Hollow density channels and transport in a laser irradiated plasma slab

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A three dimensional Particle-In-Cell simulation describing the interaction of an intense laser beam with a plasma slab is presented. It is observed that the laser generated electron current decays into magnetically isolated filaments. The filaments grow in scale and magnitude by a merging process in the course of which the field topology changes. The opposite process also takes place occasionally. The laser driven charge and energy flows and the reconnecting magnetic field mutually interact. At the end of the merging process flows and fields are confined close to the laser irradiated surface of the plasma slab. Both decay rapidly in the bulk plasma. Due to the magnetic pressure in the filaments hollow density channels in the electron and ion densities are formed. The simulation reveals that charge flows in these channels can exceed the Alfvén current.

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Key issues of many applications concerning the interaction between lasers and matter at high intensities are laser absorption and charge and energy transport through a plasma. A typical application of intense laser-matter interaction where this is of relevance is Fast Ignition (FI) in Inertial Confinement Fusion (ICF). In the present paper we study issues of transport in a thick plasma slab with the help of Particle-In-Cell (PIC) simulations over a few hundred femtoseconds simulation time. Binary collisions are included. Details of the collisional model will be presented elsewhere. The density of the plasma slab is about 20 times over-critical.

A reasonable definition of thickness has some ambiguity. We call a slab thick when its depth exceeds many times the skin lengths \( l_s = c/\omega_p \) where \( \omega_p \) is the plasma frequency. In addition, the thickness of the plasma slab must be larger than the penetration depth of the charge flow. The plasma slab investigated in this paper has a thickness which is large enough to exceed the latter sufficiently. Two dimensional (2D) transport simulations in the plane perpendicular to the laser direction have recently been reported. In these simulations the slab thickness vanishes, the laser is neglected and fast particles have been injected by hand. In addition, 2D geometry severely limits the available degrees of freedom for current transport and magnetic field evolution.

In the present paper we investigate properties of laser-generated charge flows in a thick plasma slab in 3D where the fast particles are generated by laser irradiation. We show that magnetic filament merging is an important process to form large filaments and magnetic field strengths. In 3D the process represents a simple form of magnetic reconnection in the sense that the field topology changes in the course of the latter. Laser generated charge flows found in the simulation exceed the Alfvén limit. Furthermore, it is observed that the magnetic fields dominate the properties of current transport. Both, electric and magnetic fields are localized close to the front surface of the plasma slab as is the laser generated charge flow.

The slab has a thickness of 6.0 \( \mu \text{m} \) and a width of 4.0 \( \mu \text{m} \times 4.0 \mu \text{m} \). The box size is 4.0 \( \mu \text{m} \times 4.0 \mu \text{m} \times 8.0 \mu \text{m} \). All fields depend on \( x \), \( y \), and \( z \). The numerical grid has 152 \times 152 \times 800 \text{ cells}. Lateral directions are periodic. Electrons and ions are presented by 1.44 \times 10^8 \text{ quasi-particles}. The initial electron and ion temperatures are 10.0 keV and 1.0 keV respectively. The laser beam propagates in \( z \) and is linearly polarized along \( x \). After a rise time of three optical cycles the laser intensity is kept constant. The incident laser beam has a Gaussian envelope laterally with a width of 2.0\( \mu \text{m} \) at full-width-half-maximum. The irradiance is \( I \lambda^2 = 5.0 \cdot 10^{19} \text{Wcm}^{-2}\mu \text{m}^2 \). The slab has a marginal initial deformation to enhance absorption. The deformation is parameterized by \( z(x,y) = \delta \exp \left(-(x-x_0)^2/r^2 + (y-y_0)^2/r^2 \right) \) where \( \delta = 0.4\mu \text{m} \), \( x_0 = y_0 = 2.0 \mu \text{m} \) and \( r = 2.5 \mu \text{m} \). The center of the slab is located at \( z = 4.2 \mu \text{m} \). The background plasma consist of protons. The initial electron plasma density in the simulation is \( n_e = 3.33 \cdot 10^{22} \text{cm}^{-3} \). The laser radiation is turned off after 200 fs. The simulation itself is stopped after 400 fs. The total simulation is carried out on a parallel computer using 361 compute nodes and consumes 29000 CPU hours in total. The coordinate system used in the simulations is right handed. Hence, the positive \( z \)-axis points out of the \( xy \)-plane shown in the figures. In what follows we will always use the positive \( z \)-axis for reference.

Plots (a,b,c) of Fig. show the plane \( z = 2.0 \mu \text{m} \) of the cycle averaged magnetic field \( |B| \) defined in the figure caption. Time proceeds from plots (a,d) to (c,f). Filaments of different scale are observed. The white arrows indicate the direction of the magnetic field. It is seen that the magnetic field lines in the filaments are closed. As is seen from plots (a,b) the filaments attract each other. In case the attractive forces between them are strong enough magnetic field lines start to reconnect to form larger filaments with again closed field lines. The topology of the magnetic field changes. The inverse process takes place occasionally. The largest filament scale in our simulation is shown in plot...
The peak magnetic field strength in this filament is about $45000 \, \text{T}$. Plots (d,e,f) show $\int dxdy |\mathbf{E}|$ and $\int dxdy |\mathbf{B}|$ obtained from the cycle averaged fields $\mathbf{E}$ and $\mathbf{B}$ in the simulation box. They illustrate the magnitude of $\mathbf{E}$ and $\mathbf{B}$ along $z$ in the bulk of the plasma. The plots show that close to the front surface and in the bulk of the plasma slab the magnetic field $\mathbf{B}$ is larger than the electric field $\mathbf{E}$. At the rear of the slab $\mathbf{E}$ is larger than $\mathbf{B}$. The electric field $\mathbf{E}$ at the rear of the slab points along the positive $z$-axis. At the front surface it points in the opposite direction. Furthermore, the relations $E_x \gg E_{xy}$ and $E_z \ll E_{xy}$ are obtained in the simulation. Since the electric field is largest at the rear surface back surface acceleration of protons is most efficient in this simulation.

The singular electrons are those that are capable of transporting large currents. The simulation yields approximate around the magnetic field lines while the singular current contains mainly electrons that meander between field lines.

The quantity $P_{ij}$ in Eq. (1) is the pressure tensor which is calculated directly in the simulations. Rewriting Eq. (1) yields

$$j_z \approx \frac{1}{\gamma} \partial_r \left( \frac{r P \perp}{B_\theta} \right) + \frac{P \perp}{B_\theta^2} \partial_r B_\theta .$$

Equation (2) is obtained from Eq. (1) assuming cylindrical geometry for a filament and rewriting $P_{ij}$ with the help of the pressure $P \perp$ in radial direction normal to the $z$-axis. The magnetic field has been approximated by $B_\theta$ and the current density by $j_z$. Cylinder symmetry is approximately applicable to the situation found in the simulation. Hence, the calculation reveals the impact of geometry, pressure, and current density on the total current that can flow. Ambiguities inherent in the calculation of $I_A$ as discussed above are avoided. The singular current $I_s$ is obtained with the help of Eq. (2)

$$I_s = I - I_{gc} = -4 \pi \epsilon_0 c^2 \frac{P \perp (0)}{j_z (0)} .$$

For a mono-energetic cold electron beam with electron density $n_0$ and velocity $v$ for which we have $P \perp = m_e n_0 v^2$ and $j_z = -e n_0 v$ the singular current $I_s$ in Eq. (3) yields the Alfvén current $I_A$. These formulas have been obtained.
in the context of Z-pinches \[11\]. In hot laser plasma \(I_s\) can become much larger than \(I_A\) since hollow cylinder-like density channels form and a significant lateral pressure is present. As a consequence, larger total currents than the Alfvén current are possible in a single filament. From the simulation it is obtained that the singular current \(I_s\) in the central filament of plot (b) in Fig. \[3\] is about 100 kA. Roughly this value is also obtained for \(I = \int dx dy j_z\) from the simulation by integrating over the cross sectional area of this filament.

Figure \[4\] shows the electron energy spectrum (a), the integrated longitudinal and lateral charge and energy flows (b), and the electron number and energy densities in the plasma slab (c). The longitudinal flows have been split into positive and negative components. The return energy flow is negligible. For the lateral flows the integrated absolute values are taken. The fastest electrons obtained in the simulation have about 30 MeV while fractional absorption of the laser is about 35\%. The absorbed power of the laser is transported away by the energy flow \(q_z\) shown in plot (b). The latter consists predominantly of fast electrons. The energy flow penetrates much deeper into the plasma than the charge flow but still decays rapidly. Plot (c) shows that the energy density is large only in the front layer of the plasma slab. Since the longitudinal and lateral charge flows are only sizeable where the magnetic field is large (see Fig. \[3\]), the implication is that the mutual interaction between current and magnetic field confines most of the total charge and energy flows to the front surface of the slab. Since time-averaged electric fields in the simulation are much smaller than time-averaged magnetic fields the transport regime is of magneto-hydrodynamic nature.

In conclusion it has been shown that large charge flows generated by intense laser radiation decay into current filaments. The current filaments are isolated by magnetic filaments which reconnect until larger ones are obtained. This process proceeds until a dominating filament is obtained in the plasma. The magnetic pressure associated with the magnetic filaments leads to hollow density channels. Hollow density channels, however, can support total currents that exceed the Alfvén current. This regime of transport is different from the one investigated by Bell \textit{et al.} \[12\].

Despite hollow channel transport severe charge and energy flow inhibition are observed. We note that the Alfvén current limit is difficult to apply in the context of a hot laser plasma since it has many ambiguities. We note that the plasma volume investigated is small due to numerical expense and that lateral boundaries are periodic. Hence, some care has to be taken when extrapolating the results reported here to FI relevant problems.

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\[\text{References}\]

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FIG. 1. Merging of magnetic filaments and cycle averaged \( E \) and \( B \) fields vs \( z \) in units \( E_0 \) and \( B_0 \). Plots (a,b,c) show the planes \( z = 2.0 \mu m \) of the cycle averaged magnetic field \( B = (B_x^2 + B_y^2 + B_z^2)^{0.5} \) at different times. Plots (d,e,f) show \( E = \int dxdy (E_x^2 + E_y^2 + E_z^2)^{0.5} \) (dashed) and \( B = \int dxdy (B_x^2 + B_y^2 + B_z^2)^{0.5} \) (solid) averaged over the lateral area and a laser cycle. The times are \( t = 71 \) fs (a,d), \( t = 125 \) fs (b,e), and \( t = 179 \) fs (c,f). The arrows in (a,b,c) indicate the direction of the cycle averaged magnetic field \( \mathbf{B} \). The parameters are \( E_0 = 1.0 \cdot 10^{11} \) V/m and \( B_0 = 8.76 \cdot 10^2 \) Vs/m².

FIG. 2. Cycle averaged \( j_z \) in units \( j_0 \). Plots (a,b,c) show the planes \( z = 2.0 \mu m \) of the cycle averaged current density \( j_z \) at different times. Plots (d,e,f) show \( I = \int dxdy j_z \) split into flow (dashed-dotted) and return flow (solid) averaged over a laser cycle. The total current in the central filament (blue color) is approximately 200 kA. The times are \( t = 71 \) fs (a,d), \( t = 125 \) fs (b,e), and \( t = 179 \) fs (c,f). The arrows in (a,b,c) indicate the direction of the cycle averaged magnetic field \( \mathbf{B} \). The parameter is \( j_0 = 1.66 \cdot 10^{16} \) A/m².

FIG. 3. Hollow density channels. Cycle averaged electron density \( n_e \) in units \( n_0 \). Plots (a,b,c) show the planes \( z = 2.0 \mu m \) at different times. Plot (d) shows the plane \( x = 2.0 \mu m \). The times are \( t = 71 \) fs (a), \( t = 125 \) fs (b), and \( t = 179 \) fs (c,d). The parameter is \( n_0 = 1.0 \cdot 10^{28} \) m⁻³. The location of the hollow density channels coincides with magnetic filaments as is seen by comparing with plots (a,b,c) of Fig. 1.

FIG. 4. Energy spectrum (a), total current and energy flows in units \( I_0 \) and \( q_0 \) (b), total electron and electron energy density in units \( n_0 \) and \( \epsilon_0 \) (c). Plot (a) shows the electron energy spectrum obtained from all the particles in the plasma. The fastest electrons have 30 MeV. The thin solid lines of plot (b) show the integrated current and return current \( I = \int dxdy j_z \). The thick solid line indicates \( I = \int dxdy (j_x^2 + j_y^2) \). The thin dashed-dotted lines indicate the energy and return energy flows \( q_z = \int dxdy \int d^3p v_z (c\sqrt{m^2c^2 + p^2} - mc^2) f \). The thick dashed-dotted line shows the lateral energy flow \( q_L = \int dxdy \int d^3p \sqrt{v_x^2 + v_y^2} (c\sqrt{m^2c^2 + p^2} - mc^2) f \). The solid line of plot (c) shows the integrated electron energy density \( \epsilon = \int dxdy \int d^3p (c\sqrt{m^2c^2 + p^2} - mc^2) f \). The dashed-dotted line gives the electron number density \( n_e \rightarrow \int dxdy n_e \). Fractional absorption is about 35.0 %. The time is \( t = 179 \) fs. The parameters are \( I_0 = 10^7 \) A, \( q_0 = 10^{12} \) W, \( \epsilon_0 = 10^4 \) J/m, and \( n_0 = 10^{17} \) m⁻³.
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