Ultraintense laser interaction with nanoscale targets: a simple model for layer expansion and ion acceleration

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Abstract. A simple model has been derived for expansion of a thin (up to 100s of nm thickness) target initially of solid density irradiated by an ultraintense laser. In this regime, ion acceleration mechanisms, such as the Break-Out Afterburner (BOA) [1], emerge with the potential for dramatically improved energy, efficiency, and energy spread. Ion beams have been proposed [2] as drivers for fast ignition inertial confinement fusion [3]. Analysis of kinetic simulations of the BOA shows the period of enhanced acceleration occurs between times \( t_1 \), when the target becomes relativistically transparent to the laser, and \( t_2 \), when the target becomes classically underdense and the enhanced acceleration terminates. A simple model for target expansion has been derived that contains early, one-dimensional (1D) expansion of the target and three-dimensional (3D) expansion at late times. The model assumes expansion is slab-like at the instantaneous ion sound speed and requires as input target composition, laser intensity, laser spot area, and the efficiency of laser absorption into electron thermal energy.

1. Introduction
Laser-ion accelerators have been proposed as drivers for fast ignition inertial confinement fusion [2]. If a laser pulse with very low pre-pulse is employed, an ultrathin, target of solid density with thickness as small as a few nm may be used. Such targets enable new acceleration mechanisms, such as the Break Out Afterburner [1, 4], and Radiation Pressure Acceleration/Phase-Stable Acceleration [5] to be accessed. These mechanisms may lead to order-of-magnitude improvement in beam energy and efficiency over target-normal sheath acceleration [6], while at the same time maintaining high beam quality (low \( \Delta E/E \)) as well as accelerate mid-Z ion species like carbon, as in recent studies of ion-driven fast ignition [7].

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In this paper, we focus on the BOA, which relies on a transition of the target from opaque to relativistically underdense as the target expands and its electrons are heated. As the laser penetrates the target, at time denoted $t_1$, rapid acceleration of target ions ensues until time $t_2$, when the target becomes classically underdense ($n_e = n_{ct}$). Optimal energy of such beams is obtained when peak intensity of the laser pulse falls between $t_1$ and $t_2$.

To guide experimental design, it is fruitful to have a simple model for the dynamics of the expanding target subject to a laser drive. Such a model is presented here, along with its application to a setting relevant to those obtained at the LANL Trident facility. It should be noted that a self-similar analysis of a similar problem has been reported by Yan et al. [8].

2. Model of Layer Expansion

We consider a target of thickness $\ell_0$ irradiated by an ultraintense ($I > 1.4 \times 10^{18}$) laser with spot area $A$. We further assume laser energy absorption at efficiency $\varepsilon$ by target electrons (of initial density $n_0$) and that the electrons have a single temperature $T$ that evolves in time. The target will exhibit 1D longitudinal expansion initially, until instantaneous target thickness $\ell(t) \sim \sqrt{A}$ and lateral expansion of the plasma must be taken into account. We allow the plasma to expand at the ion sound speed $c_s = (5Z_iT/3m_i)^{1/2}$; here $Z_i$ denotes ion core charge.

According to the First Law of Thermodynamics, laser heating should balance the increase in electron internal energy, $PdV$ work, and losses (radiative and conductive). In time $dt$,

$$\varepsilon AI dt = \frac{3}{2} n_0 A \ell_0 dT + n T dV - (P_{Br} - P_{CT}) V dt,$$

where $n(t)$ is instantaneous electron density of the slab, $V$ is the expanding plasma volume, and $P_{CT}$ and $P_{Br}$ are power densities from thermal conduction and radiation losses respectively. This expression is valid for optically thin (to thermal xrays) targets, as appropriate for solid density or lower, fully ionized plasma at sub-micron thickness and $T > \sim 1$ keV. At lower temperature (though still fully ionized), the plasma is opaque and bremsstrahlung is radiated only from the outer optical depth of plasma; the above expression is an upper bound to such losses.

Lateral thermal conduction can be ignored generally for sub-micron target thickness. Radiative power loss requires more care: in optically thin plasma [9], $d \log T/dt = P_{Br}/(nk_B T) = 3.4 \times 10^{-15} n_{[\text{cm}^{-3}]} Z_i T^{1/2}_{[\text{keV}]} s^{-1}$. For $n \sim 10^{23}$ cm$^{-3}$ and $\Theta \sim$keV, the radiative cooling time is $\sim 100$ ps, well exceeding the pulse length; later, $n$ is lower, $T$ is higher, and relative losses to radiation are lower still. Consequently, we ignore radiation power losses in our model to leading order.

To accommodate the transition from 1D to 3D expansion, we use the ansatz

$$n(t) = n_0 \frac{\ell_0}{\ell} \left[ \frac{A + C \ell_0^2}{A + C \ell^2} \right],$$

where

$$\ell(t) = \ell_0 + \int_0^t dt' c_s(t')$$

and

$$V \sim \ell(A + C \ell^2),$$

where $C$ is a numerical coefficient of order unity. At early time, $\ell^2 \ll A$, the bracketed term in (2) is approximately unity, and $dV \approx Ad\ell$, so the expansion is 1D; at late time, $n \sim \ell^{-3}$ and $dV \sim \ell^2 d\ell$, as appropriate for 3D expansion.

It is convenient to express this equation in scaled units: we normalize time $s \equiv ct/\ell_0$, distance $z = \ell/\ell_0$, and temperature $\Theta \equiv T/m_e c^2$ and write scaled sound speed as $c_s = c\Theta^{1/2} X_I$, where
\[ X_i \equiv [(5/3) (m_e/m_p) (Z_i/A_i)]^{1/2} = 0.030 (Z_i/A_i)^{1/2} \] for ion mass \( m_i = A_i m_p \). We define a normalized intensity \( \tilde{I} = \varepsilon I/n_0 m_e c^3 \) and let \( \delta = \ell_0^2/A \ll 1 \). If we assume the target foil matter beneath the laser spot expands at late time into a hemisphere (\( C = 2\pi/3 \)), the evolution obeys

\[
\begin{align*}
\dot{z} &= X_i \Theta^{1/2} \\
\Theta' &= \frac{2}{3} \left( \tilde{I} - X_i \frac{\Theta^{3/2}}{z} \left[ \frac{(1 + C \delta)(1 + 3C \delta z^2)}{1 + C \delta z^2} \right] \right),
\end{align*}
\]  

with primes indicating \( d/ds \). (A different expansion profile would entail a different value of \( C \); though the values of \( t_1 \) and \( t_2 \) would change somewhat with different values of \( C \), the essential behavior of the model would remain the same). The initial conditions are that \( z(0) = 1 \) and \( \Theta(0) = \Theta_0 \). In the \( \delta \to 0 \) limit, this reduces to the second-order, nonlinear ODE for \( \Theta \) reported in Henig et al. [10].

Times \( t_1 \) and \( t_2 \) are obtained readily from the model: \( n(t_1) = \langle \gamma \rangle n_{cr} \) (\( n_{cr} = m_e \omega_0^2/4\pi c^2 \) is the critical density in CGS units); \( n(t_2) = n_{cr} \). The average relativistic factor of the electrons follows from the expression for internal energy of the electrons \( \frac{\gamma}{2} T = m_e c^2 (\langle \gamma \rangle - 1) \), from which

\[ \langle \gamma \rangle = 1 + \frac{3}{2} \Theta. \]  

As described in Ref. [10], maximum ion energy occurs when the peak of the laser intensity falls between \( t_1 \) and \( t_2 \), a point graphically illustrated in the left panel of the Figure.

3. Application to Recent Trident Experiment and VPIC Kinetic Simulations

We consider the application of this model to the expansion of a diamond-like-carbon (DLC) layer heated via a laser pulse of 1 micron light similar to that attained at the LANL Trident User Facility. We assume that the laser pulse has sine-squared intensity profile (in time) with FWHM of 540 fs and peak intensity \( 2 \times 10^{20} \) W/cm\(^2\) focused into a spot size 7 microns in diameter with negligible pre-pulse or pedestal. The DLC layer has \( n_0/n_{cr} = 821 \) and is assumed to absorb the laser pulse with 50% efficiency. These experimental parameters are similar to those reported by Henig et al. [10].

The Figure shows the evolution of the target layer for a particular choice of target thickness (\( \ell_0 = 80 \) nm) near the optimal thickness. The thick, solid curve is \( n_e/n_{cr} = 1 \) as a function of time for a 3D expanding layer. The dashed curve is \( \langle \gamma \rangle \) as a function of time and the time \( t_1 \approx 400 \) fs is where the two cross. The time \( t_2 \approx 700 \) fs is when \( n_e/n_{cr} = 1 \). The dotted curve is the laser intensity profile (arb. units.) and the peak of the profile, at 540 fs, is between \( t_1 \) and \( t_2 \). The dot-dashed curve is the same as the solid curve, but for a 1D expansion (\( A \to \infty \) limit); for this set of target parameters, the pulse terminates before \( t_2 \).

The right panel of the Figure shows average electric field envelope amplitude \( \langle E \rangle \) averaged between \( t_1 \) and \( t_2 \) for the same laser and target parameters as in the left panel. Analysis of a suite of 1D, 2D, and 3D kinetic plasma simulations of the BOA using the VPIC particle-in-cell code [11] as well as analytic theory [8, 12] show that in the BOA, peak ion beam energy scales linearly with \( \langle E \rangle \). In this case, the peak ion energy is determined to be near \( \ell_0 = 80 \) nm.

4. Conclusions

This simple model cannot capture the full dynamics of the expanding layer. Kinetic simulations of BOA [4] show that electron phase space possesses complicated structure and may not be represented well by an electron gas that instantaneously relaxes to a single, equilibrium temperature. Moreover, relativistic nature of the electron gas is not treated rigorously and the model employs an ad hoc assumption about laser absorption. Finally, though the model
Figure 1. Left panel: Density $n_e/n_{cr}$ of electrons in a DLC layer as a function of time for a 20 µm diameter laser spot (solid curve) and one of infinite size (dot-dashed) for a laser of peak intensity $2 \times 10^{20}$ W/cm$^2$. The sine-squared pulse profile (arb. units) is shown by the dotted curve. The dashed curve is $\langle \gamma \rangle$. The time $t_1$, when the BOA starts, is around 400 fs, where the solid and dashed curves cross; $t_2 = 700$ fs for 3D expansion (where the solid curve crosses $n_e/n_{cr} = 1$. Right panel: Laser electric field amplitude $\langle E \rangle / E_{\text{max}}$ averaged between $t_1$ and $t_2$.

recovers the appropriate limiting dynamics of an expanding 1D and 3D gas, the transition is treated heuristically. Recent work by Yan et al. remedies many of these issues [8]. Despite its shortcomings, the simple model presented here yields insight into the dynamics of layer expansion, which lie at the heart of the BOA.

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