

Field ionization in laser pulse interaction with thin foil

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As high contrast ratio becomes available for relativistically intense laser pulses, electron acceleration schemes using ultra-thin solid density targets start to be increasingly attractive for large electron current production. In such a scheme a foil is partially transparent to the laser, as the relativistic skin depth is of the order of somewhat exceeds the foil thickness and electrons can be pushed out of the foil in the forward direction very effectively.

When laser pulse propagates through semi-transparent foil the electrons from inner atom shells remain bound during the rise time of the laser pulse and these ions are further ionized at laser intensities near its maximum amplitude, which satisfies the best injection condition for subsequent acceleration of the released electrons [1]. We demonstrate this scenario by an example with parameters relevant to recent experiment on quasimonoenergetic electrons production from nanothickness diamond-like carbon (DLC) foil [2].

The 3D3V PIC code PICNIC was used for simulation of a linearly polarized laser pulse with a wavelength $\lambda=1.053 \mu\text{m}$ normally incident onto nano-sized DLC target. There is no preplasma at the target front side because a high intensity contrast ratio is assumed, for example, such as in Ref. [2] (5×10^{-10}). The normalized amplitude $a_0=eE_0/m_e c \omega_0$ of laser field E_0 (ω_0 is the laser frequency) is equal to 12.8 ($2 \times 10^{20} \text{ W/cm}^2$). The laser with $D=9.4 \mu\text{m}$ FWHM gaussian focal spot propagates in x-direction (the foil is at $x=0$). The pulse duration is $\tau=30 \text{ fs}$.

We performed simulations for 3 cases: (1) 5 nm carbon foil ionized due to field ionization (FI), (2) the same, but already ionized foil, i.e. the foil in the form of a plasma slab with average charge $\langle Z \rangle=3.4$; (3) 42 nm carbon foil with FI. In the cases 1 and 3 the initial state of atoms changes from the neutral to ionized one which charge is determined

by ionization dynamics for the given laser pulse parameters. The case 2 corresponds to typical PIC simulations ignoring the FI effect. Using $\langle Z \rangle = 3.4$ is imposed upon the averaged ion state corresponding to the case 1.

First we consider the 5 nm foil which is semi-transparent to incident light. In a standard PIC model a target is assumed to be a plasma with given average ionization state $\langle Z \rangle$. For the scenario 1, initially the laser pulse meets non ionized C-atoms. When laser intensity reaches the value which is enough to produce C^{+1} , the first of electrons is born. This happens at the very front of the laser pulse. The density of these electrons is low, much less than for the scenario 2, where a target is fully ionized up to high degree from the very beginning. Thus, deeper laser field penetration into a target takes place for the scenario 1. The electrons generated are trapped in the pulse and begin to accelerate. The next population of electrons appear when the laser intensity grows to a value which is enough to ionize C^{+1} , i.e. one after another groups of electrons appear from each atomic shell and are trapped in the laser pulse until its intensity is able to ionize C^{+5} (Fig. 1a). Being injected and trapped in the pulse, one group of electrons after another is accelerated in accordance with the scenario of Ref. [1]. For quasi-plane pulse propagation and negligible ion Coulomb attraction these groups of electrons could form peaked spectra. However, for real conditions due to close ionization potentials for outer ($Z \leq 4$) and inner ($Z = 5, 6$) atomic shells, the electron spectrum gets smeared and only the contribution of electrons after ionization of C^{+4} and C^{+5} form well pronounced peak (Fig. 1c, curve 1). Note, that for the 5 nm target about 60% of the electromagnetic energy transmits through it.

In the case 2, an incident pulse front pushes a lot of electrons which already are in a target. Their number is restricted by the ion Coulomb attraction. The laser field poorly penetrates into the foil due to the high electron density that uniquely corresponds to the starting plasma model. About 80% of incident electromagnetic energy is reflected, considerably more than in the case 1. The number of high-energy electrons is smaller. They are affected by the stronger charge separation field and have larger angle spread because of the field. The electron spectrum is shown in Fig. 1c (curve 2).

For the case 3 a thick target (42 nm) is non-transparent to the incident light and is not a good electron injector into the laser pulse. In this case the laser-foil interaction is qualitatively similar to numerous interactions with micron thick targets which have been

well studied since the 1990's. The resultant spectrum is of the Maxwellian like type (Fig. 1c, curve 3).

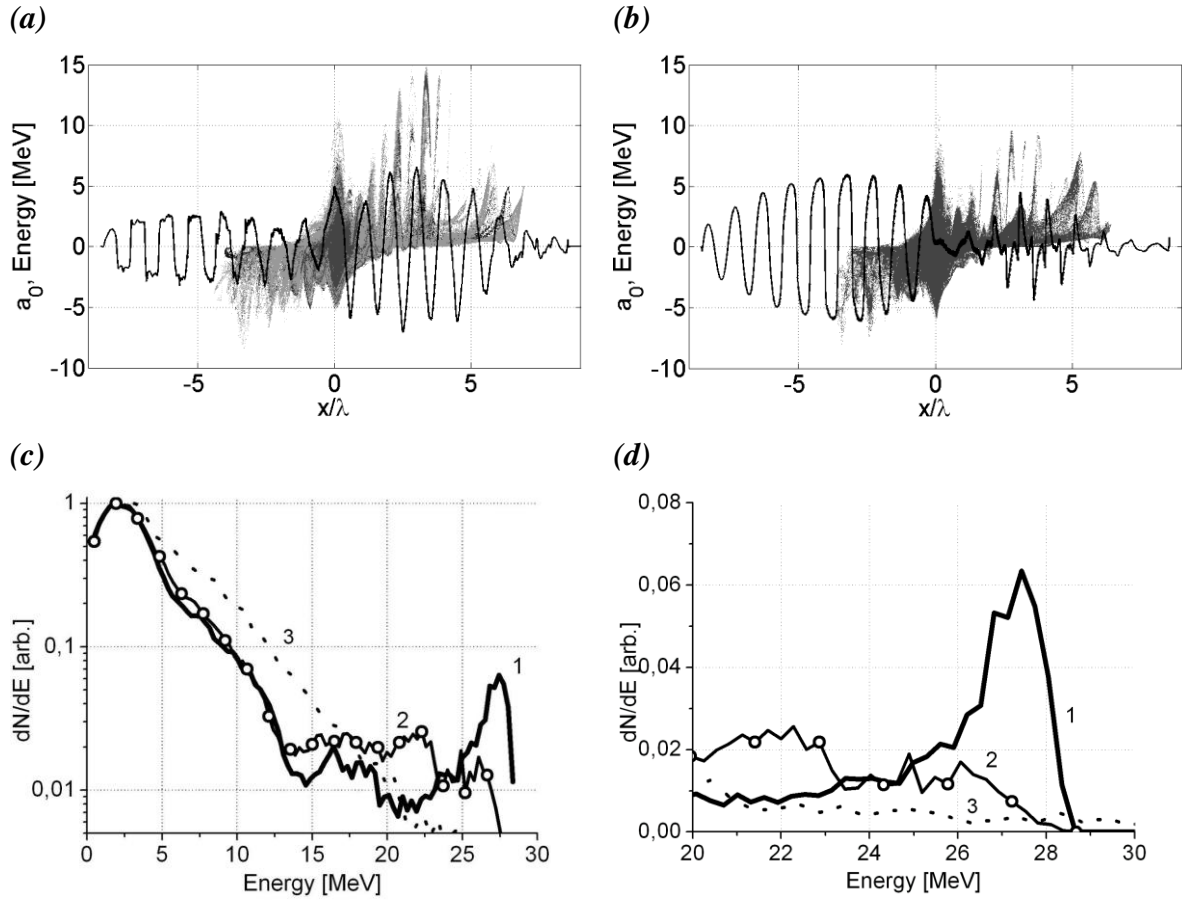


FIGURE 1. Phase diagrams (electron energy vs coordinate x) and dimensionless laser pulse amplitude for (a) case 1 and (b) case 2, and electron spectra (c) for the three cases under consideration shown by the curves 1, 2, and 3, and the corresponding high energy spectra (d).

Under the plane-wave approximation, a single electron, which is produced as a result of FI of an atom can be accelerated by the laser pulse up to energy $\sim mc^2 a_{th}^2/2$, where a_{th} is the threshold laser field for ionization from a given shell. To analyze how electrons from different shells accelerate, we considered two typical electron groups: nonrelativistic ones from the levels 1-4 ($a_{th} \sim 0.03$) which we will call group 1 and relativistic electrons from the levels 5-6, i.e. K-shell, ($a_{th} \sim 2$) which we will call group 2. All the electrons are born with zero energy, but they almost instantly are accelerated up to the velocity corresponding to local field amplitude a_{th} . In accordance with the above estimation, the maximum final electron energy is expected to be for the second group of electrons and equal ~ 1 MeV. However, for the focused laser pulse the plane-wave approximation is not valid and leads to a violation of adiabatic particle acceleration [3,4].

If laser amplitude a_R at the Rayleigh length (l_R) exceeds a_{th} the electron acquires higher energy, $\varepsilon_{max} \sim mc^2 a_R^2 / 2$, where a_R should be found from the relation [3] $l_a \sim l_R \sim D^2 / \lambda \sim 100 \mu m$, where l_a is the acceleration length, $l_a \sim c(\tau/2) a_R^2 / 2$. Correspondingly, one gets $\varepsilon_{max} \sim 4mc^2 D^2 / c\tau\lambda \sim 22 \text{ MeV}$, which is close to the observed maximum electron energy 28 MeV . By properly adjusting the pulse length to the Rayleigh length, in principle, electrons may reach energy as high as $mc^2 a_0^2 / 2 \sim 36 \text{ MeV}$.

Electrons could also acquire the same maximum energy in the case 2. However, their initial space-energy spread is unfavorable for quasi-monoenergetic bunch production that occurs for the electrons of the group 2 in the case 1 (cf. Fig.1c). Similarly, the electrons of the group 1 being initially widely distributed due to the spread in a_{th} for different atomic levels do not form a spectrum with a monoenergetic feature.

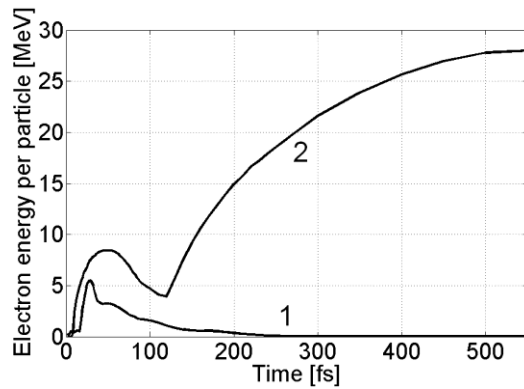


FIGURE 2. (a) Electron energy evolution for representative particles of groups 1 and 2

The electron energy evolution for representative particles of the groups 1 and 2 is shown in Fig. 2. Electrons from the outer atomic levels appear first with low energy and are affected strongly by the ion attraction field which prevents them from getting high energy from the laser pulse. Most of them oscillate near the target and only a small number leave the foil with the laser pulse. Electrons

from the inner levels appear some time later but quickly overtake these low energy electrons which shield them from the decelerating Coulomb attraction. A significant number of the electrons from inner shells travel with the pulse and acquire the energy close to the maximum $\sim mc^2 a_0^2 / 2$ (28 MeV), while the electrons of the group 1 get considerably less energy (5 MeV).

This work was partly supported by the Russian Foundation for Basic Research.

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