Laser electron acceleration in the prepulse produced plasma corona

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Abstract. The generation of hot electrons at grazing incidence of a subpicosecond relativistic-intense laser pulse onto the plane solid target is analyzed for the parameters of the petawatt class laser systems. We study the preplasma formation on the surface of solid Al target produced by the laser prepulses with different time structure. For modeling of the preplasma dynamics we use a wide-range two-temperature hydrodynamic model. As a result of simulations, the preplasma expansion under the action of the laser prepulse and the plasma density profiles for different contrast ratios of the nanosecond pedestal are found. These density profiles were used as the initial density distributions in 3-D PIC simulations of electron acceleration by the main P-polarized laser pulse. Results of modeling demonstrate the substantial increase of the characteristic energy and number of accelerated electrons for the grazing incidence of a subpicosecond intense laser pulse in comparison with the laser–target interaction at normal incidence.

1. Introduction
For relativistic intensities of the main pulse, even high-contrast beams can produce plasma on the target surface due to a long nanosecond and picosecond prepulses action, which results in an early smearing of the target, and influences deeply to the main pulse interaction with target [1–3]. In this paper, the generation of hot electrons at grazing incidence of a subpicosecond intense laser pulse onto the plane solid target is analyzed for the parameters of the petawatt class laser system PHELIX [4] using 3-D PIC modeling [5] and the wide-range hydrodynamic modeling [6] of the preplasma expansion under the action of the laser prepulse.

For different laser systems the nanosecond prepulse (ASE pedestal) contrast can vary in a wide limits from $10^{-6}$ to $10^{-12}$ and higher when plasma mirror focusing is used. The normal ASE contrast is between $10^{-6}$ and $10^{-7}$, if no any special measures are used. The typical time structure of the petawatt class laser pulse is shown in figure 1 [7], where the pulse shape of the PHELIX laser is shown for different parameters of the contrast boosting module. For simulation of the laser-matter interaction at the nonrelativistic prepulse intensities, we have elaborated and used a two-temperature single-fluid radiation hydrodynamic model [3, 6]. This wide-range model describes the laser energy absorption, electron-ion coupling and two-temperature effects, radiation transport, thermodynamic properties of materials and ionization from normal conditions at room temperature to weakly non-ideal high-temperature plasma [8]. Using the model we have studied pump-probe experiments [6], double-pulse regimes [9] as well...
as the action of a nanosecond prepulse on thin films [2, 3] and annular-focused beams on bulk targets [10].

2. Preplasma formation under the action of different prepulse contrasts

While nanosecond ASE prepulse can be substantially reduced by different measures, the prepulse emission on the timescale of a few tens of picoseconds is present practically in any case (see figure 1). In our modeling of the plasma formation we analyzed first the bulk Al target heating by the picosecond prepulse only for the time interval $[-100, -5]$ ps, as shown in figure 2 for high contrast level $\sim 10^{-10}$ at time less than $-100$ ps (zero time moment corresponds to the maximum of the laser pulse intensity).

The electron and ion densities distributions at $t = -5$ ps are demonstrated in figure 3 for the P-polarized PHELIX laser pulse with the angle of incidence 80 degrees and maximum intensity $4 \times 10^{19}$ W/cm$^2$. For the electron densities less and about the reflection point ($n_{e,ref} \approx 0.03 \times n_{cr} \approx 0.03 \times 10^{21}$ cm$^{-3}$ for the angle of incidence 80 degrees) the density profile can be well approximated by the rarefaction wave exponent with characteristic scale length $L_r = 1.8 \mu$m. This exponential electron density profile of the prepulse produced plasma was used for modeling of the electron acceleration by the main picosecond laser pulse with high contrast nanosecond ASE pedestal (of the level $\lesssim 10^{-12}$ when its influence can be neglected and only picosecond prepulse can produce plasma before the main pulse action).

The influence of the nanosecond ASE pedestal of the level of $10^{-10}$ and one nanosecond duration for the same main laser pulse parameters, see figure 2 (P-polarization, angle of incidence 80 degrees and maximum intensity $4 \times 10^{19}$ W/cm$^2$) on the preplasma electron density distribution is shown in figure 4. In this case, for the electron densities less and about the reflection point ($n_{e,ref} \approx 0.03 \times n_{cr} \approx 0.03 \times 10^{21}$ cm$^{-3}$) the density profile can be well approximated by the rarefaction wave exponent with characteristic scale length $L_r = 3.6 \mu$m. These modeling results evidently show that even at rather high contrast laser pedestal of the order of $10^{-10}$ and one nanosecond duration, the characteristic scale length of the produced preplasma can be increased two times before the main short laser pulse action.

The exponential electron density profiles of the prepulse produced plasma with characteristic
scale lengths $L_r \sim 2-4 \, \mu\text{m}$ near reflection point were used for modeling of the electron acceleration by the main sub-picosecond laser pulse with different contrast levels of the nanosecond ASE pedestal.

3. Laser-plasma electron acceleration

The density profiles obtained by the wide-range hydro modeling of the preplasma expansion under the action of the laser prepulse were used in PIC simulations as the initial density distributions for the main P-polarized pulse interaction at the pulse duration 400 fs with the angle of incidence 80 degrees and maximum intensity $4 \times 10^{19} \, \text{W/cm}^2$. Figure 5 shows the energy spectra of accelerated electrons for the initial density scale lengths $L_r = 1.8 \, \mu\text{m}$ and $3.6 \, \mu\text{m}$, and also the spectrum with a hot temperature $T_h = 3.73 \, \text{MeV}$ predicted by the ponderomotive electron energy at pick laser intensity [11]. With an increase of the plasma density scale within a few micrometers the number of accelerated electrons drops for energies higher than 30 MeV. But this dependence takes place for the plasma density scales less than $10 \, \mu\text{m}$ only.

For longer preplasma density scales that can be produced by the nanosecond ASE pedestal of the laser pulse, the accelerating mechanism changes and the maximum energy of accelerated electrons growth up to 300 MeV for the density scale $L_r = 20 \, \mu\text{m}$ (at the expense of the number particles decrease in the energy range 50–100 MeV).

4. Conclusions

In conclusion, we have analyzed the influence of the laser prepulse time structure on the preplasma formation on the surface of solid Al target. Using the wide-range hydro modeling of the preplasma expansion under the action of the laser prepulse, the plasma density profiles for different contrast ratios of the nanosecond pedestal are found. Obtained results indicate the substantial increase of the characteristic energy and number of accelerated electrons for the grazing incidence of a subpicosecond intense laser pulse onto the plasma boundary (produced by the laser prepulse on a plane solid target) in comparison with the laser interaction at normal (not grazing) incidence.
Figure 5. Electron energy spectra for the initial density scale length $L_r = 1.8$ µm (solid line) and $L_r = 3.6$ µm (dashed line) for the main P-polarized (ppol) laser pulse. Dotted line shows the spectrum for a hot temperature $T_h = 3.73$ MeV predicted by the ponderomotive electron energy.

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