Simulations of laser plasma interaction for shock ignition in the high intensity regime

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A preassembled fuel is ignited by a strong converging shock in the shock ignition (SI) [1, 2] approach to inertial confinement fusion (ICF). The shock is launched by a high power laser with the intensity $10^{15} - 10^{16}$ W/cm^2 and the wavelength 351 nm. At the lower boundary of this intensity range, the laser plasma interaction is dominated by collisional absorption and nonlinear processes are of minor importance [3]. However, if the intensity is close to 10^{16} W/cm^2, either due to higher laser power or just locally due to the presence of high intensity speckles, the collisonal processes turn over and the interaction is dominated by collective processes such as stimulated Raman (SRS) and Brillouin (SBS) scattering two-plasmon decay (TPD) and cavitation. This regime of interaction has been studied in our papers [4, 5] using 1D (2D) relativistic electromagnetic collisional Particle-in-Cell (PIC) simulations for realistic plasma conditions corresponding to SI.

We study the absorption process in the higher intensity domain ($2.4 - 24 \times 10^{15}$ W/cm^2) in details using one-dimensional large scale PIC simulations in this paper. The simulations of the laser plasma interactions consider realistic profiles of plasma parameters obtained from hydrodynamic simulation of recent spherical SI experiments at Omega. These profiles have been already used in [3].

The laser plasma interaction in higher intensity domain proceeds through two successfull steps, which are demonstrated in the temporal evolution of reflectivity in Fig. 1 a) - a transient stage with high reflectivity (80%) dominated by SBS followed by a quasi-steady stage with higher absorption (70%) dominated by SRS and cavitation. SBS has much higher gain than SRS [3] for the conditions used here and thus the scattered light is efficiently amplified during its propagation down the density profile. As there are no processes, which can suppress SBS initially, this instability can backscatter most of the pump wave energy.

SRS is an absolute instability at $1/4\ n_c$ (n_c is critical density) and it may grow also during the initial stage of interaction on a smooth density profile. When the local field induced by this instability becomes high, it expels electrons and the subsequent Coulomb explosion of ions produces density cavities, which partially trap the light and accelerate the particles [5]. The cavities are first produced at $1/4\ n_c$ in our 1D simulations and they have been also observed in

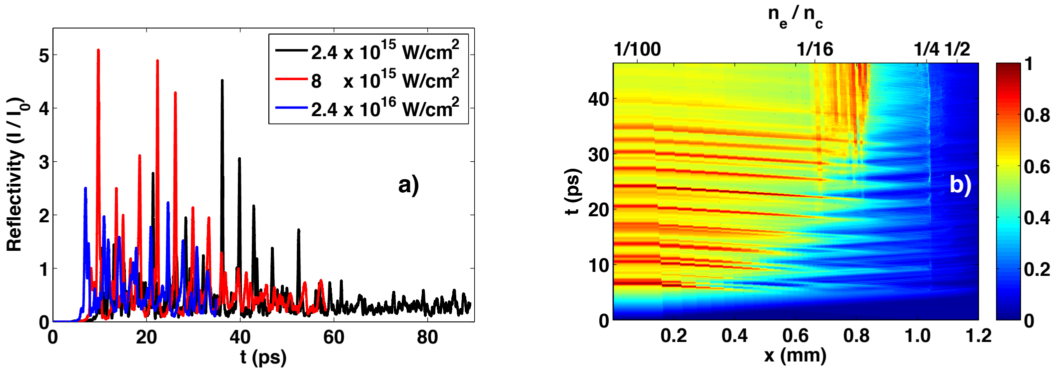

Figure 1: a) Temporal evolution of the reflectivity in simulations with the laser pulse intensity 2.4, 8 and 24 $\times 10^{15}$ W/cm^2. The simulations with higher intensity are stopped earlier because the density profile is strongly modified in later time. b) Temporal evolution of the electromagnetic field energy density inside the target in the simulation with 8 $\times 10^{15}$ W/cm^2.

2D simulations in smaller scale plasmas [4].

The light scattered by the absolute SRS from $^{1}/_{4}\ n_c$ can be rescattered at $^{1}/_{16}\ n_c$ on its way out of the target. This rescattering at the resonance point may also result in cavity formation. Once they develop, the cavities efficiently suppress SBS because they discontinue its spatial amplification. This can be seen in Fig. 1 b) where the temporal evolution of electromagnetic field energy density is plotted. The flashes due to SBS (propagating out of the target to the left) are clearly observed during the transient stage, which lasts for about 35 ps. The cavities around $^{1}/_{16}\ n_c$ start to develop at about 30 ps. They can be clearly observed in the figure as vertical strips as they trap a significant electromagnetic energy.

The absorption of the laser pulse becomes quite efficient (70%) in the quasi-steady stage of the interaction after the cavities develop. Most of the absorbed energy goes into hot electrons with a temperature in the 20-40 keV range. The energy distributions of hot electrons accelerated into the target are shown in Fig. 2. The absorption coefficient and the temperature of hot electrons do not depend on laser intensity in the considered intensity domain, while the number of hot electrons scales linearly with laser intensity.

The electron plasma waves due to SRS can propagate and accelerate electrons only along the density gradient in our 1D simulations. On the other hand, the strong electromagnetic fields in cavities may accelerates electrons also obliquely. This asymmetry in the momentum distribution can be used to find the temperatures of hot electrons due to SRS and due to cavitation. The momentum distribution is shown in Fig. 2 b) and the corresponding temperatures are 35 keV for SRS assuming monodirectional distribution and 30 keV for cavitation assuming symmetry

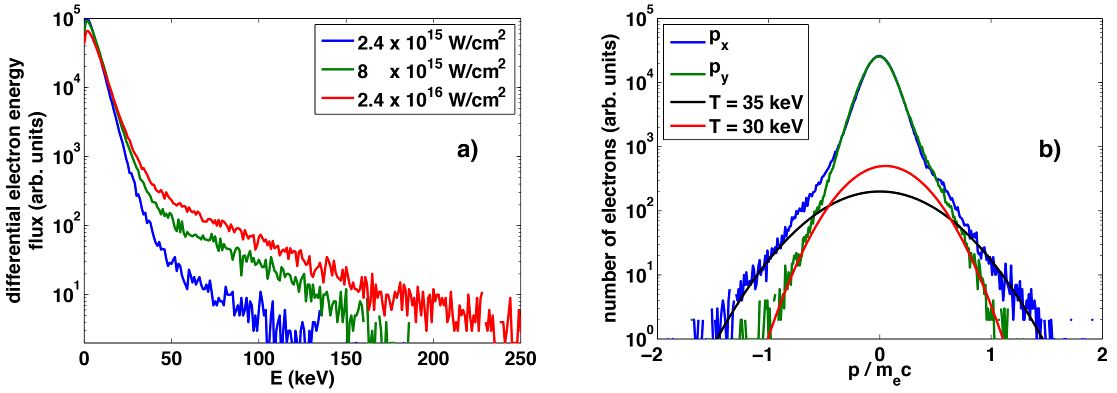

Figure 2: a) Temporally averaged flux of electrons flying into the target differential in energy (recorded close to the target rear side). The corresponding hot electron temperature is about 30 keV. b) Momentum distribution of electrons in the simulation with the laser intensity 8×10^{15} W/cm^2, x is the direction parallel and y perpendicular to the density gradient.

in the interaction plane.

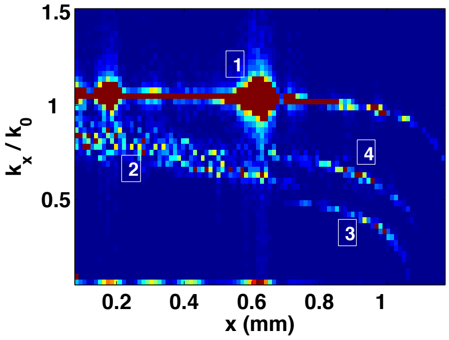

Figure 3: K-spectrum of the electromagnetic field inside the target in the simulation with the intensity 8×10^{15} W/cm^2 at 7.6 ps. Signals marked by numbers are described in the text.

Three simulations with a reduced density profile and the laser intensity 8×10^{15} W/cm^2 have been performed to find the contribution of SRS and cavitation to the overall absorption. The first reduced simulation includes the density profile from 0.01 to 0.3 n_c. The agreement of calculated absorption of 70% with the full scale simulation discussed above indicates that the absorption takes place below or around the quarter critical density. The second simulation includes only the region $0.01 - 0.16$ n_c with the cavities around $^1/_{16}$ n_c. This simulation has been realized from the first reduced simulation by removing the denser part ($0.16 - 0.3$ n_c) of the profile after the cavities have already developed. It has been found that the cavities at $^1/_{16}$ n_c do not influence the laser light propagating into the target (neither the intensity nor the spectrum). The third reduced simulation includes only the region around the $^1/_4$ n_c ($0.16 - 0.3$ n_c). The absorption is 50% and the reflectivity 38% here. The reflected light is concentrated around $^1/_4$ ω_0 (ω_0 is laser frequency) and from this we can deduce that the absorption due to SRS is 38%. The rest 12% of absorption is thus due to cavitation. Similar processes take place at $^1/_{16}$ n_c to the light reflected at $1/4\ n_c$ (38% of the incident intensity) resulting in the overall absorption of 69%.

Fig. 3 shows the k-spectrum of the electromagnetic field inside the target calculated with the intensity 8×10^{15} W/cm^2 at the time 7.6 ps before the cavitation starts. One can see the laser pulse propagating into the target and several pulses induced by parametric instabilities, which are denoted by the numbers: **1** - SBS, **2** - convective SRS, **3** - absolute SRS induced at $1/4\ n_c$ and **4** - the convective SRS induced by the strong flash of SBS **1**. The first three pulses are propagating out of the target while the last one propagates into the target because it comes from backscattering of the backscattered pulse. This SBS induced SRS contributes to saturation of the SBS reflectivity at higher intensities. It is observed also in Fig. 1 a) where the relative amplitude of reflectivity is lower for the highest intensity. The SBS induced SRS may also contribute to absorption of the laser pulse even if this is not very significant for the conditions of our simulations. The forward propagating SRS light has broader spectrum with the central frequency about $3/4\ \omega_0$ and it can thus propagate deeper into the target without being significantly influenced by parametric instabilities.

In this paper, we demonstrate that at high intensities ($\approx 10^{16}$ W/cm^2) SBS is suppressed by SRS accompanied by cavitation, which results in the absorption of about 70% of the laser energy on the longer time scale. The absorbed energy goes in particular into hot electrons with temperature of about 20-40 keV. The absorption coefficient and the hot electron temperature are independent of laser intensity in the studied domain. The reduced simulations indicate that 50% of absorption takes place at the quarter critical density, 38% due to the SRS which produces directional distribution of electrons with temperature about 35 keV and 12% due to cavitation which produces a more isotropic distribution of hot electrons with the temperature 30 keV. SBS may induce secondary SRS at higher intensities, which contributes to SBS saturation and absorption of the laser pulse.

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