 2b depicts both the piling up of the electrons in front of the laser pulse and excitation of such the wake right behind this front.

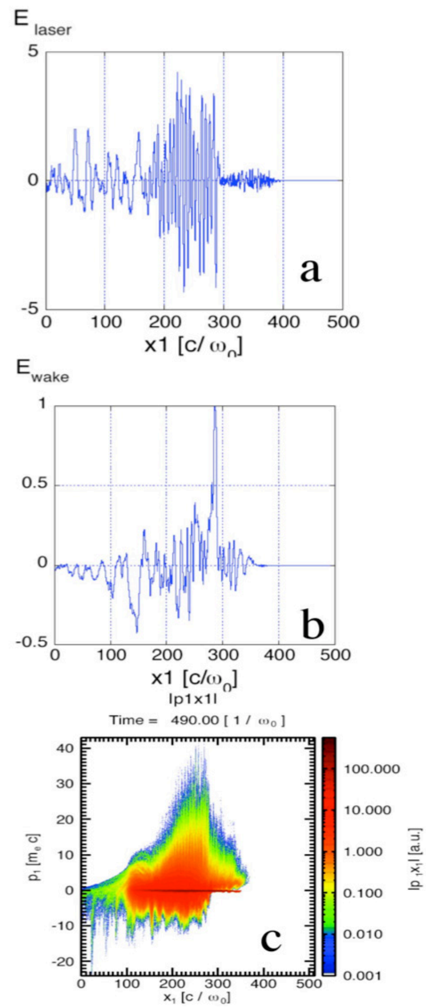

Figure 2: Laser field (a), electrical field of plasma (b), and phase space p1-x1 distribution of electrons (c) at t=2.8 ps for the 0.75 n_c target.

The phase space distribution of hot electrons on laser beam axis in Fig. 2c uncovers the dynamics of electron acceleration. In simulations, a group of electrons is accelerated to a temperature of approximately 4 MeV in a front part of the plasma where the plasma density is below 0.25 n_c. However, some much hotter electrons with an energy reaching 15 MeV are observed in the part of the plasma where the plasma density is above 0.25 n_c but the laser field is peaked. This may be attributed to an additional acceleration of electrons caused by the increasing poderomotive force of the laser which is strongly enhanced due to the relativistic self-focusing effect in this part of the target. Indeed an enhanced value of up to a_0~4 in Fig. 2a recorded in the part of the target where this additional acceleration is observed. The highest energy electrons leave the plasma producing a target potential which in turn combines the rest of the heated electrons.

The ion phase space distribution P_1 along the laser axis direction X_1 at t=21 ps long after the laser pulse has traversed the plasma is shown in Fig. 3a. The highest proton velocity of ions reached in the underdense laser-plasma interactions is 0.085c, which corresponds to the kinetic energy of 3.4 MeV. There are two distinct spatial features both giving rise to energetic protons. The first and the most important is located at the rear surface of the target, where the most energetic ions are being produced. The second is apparently acceleration throughout the target. The nature of these features can be understood based on the analysis of the phase space distribution of ions in the P_1-P_2 plane shown in Fig. 3b. Here we see that there are two groups of accelerated ions. The first is a highly directional beam of ions propagating forward ($P_1>P_2$). But in addition there is a group of ions with a lower energy that are expelled in all directions ($P_1 \sim P_2$). This latter group has a velocity smaller than 0.025c (low proton kinetic energy < 0.2 MeV). The first group of particles however, is fairly well collimated in a forward direction, propagates exactly at normal to the target's rear surface and has energies in the range 0.4-3.4 MeV (velocity 0.01-0.085c). Note that by increasing the front ramp to 400 μm, the maximum energy reached 5 MeV. The maximum energy of the uncollimated group of particles can be estimated by balancing the electrostatic potential between the protons and the expelled electrons and the laser ponderomotive potential, which expels the electrons in first place [3].

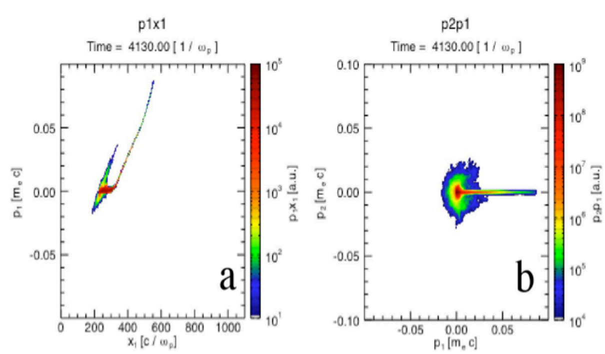

Figure 3: Proton density distribution at t=3.6 ps when the peak of the 3 ps CO_2 laser pulse reaches the center of the $0.75n_c$ target (a), and t=6.6 ps (b).

The relativistic ponderomotive energy U can be estimated as, $U=mc^2 (\gamma-1)$, where $\gamma = (1+a_0^2)^{0.5}$ is the relativistic factor of the electron quiver motion in the laser field. For $a_0=1$ this energy is equal to 0.2 MeV and in a good agreement with the maximum energy obtained in the simulations for transversely accelerated protons. Note that even an enhanced value of $a_0=4$ would result in a proton energy of 1.5 MeV. However, a collimated proton beam propagating forward has much higher energy that indicates that other mechanisms are involved in electron and ion acceleration of this group. As was shown above, the self-modulated laser wakefield acceleration of electrons is the main mechanism for the electron heating in our case. The plasma density in a ramped gas target where FRS can take place varies from $10^{-4}n_c$ to $0.25n_c$. Thus, in the case of plasma densities slightly below n_c (even at a vacuum $a_0 \sim 1$) a significant amount of ions are accelerated forward and these plasmas prove to be useful source of collimated proton/ion beams. It is important that similar enhancement in electron acceleration is also observed for overdense gas targets at 1-5 n_c plasma density.

CONCLUSIONS

A 2D PIC code study of ion acceleration in CO_2 laser-plasma interactions around the critical plasma density of 10^{19} cm^{-3} has demonstrated production of a collimated forward H^+ beam. It is shown that for 10 μm at a relatively modest laser intensity of 10^{16} W/cm^2 ($a_0=1$), the maximum achievable proton energy is 1-5 MeV. This energy is more than an order of magnitude larger than that predicted by the ponderomotive scaling [3]. The maximum energy of the hot electrons and, therefore net acceleration of protons gained in the sheath, is mainly related to self-modulated laser wakefield acceleration in the underdense plasma.

For underdense targets (0.5-0.75 n_c), nonlinear laser–plasma interactions a laser power $P > P_{cr}$ causes relativistic self-focusing and plasma channel formation and strongly enhances laser wakefield electron acceleration. For targets with the peak density above n_c (1-5 n_c) similar laser-plasma interactions and enhanced electron acceleration occur in a ~20λ-30λ thick underdense plasma layer on the front part of the gas jet.

ACKNOWELEDGMENTS

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