PROTON ACCELERATION BY TRAPPING IN A RELATIVISTIC LASER DRIVEN UPHILL PLASMA SNOWPLOW

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Abstract

We explore a novel regime of proton and ion acceleration off of overdense plasma created by a laser pulse. In Coulomb explosion, Target Normal Sheath, Acoustic shock acceleration regimes the protons are neither high-energy nor monoenergetic enough for applications such as hadron radiation therapy, fast ignition fusion research and particle physics. This calls out for exploration of effective regimes of acceleration. The proposed snowplow regime of acceleration uses a snowplow of charge created by a relativistic laser pulse at the critical density on a uphill Plasma density gradient. The relativistically moving snowplow's space charge drags the protons and its velocity can be controlled to effectively trap the protons using laser pulse shape and the uphill density profile. We describe the principles behind this mechanism. We derive analytical expressions for the Snowplow velocity and its dependence on the parameter space. We primarily explore the density gradient and laser pulse shape to optimally accelerate protons to the desired velocities. Preliminary, 1-D simulation results are presented and analyzed.

INTRODUCTION AND RELATION TO OTHER REGIMES

Accelerating ions and protons using laser-plasma interactions to a high enough energy and monoenergetically for various applications such as hadron radiation therapy fast ignition fusion research and particle physics is an area of active interest. However, laser-plasma acceleration regimes do not yet demonstrate the capabilities to meet the requirements with existing Laser technologies. There is a need to theoretically explore novel mechanisms that may enhance the acceleration of protons and ions. Scaling laws for existing mechanisms[1] in experiments on proton acceleration using thin foils with laser parameters and different regimes have been extensively studied[2].

The Coulomb explosion regime [3] and the Target Normal Sheath Acceleration (TNSA) [4] use a focused laser pulse of high enough intensity to ionize and bore a hole through a metal film target to create a fast moving electron beam whose space-charge accelerates protons. In the Electrostatic Shock regime [5] the laser's Poynting flux creates sharp density difference at the critical layer that propagates as a shock front. The Radiation Pressure Acceleration (RPA) regime [6] depends upon ultra-relativistic laser pulse to accelerate electrons and rely on space charge to drag protons.

Relativistically induced transparency acceleration regime [7] has been theoretically studied. When the normalized laser intensity vector potential, $a_0 = \frac{eA}{m_e c^2}$, is much higher than unity, the interacting electrons gather an ultra-relativistic quiver momentum, this lowers the plasma frequency and the laser can penetrate deeper than the non-irradiated plasma critical layer. This can generate a relativistic shock which moves close to the velocity of the laser pulse.

In this paper, we theoretically explore a unique scheme that utilizes the relativistic nature of a laser pulse and a plasma density gradient to accelerate the protons. In contrast with other regimes we try to control the speed of the shock by appropriately choosing the pulse shape and the plasma density profile. The plasma density is ramped longitudinally and the laser pulse interacts with denser plasma as it propagates, as shown in Fig.1. But, it can penetrate further into the plasma because its interaction with plasma electrons induces relativistic effects. When the pulse first interacts with the critical density its momentum conservation produces a snowplow like shock or "snowplow" like variation in the electron density that traps protons. Subsequently, the snow-plow accelerates by being pushed by the increasing laser pulse intensity which moves deeper into the plasma. The rate of rise of plasma density controls the formation and velocity of this snow-plow shock and can be used to maintain "phase-lock" between protons and the electron snow-plow, thereby allowing their effective "trapping".

PRINCIPLES BEHIND THE UPHILL SNOWPLOW REGIME

The wave-dispersion of the transverse component of an electromagnetic wave when interacting with an unmagnetized collisionless plasma follows Eq.(1). ω_p is the electron-oscillation frequency and depends on the plasma electron density $n_e(cm^{-3})$.

$$\omega_{laser}^2 = \omega_p^2 + k^2 c^2, \qquad \omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}} \tag{1}$$

A normally incident laser pulse (linear (LP) or circular

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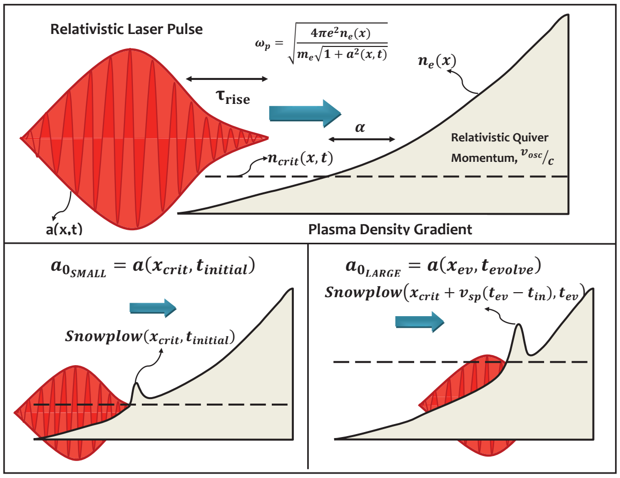

Figure 1: Conceptual diagram depicting a Snowplow and its time evolution.

polarization (CP)) interacting with a plasma density gradient forms a shock at the critical density point, $\omega_{laser} = \omega_p(x)$, where the wave-vector goes to zero. Beyond this point, initially, there is no propagation in towards the medium-plasma interface ($k = 0$) and the wave is reflected. The radiation pressure at that point, piles up the electrons in analogy with a snowplow.

To obtain an approximate expression for the velocity of the snowplow, we model the laser pulse as rising linearly with rise-time scale-length ($c\tau_{rise}$) of the pulse envelope δ, in the vicinity of its interaction with plasma.

$$a^2(x,t) = a_0^2\left(\frac{ct-x}{\delta}\right)H(ct-x) \tag{2}$$

where, a is the normalized laser vector potential and H is the Heaviside step function.

The plasma created by ablation of metallic foils or "superdense" gas puff ("overdense" at high-intensity laser wavelengths) is assumed to diffuse to create a rising plasma density, as seen by the laser pulse. This can be approximated by a linear function in the vicinity of laser-plasma interaction.

$$n_e(x) = n_{e_{crit}}\left(1+\frac{x}{\alpha}\right) \tag{3}$$

where, α is the "local-scale-length" in the vicinity of the $k = 0$ point or the critical layer.

In consideration of the laser-plasma interaction and the plasma-density gradient, the plasma frequency is a function of space and time as in Eq.(4). Since, the laser pulse interacting with the plasma is ultra-relativistic with its $a_0 = \frac{eE}{\omega m_e c} > 1$, it imparts to the plasma electrons a relativistic quiver momentum. The relativistic mass of the electrons modifies the plasma frequency as in Eq.(4).

$$\omega_p(x,t) = \sqrt{\frac{4\pi e^2 n_e(x)}{m_e\sqrt{1+a^2(x,t)}}} = \sqrt{\frac{4\pi e^2 n_{e_{crit}}}{m_e}}\sqrt{\frac{\left(1+\frac{x}{\alpha}\right)}{\sqrt{1+a^2(x,t)}}} = \omega_{laser}\sqrt{\frac{\left(1+\frac{x}{\alpha}\right)}{\sqrt{1+a^2(x,t)}}} \tag{4}$$

Under reflection of the laser-pulse at the $k = 0$ point, a snow-plow like variation in the density is formed in the plasma-density due to the photon momentum reversal. The point at which this initially occurs satisfies the defining equation, $\omega_{laser} = \omega_{p_{crit}}$. For simplification of notation, we make the following assignment, $\gamma = \frac{\omega_p}{\omega_{p_{crit}}} = \frac{\omega_p}{\omega_{laser}}$, $\beta = \frac{a_0^2}{2}$ (LP) (or) $\beta = a_0^2$ (CP).

Using Eq.(2) and Eq.(3) in Eq.(4), we get an expression for the location of the snowplow as a function of space and time.

$$x_{sp}(t) = -\frac{\alpha\left(\alpha\beta\gamma^4 + 2\delta\right)}{2\delta} \pm \frac{\alpha\gamma^2\left(\sqrt{\alpha^2\beta^2\gamma^4 + 4\beta\delta(\alpha+ct) + 4\delta^2}\right)}{2\delta} \tag{5}$$

Assuming the plasma density gradient "local-scale-length" α (as in Eq.(3)) and the "local-rise-time-length" of the Laser pulse δ (as in Eq.(2)) are stationary, then we can derive the velocity of the snowplow.

$$v_{sp_{crit}} = \frac{\partial x_{sp}(t)}{\partial t} = \frac{c}{\sqrt{1+\frac{4\delta}{\alpha\beta\gamma^4}\left(1+\frac{ct}{\alpha}+\frac{\delta}{\alpha\beta}\right)}} \tag{6}$$

SIMULATION RESULTS

Using 1-D simulations we show that the snowplow formation occurs in addition to the electrostatic shock. We use the OSIRIS 1D code for simulation[8]. A proton plasma with a mass ratio of 1836 is used. The simulation is setup with around 60 cells per λ_p, 40 particles per cell and the density ramp is a linear gradient profile. The laser pulse used is CP. The simulation evolves with time-steps of $\Delta t = 0.0499\frac{1}{\omega_{laser}}$ and a sliding window time average over one laser period is applied before fields and phase space data are dumped.

Fig.2 (a) and (b) shows simulation results depicting two different shocks moving at different velocities for plasma density gradient scale-length of $\alpha = 1667\frac{c}{\omega_{laser}}$, $\delta = 188.4\frac{c}{\omega_{laser}}$ and $a_0 = 2$. The electron snowplow is observed to be moving at 0.11c. The snowplow drags protons and this can be observed from proton density in Fig.2 (c) and (d). The proton trapping can also be observed from the proton momentum in Fig.2 (e) and (f).

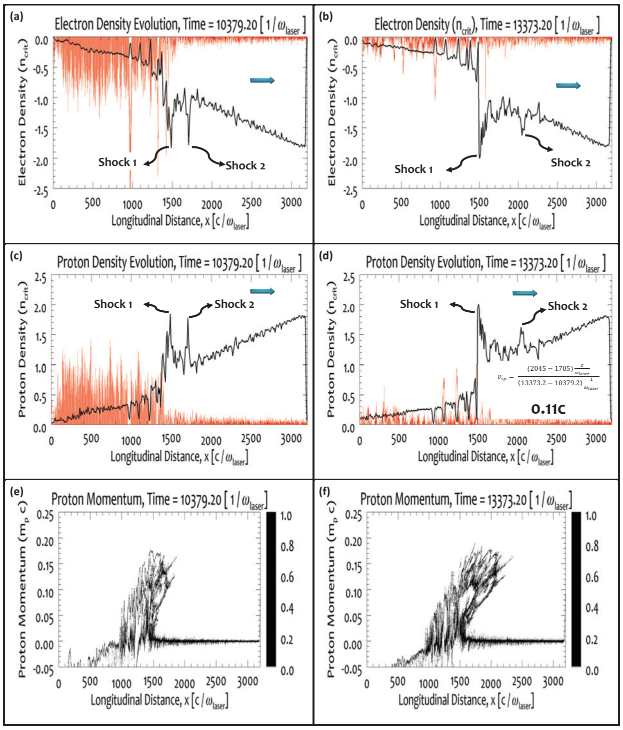

Figure 2: 1D simulation of Snowplow regime with plasma density gradient scale-length $\alpha = 1667\frac{c}{\omega_{laser}}$, laser time-rise scale-length $\delta = 188.4\frac{c}{\omega_{laser}}$ and $a_0 = 2$. (a)&(b) show electron density, $\frac{n_e}{n_{crit}}$ vs. longitudinal distance, $\frac{x}{c/\omega_{laser}}$ at $10379.2\frac{1}{\omega_{laser}}$ & $13373.2\frac{1}{\omega_{laser}}$. (c)&(d) show proton density evolution corresponding to electrons. (e)&(f) show proton momentum $\frac{p_p}{m_p c}$ at the corresponding times. From (c)&(d) we obtain, $v_{sp} = 0.11c$.

DISCUSSION

We have explored the snowplow regime of proton and ion acceleration using laser-plasma interaction. We have described an initial analysis of the snow-plow evolution and its dependence upon the laser-plasma parameter space. Some, preliminary 1-D simulations and their relevance to the understanding of snowplow regime is presented. Future work will verify the control of snowplow speed and extend models to 2-D and 3-D.

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