Collective Absorption Dynamics and Enhancement in Deformed Targets

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(March 31, 2022)

The interaction of intense fs laser pulses with thin foils that have an imposed deformation is compared with thick targets that develop bow shocks. Both target types yield good absorption. Up to 80\% absorption is obtained for a 0.2μm thick, 15 times over-dense foil at 4 × 10^{18}W/cm\(^2\). A value of 50\% is obtained for a 4μm thick, 2 times over-dense thick target at 10^{18}W/cm\(^2\). For comparable extension and curvature of the laser-plasma interfaces absorption levels in both targets become similar. In both absorption scales weakly with intensity and density. Energy transport in thin foils and thick targets, however, is different.

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Absorption of super-intense laser pulses in solids is based on collective mechanisms like the Brunel effect \cite{1,2}, anomalous skin effect \cite{3}, or \(j \times B\)-heating \cite{4} with continuous transitions from one to the other and wide overlaps among particle. Particle-In-Cell (PIC) and Vlasov simulations in one dimension (1D) have shown that absorption varies between 5 – 15\% at normal incidence to at most 60\% at about 75° incidence for irradiances not exceeding several \(10^{17}\)Wcm\(^{-2}\)μm\(^2\). Beyond this intensity emission of harmonics and effects of self-generated dc magnetic fields lead to a reduction of this maximum, as well as its shift towards smaller angles of incidence and, eventually, to the formation of secondary relative maxima in the angular absorption behaviour \cite{5}. The signature of collective absorption is the generation of jets of fast electrons in the relativistic domain. Owing to \(E^{-3/2}\) energy scaling of the collision frequency, collisional absorption becomes inefficient at irradiances \(IA^2 \geq 10^{17}\)Wcm\(^{-2}\)μm\(^2\) \cite{6}.

All beam photon conversion into fast electrons occurs over skin lengths \(l_s \approx c/\omega_p\) much less than a vacuum wavelength \(\lambda\), simply because the free electron current induced by the laser field always tends to cancel the incident field \cite{7}. If so, absorption is bounded to the thin critical layer. However, the question arises whether the geometry of the interaction region is a sensitive parameter for the degree of absorption. So far this problem has never been investigated systematically. The question to which degree absorption can increase in deformed targets and whether thin plasma layers already lead to good absorption is an interesting problem in itself, e.g. for better understanding the relevant interaction physics, as well as it is essential for applications. Three substantial applications in which good absorption is highly desirable are (i) the generation of collimated intense jets of energetic electrons, (ii) broad-band intense X-ray sources in thin foils (for instance for back-lighting), and (iii) the fast igniter scheme for ICF \cite{8}.

The problems addressed can be reduced to the following three questions: (i) How does absorption change when target deformation is naturally present due to bow shocks and hole boring or when it is imposed as for corrugated targets? (ii) What is the energy current dynamics (efficiency into forward and lateral directions) in such targets? (iii) Is there a difference between thin and thick targets? To answer these questions we make use of 2D2P (two spatial and two momentum components) Vlasov simulations for reasons of low noise and high resolution. We will show laser light absorption enhancement up to 80\% in thin deformed foils, lateral deflection of main electron jet streams, and the formation of a well collimated axial jet in thick targets. Finally, the occurrence and relevance of Weibel type instabilities and self-generated current filaments will be presented and discussed.

In our simulations all physical variables depend on the spatial variables \(x\) and \(y\). In addition, the distribution functions for the ions and electrons depend on two momentum coordinates \(p_x\) and \(p_y\). A \(350 \times 128 \times 51 \times 51\) grid for the electrons and a \(350 \times 128 \times 41 \times 41\) grid for the ions is used. Use is made of a charge conservative numerical scheme.

In order to better show how energy absorption and transport are related to the target deformation, first we consider a preformed plasma layer with an imposed Gaussian deformation in lateral direction. The deformation is given by

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$x(y) = \delta \exp \left(-\frac{(y - y_0)^2}{\gamma^2}\right)$ where $x(y)$ denotes the longitudinal position of the peak density, $\delta$ the deformation depth as indicated in plot (a) of Fig. 1, and $\gamma$ the deformation width. We take for the radial beam diameter $5 \mu m$ at full-width-half-maximum and for $\gamma = 3.8 \mu m$. For $\delta$ we use 0, 1, 2 $\mu m$ in our simulations. For the thickness of the plasma layer we take $d = 0.2 \mu m$. After a finite rise time the laser beam intensity is kept constant. The transverse locations $y_0$ for the peak of the pulse and the center of the deformation coincide.

Fractional absorption of the laser energy as a function of time is presented in plot (b) of Fig. 1. Both, deformed and planar target data are plotted. Absorption starts to rise at $t \approx 20fs$, and tends to saturate at $t \approx 80fs$. The saturation values are between 40% and 80%. Absorption in the deformed thin foils investigated in our simulations are well above those predicted for planar plasma films or thick targets [12] for comparable parameters. Simulations for saturation values are between 40% and 80%. Absorption in the defor med thin foils investigated in our simulations are found in front of the foil. As time proceeds the lateral part streaming out of the center grows. This is observed from the distribution function $f_e(y,p_y)$ which has slow and fast electrons flowing in different lateral directions. Here, the energy current out of the center already dominates. We find that the function $f_e(y,p_y)$ does not become quasi-steady. In opposition, $f_e(y,p_y)$ acquires a quasi-steady state. In that sense absorption in thin plasma layers is due to lateral energy flow.

Plots (a), (b), and (c) of Fig. 3 show the quasi-steady electron mass currents and magnetic field. The mass current flows into the center and is balanced by a lateral return current (see plot (b)). Small scale filaments are present in the center of the foil. The magnetic field filaments saturate at 16MG. Combining plots (a) and (b) we observe that the gyro-radius of the electron current after saturation is close to the local classical skin length $l_s = c/\omega_p \approx 0.08\mu m$. The structure and scale-lengths of the magnetic field and current patterns are consistent with those generated by a nonlinear Weibel instability [13] driven by the magnetic repulsion of counter-propagating charged electron beams. As is seen from plot (a) of Fig. 3 the fast electron population does not contribute to the growth of the filamentations since the longitudinal energy current is always positive (hence no mutual repulsion but collimation of fast electrons).

We now look at simulations for thick, weakly over-dense plasma foils for which we let the deformation be generated by the radiation pressure of the short pulse itself. We take $5 \mu m$ at full-width-half-maximum for the radial beam diameter. For the thickness of the plasma layer we take $d = 4 \mu m$ while the density is $n_e/n_c = 2$. After a finite rise time the laser beam intensity is kept constant. Plots (a) - (c) of Fig. 4 show results from a simulation of a thick foil of hydrogen ions. A collisionless quasi-steady bow shock is generated [14] with a shock speed of approximately $10^7 m/s$. The high shock speed generates a quasi-steady magnetic wake behind the shock-vacuum interface. The ion shock yields a deformed laser-plasma interface with $\delta \approx 0.5 \mu m$. Fractional absorption is about 50% which agrees with the values obtained from the foil simulations with comparable deformation. We note that the density at the shock front is now much lower ($\approx 3n_e$). At the shock interface fast electrons in longitudinal and lateral directions are generated as in plots (a) and (b) of Fig. 4 and schematically indicated in Fig. 5. The energy currents $\epsilon_x$ and $\epsilon_y$ are of similar magnitude. In opposition to the thin foil case, however, fast lateral electrons are now captured by the magnetic field and penetrate deeply into the plasma in front of the shock. There, they generate a magnetic field (f) which further collimates electrons (see Fig. 4(b)). Looking at the energy currents in the plasma we observe that almost the total deposited laser flux is converted into fast longitudinal electrons that propagate in the channel. For reasons of quasi-neutrality a return mass current is drawn (see Fig. 4(c)).

Instabilities may prevent the evolution of a symmetric magnetic channel along pulse propagation direction due to vacuum-plasma interface distortion and bending of the magnetic channel. However, high shock speeds and small laser diameters help to avoid the growth of Rayleigh-Taylor-like instabilities due to fast mass replacement by fast lateral ablation (ablative stabilisation). Filamentation instabilities are expected to be more relevant (see plots (a) and (b) of Fig. 5 for the case of thin foils). For counter-propagating, overlapping currents of similar magnitude they grow close to $\omega_p$ [15]. However, the energy current in the channel is unidirectional since it is not balanced by an energy return current (the fast electron population is not balanced). Hence, it has a collimating effect on the mass current. This effect can be verified by imposing mirror reflecting boundary conditions. Now the energy current is balanced and we do not obtain a magnetic channel but magnetic bubbles (filamentation) in the plasma [15].

To summarize our numerical results, we have related laser deposition and target geometry. Thin and thick foils both yield a substantial increase of short pulse absorption for moderate target deformation. For comparable lateral extension and curvature of the laser-plasma interfaces we have obtained similar levels of laser deposition ($\approx 50\%$), no matter whether the deformation has been natural or imposed. We have found that absorption depends weakly on
density and intensity but strongly on the shape of the interface. In both, thin and thick deformed targets fast electrons propagating into the center of the curved laser-plasma interface are generated. However, in thin plasma layers fast electrons cannot escape from the foil and thus heat the plasma in lateral direction. For thick foils with comparable lateral extension and curvature of the laser-plasma interface the fast electrons are captured and collimated by a magnetic field that extends deep into the plasma and enhances the penetration depth of the electrons. The plasma is now heated in pulse propagation direction. A high fraction of the total deposited laser flux is converted into longitudinal electron energy current.

We note that there are experimental indications for both transport mechanisms. In the experiment of Feurer et al. [16] evidence for significant laser-induced surface modification is given; at the same time, absorption is high (≈ 45%). Measurements also suggest the existence of two electron populations, one with an energy of ≈ 400 keV and another with a few tens of keV, but velocity mostly parallel to the target surface. This is similar to what is found in our simulations (see plot (c) and (d) in Fig. 2). Comparison of our simulations with the experimental results suggest that both, high absorption and transversely flowing electrons are related to the surface deformation.

Tatarakis et al. [17] observe a collimated plasma jet emitted from the rear of a thick solid density target. Their interferometric measurements show that the laser interacts with an expanding plasma with a longitudinal extension of some μm. Therefore the interaction conditions are similar to our thick target simulations. These latter support the conclusion by Tatarakis et al. that the fast electrons are collimated by magnetic fields.

The present work has been supported by the European Commission through the TMR network SILASI, contract No. ERBFMRX-CT96-0043. Use of the Cray T3E at CINECA was supported by INFM through a CPU grant. The authors are grateful for the usage of the computing facilities at ILE/Osaka. In particular we acknowledge Y. Fukuda and M. Okamoto as well as the CINECA staff for their valuable technical help.

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FIG. 1. Plot (a): Quasi-steady electron density for δ = 1 μm at t = 0 fs. Blue contour areas indicate low density and yellow ones high density. The orange solid and dashed lines give density values along x = 1.0 μm and y = 4.96 μm. The density is normalized to the critical electron density. Plot (b): Fractional absorption vs. time, for δ = 0 μm (solid), δ = 1 μm (dashed), and δ = 2 μm (dot dot dot dashed). The parameters are Iλ² = 4.0 · 10¹⁸ W cm⁻² μm², n_e/n_c = 15.0, m_i = 8.0 · 10⁻²⁷ kg.

FIG. 2. Plots (a) and (b): Cycle-averaged electron energy current densities ϵ_x and ϵ_y. Yellow areas show negative and blue areas positive values. The lines in (a) are along x = 1.95 μm (solid) and y = 4.96 μm (dashed) and in (b) along x = 1.71 μm (solid) and y = 3.94 μm (dashed). The density is n_e/n_c = 15.0. Plots (c) and (d): Cycle-averaged f_e(y, p_x) and f_e(y, p_y). The center of the foil is at y = 4 μm. The total lateral width for this simulation is 8 μm. The density is n_e/n_c = 20.0. The parameters are Iλ² = 4.0 · 10¹⁸ W cm⁻² μm², m_i = 8.0 · 10⁻²⁷ kg, δ = 1 μm, and t = 66 fs.
FIG. 3. Quasi-steady longitudinal mass current density \( j_x \) (a), transverse mass current density \( j_y \) (b), and magnetic field (c). White contour areas are positive and black areas negative. The lines in (a) are along \( x = 1.95\mu m \) (solid) and \( y = 3.94\mu m \) (dashed), in (b) along \( x = 2.0\mu m \) (solid) and \( y = 3.94\mu m \) (dashed), and in (c) along \( x = 2.0\mu m \) (solid) and \( y = 3.94\mu m \) (dashed). The parameters are \( I\lambda^2 = 4.0 \cdot 10^{18} \text{Wcm}^{-2} \mu\text{m}^2 \), \( n_e/n_c = 15.0 \), \( m_i = 8.0 \cdot 10^{-27} \text{kg} \), \( t = 66\text{fs} \), \( \delta = 1 \mu\text{m} \), \( j_0 = 9.15 \cdot 10^{15} \text{A/m}^{-2} \) and \( B_0 = 1.59 \cdot 10^3 \text{Vs/m}^2 \).

FIG. 4. Laser irradiated thick foil. Plot (a) is the ion density, (b) the quasi-steady magnetic field, and (c) the quasi-steady current density \( j_x \). Yellow contour areas are positive and blue areas negative. The lines in (a) are along \( x = 1.83\mu m \) (solid) and \( y = 4.97\mu m \) (dashed), in (b) along \( x = 3.5\mu m \) (solid) and \( y = 3.94\mu m \) (dashed), and in (c) along \( x = 3.34\mu m \) (solid) and \( y = 4.97\mu m \) (dashed). The white rectangle in (b) is schematically magnified in plots (a) and (b) of Fig. 3. The parameters are \( I\lambda^2 = 10^{18} \text{Wcm}^{-2} \mu\text{m}^2 \), \( n_e/n_c = 2.0 \), \( m_i = 10^{-27} \text{kg} \), \( t = 110\text{fs} \), \( j_0 = 4.58 \cdot 10^{14} \text{A/m}^{-2} \) and \( B_0 = 2.92 \cdot 10^2 \text{Vs/m}^2 \).

FIG. 5. Electron flow (a) and energy flow (b) for a thick foil. The plots illustrate the mass and energy flow conditions present in the white rectangle indicated in plot (b) of Fig. 4. Yellow areas belong to positive and blue areas to negative magnetic fields. The magnetic fields are generated by the mass current. Its flow directions are indicated by the black arrows in (a). The energy current is collimated by the magnetic channel and streams in forward direction.
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