Particle-in-cell simulations for fast ignition

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Abstract. The hole-boring scheme in fast ignition is studied via large-scale, two-dimensional particle-in-cell simulations in two steps. First, laser channeling in millimeter-scale underdense plasmas is simulated. The results show a highly nonlinear and dynamic process involving longitudinal plasma buildup, laser hosing, channel bifurcation and self-correction, and electron heating to relativistic temperatures. The channeling speed is much less than the linear group velocity of the laser. Low-intensity channeling pulses are preferred to minimize the required laser energy. The channel is also shown to significantly increase the transmission of an ignition pulse. In the second step, the interactions of the ignition pulse and a hundred-critical-density plasma are simulated to study hot electron generation and transport. The results show that at ultra-high intensities, \( I > 5 \times 10^{19} \text{W/cm}^2 \), most of the electrons transporting energy through 50\( \mu \text{m} \) of 100 times critical density plasma are in a relatively low energy range. The fraction of laser power that transits the dense plasma and is deposited into a dense core increases with laser intensity. Overall these results show the promise of using ultra-high-intensity ignition pulses in the hole-boring scheme.

1. Introduction

In the “hole-boring” scenario of fast ignition (FI) [1], an ignition pulse needs to first propagate through a millimeter-scale underdense plasma to reach a critical surface with a critical density \( n_c = \omega_0^2 m_e/(4\pi e^2) \), where \( m_e \) and \( e \) are the electron mass and charge, respectively, and \( \omega_0 \) is the pulse frequency. There the ignition pulse may continue to push forward into an overdense plasma through its ponderomotive pressure (hole-boring) and relativistic transparency. In the meantime its energy is absorbed by the plasma to generate energetic (so-called hot) electrons, which are to reach a dense core region and deposit their energy there to create a hot spot to start fusion reactions. In order to avoid energy loss of the ignition pulse in the millimeter-scale underdense plasma, a channeling pulse, which could be the prepulse of the ignition pulse or a separate pulse, has been proposed [1] to produce a low-density channel to reduce the nonlinear interactions of the ignition pulse in the underdense region.

Key information for the hole-boring scenario includes the energy needed for the channeling pulse, the ignition pulse to hot electron conversion efficiency, the spectrum of these electrons,
and the transport of the hot electrons to the core. Many of the processes involved are highly nonlinear, and no adequate theory exists. In this paper we study the scenario in two simulations, both with the fully explicit particle-in-cell (PIC) code OSIRIS [2]. The first is on the laser channeling process [3]. The second is on the ignition pulse’s interactions with the overdense plasma to study the hot electron generation and transport, assuming a low-density channel has been created through channeling and hole boring and the ignition pulse can reach the $n = 100n_e$ surface without much loss.

2. Laser channeling

Most previous experiments and simulations on laser channeling were done in 100 $\mu$m-scale plasmas [4, 5, 6, 7, 8, 9, 10]. However, the underdense region of an actual FI target is about 1000 $\mu$m long. The residual plasma in the channel can continue to interact with the latter part of the channeling pulse and make the channeling process truly dynamic. To study the channeling process in more realistic settings, we have performed full-scale two dimensional (2D) PIC simulations with an underdense region consisting of a deuterium-tritium (DT) plasma as large as 987 $\mu$m $\times$ 401 $\mu$m and with a density profile exponentially rising from $0.1n_e$ to $1.02n_e$. The channeling pulse has a Gaussian transverse profile with a full-width-half-maximum (FWHM) intensity spot size of $16-47$ $\mu$m and a peak intensity between $10^{18}$ and $10^{20}$ W/cm$^2$. Both s and p polarization are used to infer 3D effects. The channeling process is simulated for up to 15 ps. We have also performed simulations with a preformed channel to study the transmission of the ignition pulse in the channel. The 2D simulations typically employ 79 million cells and 158 million particles and run $7 \times 10^4$ steps. In addition, we have also performed 3D simulations with a plasma volume of $(90 \mu$m$)^3$. These runs employ 5.8 billion cells and 11.6 billion particles and run $10^4$ steps. For details see [3].

Channeling in millimeter-scale plasmas indeed has many new phenomena that were not present in previous short-scale experiments and simulations, including plasma buildup to above critical density in front of the laser, laser hosing/refraction, and channel bifurcation and self-correction[3]. These phenomena are illustrated in figure 1.

As a result, the channeling speed oscillates and is much less than the laser linear group velocity (figure 2b). The simulations find that the effective channeling time $T_c$ and the total energy $E_c$ to reach the critical surface scale with the laser intensity $I$ as $T_c \approx 2.9 \times 10^2(I/10^{18}$ W/cm$^2)^{-0.64}$ ps and $E_c \approx 1.7(I/10^{18}$ W/cm$^2)^{0.36}$ kJ. The scaling for the first time shows that low-intensity channeling pulses are preferred to minimize the required energy but with an estimated lower bound on the intensity of $I = 5 \times 10^{18}$ W/cm$^2$ if the channel is to be established within 100 ps (figure 2a). To study the effect of the channel on the transmission of the ignition pulse, we have also performed simulations with a preformed channel. The preformed channel has a plasma density of $0.05n_e$, a width the same as that of the incoming pulse, and a length of 987 $\mu$m. The plasma temperature is the same as that outside the channel (1 keV). Figure 2c plots the forward Poynting flux within the channel received at $n_0 = n_e$, normalized to that entering the channel front, for an $I = 10^{19}$ W/cm$^2$ pulse. It shows that the front end of the pulse still suffers an energy loss but the main part can have an 80% transmittance. The increased transmission is mainly due to faster heating in a lower density plasma. In contrast, without the preformed channel, pulses of intensities of $I = 10^{19}$ W/cm$^2$ and $I = 10^{20}$ W/cm$^2$ have negligible transmission.

From a limited number of 3D runs, we have also found the channeling speed in 3D is greater than in 2D. This is because of stronger self-focusing in 3D, where the laser vector potential $a$ scales with the spot size $w$ as $a^2 \sim w^{-2}$, than in 2D, where $a^2 \sim w^{-1}$. This leads to a greater laser ponderomotive force and thus a greater channeling speed in 3D.
Figure 1. Results from a simulation with a 10 particle-per-cell, $I = 10^{19}$W/cm$^2$, p-polarized laser and $n_0 = 0.1 - 0.3n_c$: (a) ion density at $t=0.8$ ps showing micro channels formed; (b) laser E-field showing laser hosing, (c) ion density showing channel bifurcation at $t=3.4$ ps, and (d) ion density at $t=7.2$ ps showing channel self-correction.

3. Hot electron generation and transport

In the fast ignitor concept for inertial fusion a target is compressed to high density, up to 300g/cc, forming a collisional ($\nu_{ei} \approx \omega_p$ where $\nu_{ei}$ is the electron ion collision frequency and $\omega_p$ is the plasma frequency) plasma at the core of the target. The core is surrounded by collisionless plasma ($\nu_{ei} \ll \omega_p$) with a radial density profile dropping from above solid density to critical density ($n_c$) for a 1 $\mu$m laser in a few hundred microns. The energy flux generated by a high intensity laser and carried by hot electrons is used to ignite a small high density region of the core [1]. These hot electrons must couple through collisions to the high density core. This has significantly constrained the design of fast ignition experiments by limiting the intensity of the ignition laser to approximately $5 \times 10^{19}$W/cm$^2$ [11]. However, at this intensity with spot size of 20$\mu$m (the desired spot size of the spot at the core) the laser power would only be .3 PW while the desired power must be greater than .83 PW at 100% coupling efficiency [12]. If higher intensity can be used then this limit can be overcome. This question can be addressed using PIC simulations.

The focus of our 2D PIC simulations for laser absorption and electron transport is the transport of energetic electrons across the overdense collisionless plasma, the amount of energy delivered to the core, and the spectrum of the electrons that reach the core. In these simulations the initial conditions assume that the target has been compressed, and the channeling pulse has created a low-density channel in the path of the ignition laser. We have constructed a model that includes isolated boundaries, self-consistent generation of electrons at the laser plasma interface, self-consistent movement of the laser-plasma interface due to laser and plasma pressure, self consistent return currents, and an absorbing core. The simulation box is $19000\Delta \times 16400\Delta$ with the grid resolution $\Delta$ half a skin depth for 100$n_c$, the maximum density within the target (figure 3). The isolated targets in the simulations are a 50 $\mu$m-radius overdense plasma with
a 20\(\mu\) m-radius dense core offset 20\(\mu\)m to the right of center. The purpose of the offset is to increase the distance that the fast electrons must traverse from the laser-plasma interaction region to the target core. The collisional core is modeled by a velocity drag on the electrons. The drag models collisions with a massive species at rest in the lab frame in the core. The drag force, \(F_{\text{drag}} = A(v/c)^{-2}/\gamma\), is proportion to the inverse of the particle energy for relativistic particles with velocity near the speed of light and applies only for electrons with energy 20KeV < \(E\) < 10MeV. The drag coefficient, \(A\), is set so that a free streaming 1 MeV beam of electrons would penetrate 10\(\mu\)m into the core. This allows simulations to run for long times, at least 2.5 ps, without high-energy electrons refluxing through the target. The integrated line density from the target edge to the core is equal to the line density of a target with an exponentially rising density profile and with a 100\(\mu\) m-scale length per decade from the target edge to a 10\(^{23}\)/cc density. This mass distribution is more compact than actual targets for simulation purposes.

The simulation can be broken into three regions: the laser-plasma interaction region where a flux of hot electrons is generated, the overdense layer of collisionless plasma through which the hot electrons are transported, and the collisional core. The electrons in the laser-plasma interaction region form a distribution such that the energy is transported to the core while allowing return currents to replenish electrons at the laser-plasma interface. In general the electron momentum distribution has characteristics of a relativistic thermal bulk with lower energy electrons moving toward the laser-plasma interface and energy transport from higher-energy electrons in the bulk directed toward the core.

**Figure 3.** Schematic of target in simulation box. A laser strikes the target on the left generating hot electrons. The hot electrons traverse a large volume of overdense collisionless plasma and are absorbed into the core.

**Figure 4.** Spatial distribution of electron energy density in the target for \(I = 2 \times 10^{20}\)W/cm\(^2\) laser after 2ps. A sharp discontinuity exists at the laser-plasma interface (on the left) where the laser and hot plasma are in pressure balance. A hot spot builds up in front of the laser, and hot electrons are absorbed into the core.

The spatial distribution of electron kinetic energy shows a sharp interface where the energy is absorbed from the laser, as illustrated in figure 4. At this interface the electron energy density is in pressure balance with the energy density of the laser. Downstream a hot spot has developed in the collisionless plasma between the laser-plasma interface and the core. This hot spot is caused by wave turbulence generated as the hot electrons move through the bulk toward the core. The amount of energy that is transported into the core and the efficiency with which that energy is deposited determine the viability of any fast ignition scheme. The coupling efficiency, defined as
power transmitted to the core normalized by the laser power, increases with laser intensity, while the bulk of this energy is still carried by electrons that are energetically able to interact with the target core. This is the advantage of higher-intensity lasers. Ultra-high-intensity ignition lasers deliver greater power because of both higher efficiency and higher energy density.

4. Summary
We have simulated the hole-boring scenario in FI in two PIC simulations. The laser channeling simulations have shown that, despite channel bifurcation from laser hosing, a low-density straight channel can be created with a speed approaching the hole-boring speed. Low-intensity channeling pulses are preferred to minimize the required laser energy. The channel is also shown to significantly increase the transmission of the ignition pulse to 80%. The simulations on hot electron generation and transport have shown that even an \( I = 8 \times 10^{20} \text{W/cm}^2 \) pulse converts its energy mainly to hot electrons whose energy is suitable for FI. This is in contrast to previous predictions based on the ponderomotive scaling [13] that ultra-intense pulses would produce electrons too energetic to stop in the core. These results open up the prospect of using ultra-intense pulses in FI.

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