On ionization dynamics of metal targets irradiated by high-contrast relativistic-intense laser pulses

M E Povarnitsyn\textsuperscript{1}, O N Rosmej\textsuperscript{2} and N E Andreev\textsuperscript{1,3}

\textsuperscript{1} Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13
Bldg 2, Moscow 125412, Russia
\textsuperscript{2} GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, Darmstadt 64291,
Germany
\textsuperscript{3} Moscow Institute of Physics and Technology, Institutskiy Pereulok 9, Dolgoprudny, Moscow
Region 141700, Russia

E-mail: nikolay.e.andreev@gmail.com

Abstract. We perform simulation of irradiation of metal targets by high-contrast relativistic-intense laser pulses. The results of modeling show that the locally equilibrium mean charge of ions calculated with the aid of the Thomas–Fermi model is in good agreement with the model that considers time dependable collisional-radiative population kinetics of ground and excited states of ionized atoms. The main reason for this is a high density of plasma free electrons in the case of interaction of the high-contrast laser pulse with a step-like plasma density profile.

Recent experiments on interaction of relativistic laser pulses with targets of a step-like solid density profile, which is characteristic for high laser contrast, show the presence of highly charged ions of mid-Z elements such as Fe, Zn, Cu \cite{1}. In order to reach He- and H-like ionization states obtained in the experiments \cite{2} in a time below hundreds of femtosecond, both keV bulk plasma temperature and near solid electron plasma density are required. In this paper, we compare two approaches for simulation of the ion charge evolution in plasma caused by collisions with free plasma electrons.

In order to describe collisional heating of bulk electrons in the skin layer, pilot one-dimensional hydrodynamic (HD) simulations of the metal target dynamics beginning from room temperature up to the conditions of weakly coupled plasma were performed. In the simulations, we used a wide-range model \cite{3–7} with a two-temperature equation of state, a wide-range description of all transport and optical properties and took into account self-consistently the laser energy absorption in a target (Maxwell equations with a wide-range permittivity), ionization, electron and radiative heating, the pressure of electromagnetic wave and plasma expansion. It should be noted that a very high laser pulse contrast ensures a near solid step-like electron density in the skin layer, and thus, a strong reduction of the laser field in the absorption region that provides a nonrelativistic electron motion supposed in the modeling \cite{1}.

The HD simulations were performed for a Cu-target and laser pulse of 400 nm wavelength (second harmonics of a Ti:sapphire laser set-up), 45 fs pulse duration, p-polarization, 45° angle of incidence and peak intensity $2 \times 10^{19}$ W/cm\textsuperscript{2}. It was assumed that the target initially is the solid state matter at room temperature. Due to high laser contrast, in addition provided by conversion of the fundamental laser frequency, $\omega$, in $2\omega$, the energetic of the prepulse stays below the plasma generation threshold in metals until the rising edge of the laser pulse reaches
Figure 1. Electron temperature and target density dynamics at $z = -50$ and 100 nm.

the target at $t = -50$ fs ($t = 0$ corresponds to the peak of the laser intensity). The axis $z$ is normal to the target surface, and the target is initially located at $z \geqslant 0$. In figure 1 we show the dynamics of density and electron temperature changes in two cross sections: $z = -50$ and 100 nm.

For calculation of the mean charge of ions $\langle Z \rangle$ in plasma, we use two approaches: the Thomas–Fermi (TF) model [8] and multi-level kinetics. The TF model treats all electrons in the atom semi-classically, and hence is usually applied at very high pressures. Thermodynamic functions of electrons by the TF model satisfy the asymptotes of the ideal Boltzmann (at high temperatures and volumes) and the ideal Fermi (at low temperatures and volumes) gases. Hence this model can be considered as a wide-range one. However, apart from its region of applicability, the TF model gives significant distinctions in comparison with more sophisticated models. The second approach is realized in the code FLYCHK [9] was used to simulate level population kinetics of Cu-atoms in plasma and to provide a charge state distribution of Cu-ions in dependence on the electron density, the electron temperature and time. The history-files $(t, T_e(t), \rho(t))$ with evolution of electron temperature $T_e$ and target density $\rho$ for different target depths from $z = -50$ to 150 nm, were taken from the HD-simulations based on the wide-range model for every layer.

For simulations of the kinetics of the level population, a collisional-radiative model is used that considers collisional and radiative processes governing the population of the atom and ion ground and excited states in plasmas and presents the more general case compared to “Corona” and LTE [9]. Charge exchange processes such as ionization by collisions with free plasma electrons; photo- and auto ionization (Auger process), three-body, photo and dielectronic recombination are responsible for establishment of the ion charge state distribution characteristic for a given electron temperature and an electron density. In case of the non-stationary plasmas, the ion charge states distribution will depend not only on plasma parameters but as well on time.

The mean ion charge is calculated by summing up the normalized ground and excited states populations that belong to the ion with charge

$$
\langle Z \rangle = \frac{\sum_{k=1}^{Z_a} \sum_{j=1}^{N_L} k N_{kj}}{N_a},
$$

where $N_{kj}$ is the time dependent population of the level $j$ for ions with charge $k$, $Z_a$ is the atomic number and $N_L$ is the number of levels included in calculations, $N_a$ is the total number of atoms, see result in figure 2.
Figure 2. Comparison of the mean ion charge obtained via FLYCHK code (dashed red curves) and using TF model (solid black curves). Evolution of mean ion charge in different cross sections is presented: z = −100 (a), −50 (b), 0 (c), 50 (d), 100 (e) and 150 nm (f).

Although plasma created during short laser pulses is primarily transient, an extremely high electron density and correspondingly high rates of collisions governing the development of the ion charge and the population of the ion excited states allow for application of a quasi-stationary approach. The situation changes for lower electron densities, e.g. in a case where the laser pulse interacts with well-developed under-dense pre-plasma since the requirement on the plasma electron temperature demanded to reach highly ionized atomic states is strongly coupled to the $n_e \tau_p$ parameter, where $n_e$ is a plasma electron density and $\tau_p$ is the plasma life-time in a hot and dense state. For low $n_e \tau_p$, the charge state distribution of the ionized atoms will be far from those defined only by the electron temperature and density [10]. In this case, when the temperature rises, ions will be less ionized, showing up lower charge states than it would be expected for given plasma parameters, while in the recombination phase, when the temperature drops, the situation is opposite.

In conclusion, the results of modeling show that the locally equilibrium mean ion charge calculated with the aid of the TF model is in a good agreement with the model that considers time dependable collisional-radiative population kinetics of ground and excited states of ionized atoms. The main reason for this is a high density of plasma free electrons in the case of interaction of the high contrast laser pulse with a target of a step-like profile of the plasma density. For the
considered laser and plasma parameters, characteristic relaxation times of the kinetic governing the ion charge development are shorter than the evolution time of mean charge determined by the locally quasi-stationary approach by the TF model.

Acknowledgments
This work was supported by the Presidium RAS programs on the fundamental research.

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