CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Nuclear Sciences and Physical Engineering
Department of Physical Electronics

Ondřej Klimo

SIMULATIONS OF ULTRASHORT-PULSE LASER SOLID-TARGET INTERACTIONS

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Ondřej Klimo

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Uchazeč: Ing. Ondřej Klimo
Katedra fyzikální elektroniky
FJFI, ČVUT v Praze
Břehová 7, Praha 1, 115 19

Školitel: Prof. Ing. Jiří Limpouch, CSc.
Katedra fyzikální elektroniky
FJFI, ČVUT v Praze
Břehová 7, Praha 1, 115 19

Oponenti: RNDr. Karel Rohlena, CSc.
Oddělení plynových laserů / Centrum PALS
Fyzikální ústav Akademie věd České Republiky
Na Slovance 2, Praha 8, 182 21

Ing. Václav Petržílka, DrSc.
Ústav fyziky plazmatu Akademie věd České Republiky
Za Slovankou 3, Praha 8, 182 00

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Doc. Ing. Richard Liska, CSc.
předseda oborové rady
Fakulta jaderná a fyzikálně inženýrská ČVUT,
Břehová 7, Praha 1

Contents

1 Introduction - state of the art

During the few past decades generation of ultrashort intense laser pulses became possible with the advent of techniques that enable locking of laser modes in the resonant cavity [8] and amplifying of chirped laser pulses [29]. State of the art Ti:Sapphire laboratory laser systems are able to deliver to the target several milijoules of energy in a pulse as short as several tens of femtoseconds and with repetition rate reaching even kHz [1]. On the other hand the peak power of the large scale factory hall laser systems may exceed even petawatt [24].

The interaction of ultrashort intense laser pulses with solid targets results in rapid formation of plasma and under certain conditions coupling efficiency of laser energy into the target is very high, of order of tens of percents. Short pulse laser irradiated solid targets are characterized by rapid rise of energy density and they may serve as sources of beams of energetic particles (electrons, ions, photons) with unique properties and applications in various fields of science, technology, etc. [11, 27, 31, 6].

Even if most of the physics of laser plasma interaction is described by four Maxwell's equations and the Lorentz force equation, these equations are very difficult to solve for realistic problems. Laser plasma is often rapidly evolving, highly nonlinear, and even unstable. Thus theoretical models describing the interaction can often be solved only numerically. There are two principal types of theoretical models which describe temporal evolution of plasma. Models of the first type are called kinetic and they treat plasma as an ensamble of charged particles. The governing equation of kinetic theory, Vlasov equation, states the temporal evolution of charged particle distribution functions in macroscopic electric and magnetic fields. In the second type of theoretical models plasma is considered as fluid. Equations of the fluid model are derived from the kinetic plasma theory by taking the moments of Vlasov equation with the Boltzmann-Maxwell velocity distributions of particles assumed. In the fluid model plasma is in a local kinetic equilibrium.

In ultrashort pulse laser plasma interactions the assumption of local kinetic equilibrium is often violated and kinetic description of plasma must be applied. Numerical solution of the Vlasov-Maxwell system of equations is dominated by simulation codes based on the Particle-in-Cell method. The PIC code used throughout the thesis evolved from the code LPIC++ [18] originally developed in the Max-Planck Institute für Quantenoptik in Garching. This code is relativistic, electromagnetic, one-dimensional in space and three-dimensional in velocity. The code LPIC++ was previously modified in the frame of two master theses and enhanced to treat binary Coulomb collisions [3, 7].

2 Aims and contributions of the thesis

The presented thesis aims to study ultrashort intense laser pulse interactions with solid targets. During these interactions laser energy coupling into a small population of very hot electrons is often efficient. The phenomena related with acceleration of hot electrons and their transport inside the target are of fundamental importance for many applications []. For these reasons our investigation concentrates particularly on the population of hot electrons, parameters characterizing this population and processes leading to its formation. Transport of hot electron beam further inside the target and the related phenomena including target ionization, induction of self-consistent fields, rise of the neutralizing return current and ion acceleration at the rear surface of a foil target are studied as well.

2.1 Modifications of the PIC code

Simulation with numerical code based on the Particle-in-Cell (PIC) method are utilized to treat short pulse laser plasma interaction. In the frame of the thesis the PIC code LPIC++ has been modified and its applicability has been extended by the addition of new physical processes and some functionality options.

- **Variable plasma ionization has been implemented.**
  In the interactions of ultrashort intense laser pulses with targets the ionization process is often very fast. The average ion charge may increase even several times during the interaction and therefore incorporating variable plasma ionization into the theoretical description is indeed important. Two plasma ionization processes are the most important in this context, the collisional ionization, and the ionization induced by the optical and the plasma electric fields. The former one operates efficiently in the dense matter inside the target while the later is

dominant in the underdense plasma where the laser pulse propagates. The algorithm of plasma ionization implemented into the code LPIC++ accounts for both these ionization processes. PIC codes suitable for simulations of short pulse laser target interaction with variable plasma ionization are computationally expensive and also relatively rare [12, 36]. In this respect our code is a rather unique tool at this moment.

- **Binary collisional algorithm has been revised.**
  The algorithm of binary collisions previously implemented into the code LPIC++ [7] is based on a relatively obsolete method with limited applicability. To be applicable to certain simulations of hot electron transport in a cold solid density dielectric target binary collisional algorithm had to be revised. The newly implemented computational procedure is valid over larger range of collisional frequencies and takes into account elastic scattering of electrons from neutral atoms as well.

- **Target may consist of multiple species of ions/atoms.**
  To make the code LPIC++ more realistic and produce results in a better agreement with experiments the code has been extended to treat targets composed of multiple elements. This enhancement is of particular importance for targets consisting of multiple layer from different materials or for the case when the target material is already a compound of several elements, e.g. water, polyethylene etc. Multiple ion species constitution of the target manifest itself especially in the calculations of ion acceleration where the ion charge to mass ratios of is very important.

2.2 Applications of the adapted code

The adapted PIC code has been applied to study especially those issues where its new properties could be beneficially utilized. Namely, the following problems are studied:

- Acceleration of hot electrons in the interactions of ultrashort subrelativistic laser pulses with solid targets and the impact of variable plasma ionization on the efficiency of this acceleration process.

- The angular distribution of hot electrons accelerated during the interactions of ultrashort relativistic laser pulses with solid targets and the influence of variable plasma ionization on this angular distribution.

- Propagation of the high-current relativistic electron beam in cold solid density dielectric material where the free electrons provided by the target ionization form a highly collisional return current.

- Ion acceleration by the self-consistent electric field produced by the hot electron cloud at the rear surface of thin foil targets irradiated by ultrashort high intensity laser pulses.

3 Applied methods

In short high intensity laser pulse interactions with solid targets the field of the laser wave is usually very strong while the Coulomb collision period is much longer than both the laser and the plasma periods. The appropriate model handling the main physical aspects of the interaction cannot assume kinetic equilibrium with Maxwellian distributions of charged particles but on the contrary it must include the temporal evolution of these distributions self-consistently. The temporal evolution of particle distributions is described by the kinetic theory which yields the Vlasov equation in the case of collisionless plasma. Vlasov equation is often solved numerically using the PIC method.

3.1 PIC method

Plasma is in fact a huge ensemble of charged particles, electrons, and ions that interact with each other due to self-consistently induced electric and magnetic fields. PIC methods treat plasma right this way with two exceptions. The number of charged particles is cut down by many orders of magnitude and the self-induced fields are discretized on a grid.

It is assumed in the PIC method that real charged particles are locked together in clouds and the number of particles is thus reduced to the number of clouds, macroparticles. The virtual macroparticles have a given fixed spatial distribution and a single velocity. This

'Particle' aspects of the method is connected with the representation of the particle distributions contained in the Vlasov equation.

The second, 'In-Cell' aspect of the method is connected with Maxwell equations, i.e. electric and magnetic fields and charge and current densities. The non-collective interactions are screened on the distance of order of Debye length in plasma. In the PIC method the binary interactions between particles separated by less than the Debye length are neglected and only the collective interactions are taken into account. Thus the fields are not evaluated directly for individual particle but they are calculated on a spatial grid and interpolated on particle position.

The PIC model is separated into two parts, the particle-mover and field-solver. The particle-mover part uses the known fields discretized on the grid to calculate charged particle acceleration according to the Lorentz force and to advance particle positions according to their new velocities. Afterwards charge and current densities are deposited back onto the grid and the field-solver part advances the electric and magnetic field according to the Maxwell's equations. Additional physical processes like elastic binary collisions or ionization are usually calculated at the end of the particle-mover part.

3.2 The code LPIC++ and its modifications

The simulation code LPIC++ [18] used in the thesis was developed in Max-Planck Institute für Quantenoptik in Berlin. It is electromagnetic, relativistic, one-dimensional in space and three-dimensional in velocity. Oblique incidence of the laser wave onto the target is enabled using a boost frame transformation [4]. The code was previously modified in the frame of two master theses [3, 7]. Binary Coulomb collisions were implemented using the Takizuka-Abe Monte Carlo approach [32] and the collisional algorithm was corrected to treat collisions of electrons with relativistic velocities correctly. The option of exponential plasma density profile on the target surface was added to enable start of the calculations with more realistic initial conditions given by the isothermal model of free expanding plasma. Option of absorbing boundary condition for fast electrons was also added.

The main objective of the thesis has been to modify the code LPIC++ to treat some additional physical processes and to utilize the adapted code for laser solid target interaction studies. Of our particular interest is the influence of variable plasma ionization (due to both the electric fields and the inelastic collisions) on the dynamics of laser plasma interaction. The code has also been modified to treat several different species of ions and the collisional algorithm has been revised.

3.2.1 Electric field ionization

The binding potential of ion is perturbed significantly by the potential of the external electric field when the field is very strong. The effective potential, which the outermost bound electron feels, is sum of the Coulomb potential of the ionic core screened by other bound electrons and the instantaneous electric potential of the laser or the plasma field. This effective potential shows a barrier through which electron may escape, tunnel. Tunneling ionization is the dominant electric field ionization process in the interactions of short high intensity laser pulse with solid targets.

In our PIC code tunneling ionization process has been implemented using a Monte Carlo approach similarly like in [12]. Currently, we use the ADK tunneling ionization rate [2] (for s shell electrons) to calculate ionization probability due to the local electric field which is the sum of the field of the laser wave and the plasma field. If ionization takes place new electron is injected into the simulation box on the same place as his parent ion and it is initiated with the same velocity as is the velocity of ion. To guarantee energy conservation energy spent for ionization is subtracted from the field by introducing a local artificial ionization current [21]. Before the ionization takes place we ensure that the field has still enough energy to ionize another ion and if not, the ionization process is suppressed.

3.2.2 Collisional ionization

Tunneling ionization is efficient when electric field is high. This is mostly in the lower density plasma in the laser target interaction region. In a dense plasma deeper inside the target one can expect in most cases that the electric field ionization rate is relatively low due to plasma screening effect [26]. The dominant ionization mechanism is then associated with inelastic collisions of free electrons with ions.

The collisional ionization is implemented into the code using a Monte Carlo approach too. The algorithm is local and energy conserving and it is simplified for computational reasons. We assume the collisional ionization process as advancing shell by shell from the outermost shell. The probability that electron ionizes an ion during each time step is calculated using the collisional ionization frequency which depends on the velocity of electron, density of ions and the cross section for electron impact ionization. This cross section is calculated using either the Lotz formula [19] or the binary encounter Bethe model [13].

The probability of collisional ionization is sampled for all free electrons in all simulation cells. When collisional ionization takes place an ion is randomly selected in the same cell as the ionizing electron and its charge and mass are correspondingly adjusted. A new electron is than injected into the simulation box on the corresponding place and initialized with the same velocity as its parent ion. The energy spent on ionization is subtracted form energy of the ionizing electron so that its propagation direction does not change.

3.2.3 Elastic collisions

Strongly heated plasmas like those produced during short-pulse laser irradiation of targets are far from kinetic equilibrium. Nevertheless, plasma always tends to reestablish this equilibrium and the driving force for this thermalization process is due to elastic collisions. In the PIC method only the macroscopic part of the electromagnetic field which stands in the Lorentz force equation is taken into account. The field on the scale length shorter than the Debye length is usually accounted for in a separate collisional part of the algorithm.

In our PIC code elastic collisions were treated using a binary Monte Carlo approach [32] which is local and energy conserving. The collisional model proposed in [22] is quite similar but seems to be less restrictive than the one which was implemented into the code previously. Moreover, the most part of this new model is suitable for either Coulomb or elastic electron-atom collisions. Therefore, the collisional algorithm has been revised in the frame of this thesis according to the newly proposed method [22].

Coulomb collisions take place every time step for every particle of the species for which collisions are not neglected. In these collisions, the scattering angles are randomly sampled from the distribution given in [22]. On the other hand elastic electron-atom scattering takes place only with a given probability which depends on the collisional frequency. Thus the Monte Carlo algorithm implemented for these collisions is similar to the one used for collisional ionization. The collisional frequency is calculated from the total cross section for elastic electron scattering taken from the tables [20] and the scattering angles are sampled from the distributions given in [30].

4 Results

The impact of variable plasma ionization on the energy and angular distributions of laser accelerated hot electrons, the transport of a high-current hot electron beam in a solid density dielectric target and the acceleration of ions from the rear surface of laser irradiated thin foil targets have been studied in the frame of the presented thesis.

4.1 Energy distribution of hot electrons

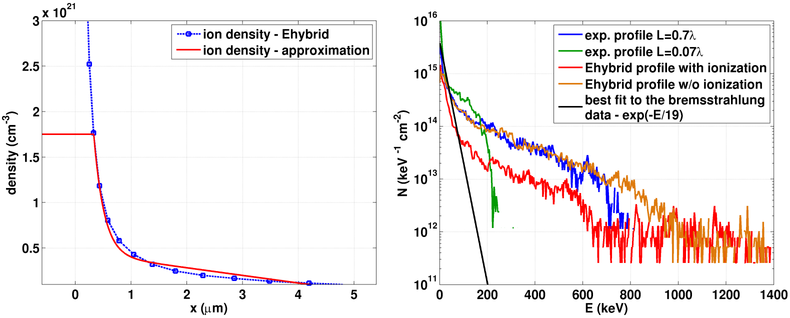
We have investigated K-α emission from short pulse laser irradiated thin foil targets in accordance with experiments carried out in the Max Born Institute in Berlin by the group of Dr. Zhavoronkov [34]. The laser system used in the experiment delivered 5 mJ, 45 fs long p-polarized laser pulses with the wavelength $\lambda = 800$ nm. The pulses were focused into about 7 μm spot on the surface of $10 - 40$ μm thick metallic foils at an angle 20° and the resulting peak intensity on target was about 10^{17} W/cm^2. The angle of incidence 20° was chosen to maximize the resulting K-α emission yield. In addition to the main laser pulse the system produced also an intrinsic laser prepulse located about 5.5 ps ahead the main pulse and several nanosecond long amplified spontaneous emission (ASE) with the intensity contrast ratios of 10^{-5} and 10^{-7} respectively.

We have employed the adapted PIC code as well as 1.5-dimensional atomic/hydrodynamic code Ehybrid [25] and the Monte Carlo (MC) code [14] to simulate this experiment. The code Ehybrid has been utilized to calculate absorption of laser prepulses and to describe the preplasma formed on the target surface before the impact of the main laser pulse. The PIC code with variable plasma ionization has been applied to calculate absorption of the main laser pulse and acceleration of hot electrons. PIC simulations have been performed with either exponential plasma density profiles with various characteristic lengths L or with the profile resulting from the code Ehybrid. In PIC simulations the hot electrons that escape from the rear side of the simulation box are recorded and substituted by thermal ones. Hot electrons are subsequently postprocessed by the MC electron transport code which was developed specially for this purpose in [14].

Exponential preplasma density profile which results from the isothermal model of free expanding plasma is widely used in the initial conditions of PIC simulation. However, the K-α yield calculated for exponential plasma density profile is about 9× higher than the experimental one for the density scale length $L = 0.7\lambda$, which is theoretically optimal for laser absorption under the conditions of the experiment. Calculated K-α yield continuously decreases with L, but even for unrealistically steep plasma density profile it is still several times higher than in the experiment. The preplasma density profile calculated by the code Ehybrid for irradiation of the target by 1 ns ASE prepulse with constant intensity 10^{10} W/cm^2 is however not only exponential. It is nearly exponential around the critical surface but the density is decreasing almost linearly in the undercritical part as can be seen in figure 1 a). This density profile is referred to as 'Ehybrid' in the following.

In the PIC simulation where the Ehybrid density profile is used we have found that the efficiency of the laser absorption and hot electron acceleration process drops down dramatically. This can be seen in the energy distribution of hot electrons plotted in figure 1 b). We have performed the same simulation with constant plasma ionization and we have found that the decrease in the hot electron acceleration efficiency is due to the optical field ionization process taking place in the undercritical plasma.

The dominant laser absorption and electron acceleration process is due to the resonant coupling of the laser field to an electron plasma wave at the critical surface for the conditions of the experiment and our simulations. However, rapid ionization in the first half of the laser pulse causes that both the laser reflection point and the critical surface are shifted toward vacuum in the case of Ehybrid density profile. The resonant field is attenuated during the phase of ionization and only a minority of electrons are accelerated. After the laser pulse maximum the processes of ionization and shifting of the critical surface turn off and a stable resonant field rises at the new critical surface. Similar situation is observed for exponential density profiles as well. However, in this case the density in the undercritical part of the density profile drops down more quickly and the effect of ionization is of minor importance unless the density profile is unrealistically long ($L \gg \lambda$).



(a) Preplasma density profile (b) Hot electron energy distributions

Figure 1: The preplasma density profile calculated by the Ehybrid code for irradiation of the target with 1 ns long Ti:Sapphire laser prepulse with intensity 10^{10} W/cm^2 in plotted in panel a). Approximation of this density profile further used in PIC simulations is included. Energy distribution of hot electrons accelerated in PIC simulations with and without variable plasma ionization and with several different density profiles are presented in panel b). Copper target is irradiated by 45 fs p-polarized obliquely incident (25°) laser pulse with wavelength 800 nm and intensity 10^{17} W/cm^2. In PIC simulations either exponential plasma density profile or the profile plotted in panel a) is used. Hot electron energy distribution deduced from bremsstrahlung measurement is included.

K-α emission yields calculated with the hot electron distribution resulting from PIC simulations with Ehybrid density profile and variable plasma ionization are in a reasonable agreement with the experiment. Moreover, the hot electron energy distribution deduced from the measurements of bremsstrahlung radiation (limited by the effective range of the detector to photon energy below 150 keV) is in a reasonable agreement only with the energy distribution of hot electrons calculated by the PIC code with variable plasma ionization for the Ehybrid density profile.

In consequence, our simulations predict that resonance absorption can be temporally suppressed by the ionization process in the undercritical plasma in front of the target. The transformation of laser energy into K-α emission could be more efficient if the ASE prepulse level would be minimized so that formation of a long undercritical preplasma profile is avoided. The results of our simulations and their comparison with experimental data have been published in [15, 35].

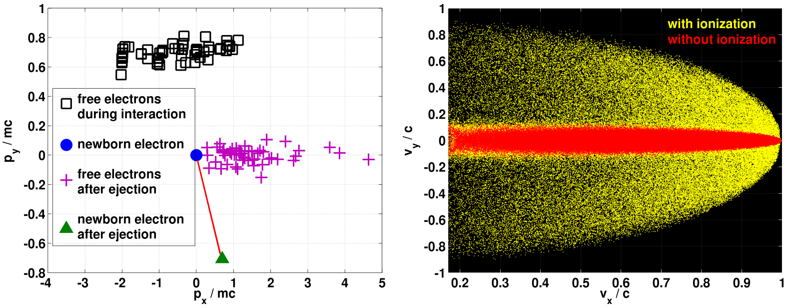
4.2 Angular distribution of hot electrons

Electron acceleration is not only due to resonance absorption or vacuum heating but also due to relativistic ponderomotive force and probably also due to other processes, e.g. Raman scattering, stochastic acceleration, in the case of relativistic laser pulse intensity. The influence of ionization on hot electron energy distribution is therefore weaker. Nevertheless, we demonstrate that ionization may have a significant effect on the hot electron angular distribution. Namely, a part of hot electrons released by electric field ionization around the laser pulse maximum propagate in directions which are forbidden if ionization is not taken into account in the simulation.

In the PIC simulations we have assume that preplasma on the target surface has an exponential density profile with scale length of 4λ and the initial ion charge is 3. Aluminum and titanium have been selected as two representative and widely used target materials and the simulations have been performed with about 50 fs long laser pulse with the peak intensity of about 10^{19} W/cm^2 and wavelength $\lambda = 800$ nm. The laser wave is incident normally or obliquely and the polarization is either linearly or circular.

In the case of normal laser incidence electrons are accelerated particularly due to the ponderomotive force and they are ejected from the interaction region perpendicularly to the target surface. The initial ion charge is relatively low and the electric field of the laser wave is strong. Therefore, the number of free electrons in the undercritical plasma increases due to optical field ionization several times during the interaction. Electrons from the outer shells are released during the first cycles of the laser wave. They are set free in the electric field maxima of the laser wave cycles, where the other already free electrons have nearly zero velocity. Therefore, the newly released electrons behave like, if they were free already initially.

The same situation does not apply to electrons released mostly from the inner shells later during the interaction near the laser pulse maximum. Due to nonlinear effects in the laser interaction with the dense plasma close to the target surface (e.g. harmonic generation, etc.) the forward propagating and the reflected laser wave build up



(a) Newborn electron out of phase (b) Velocity phase space of electrons

Figure 2: Electron momentum phase space in a simulation cells in the undercritical plasma is demonstrated in panel a). In this time a new electron is just released by optical field ionization. Final momentum of the accelerated electrons is included for illustration. The data are taken from PIC simulation with variable ionization for titanium target (normal incidence, linear polarization, $\lambda = 800$ nm, $I = 7 \times 10^{18}$ W/cm^2, $\tau = 65$ fs). The velocity phase space of accelerated electrons is presented in panel b).

an anharmonic field in front of the target. In this field, free electrons have a considerable transversal velocity in the electric field maxima and the new electrons are released in this time find themselves on a different place in the velocity phase space. This situation is demonstrated in the snapshot of the momentum phase in one simulation cell in figure 2 a).

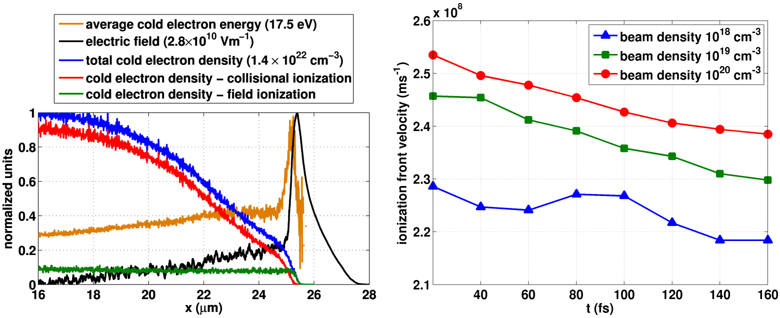
Our theory demonstrates that the newborn electrons, which are significantly displaced in the momentum phase space from other free electrons, preserve some given momentum parallel to the target surface and upon acceleration by the laser field their angle of ejection from the interaction region is significantly different from the ejection angle of the initially free electrons. The velocity distribution of hot electrons accelerated in PIC simulation into the titanium target is plotted in figure 2 b). Electrons are accelerated only in the direction normal to the target surface in simulation with constant ionization. On the other hand, there are also many electrons with different ejection angles in the case of variable ionization. The ejection angles of some electrons almost reach $\pm\pi/2$ and these electrons propagate essentially along the target surface. The pattern of accelerated electrons is symmetrical in the laser polarization plane around $v_y = 0$ (v_y being the component of velocity along the target surface). It is important to take into account that the 'yellow' electrons are covered by the red ones so there are also many 'yellow' electrons propagating normally to the target surface in figure 2 b).

The above presented effect applies particularly to relativistic laser pulses and in the thesis it has been demonstrated that it strongly depends on the target material, laser wave polarization and angle of laser incidence. We find a significant effect of variable plasma ionization on the divergence of laser accelerated hot electron beam for particular target materials and laser irradiation conditions. Certain preliminary results of this work have been presented at the international conference (EPS 2006) and the entire work is being prepared for submission to an international journal.

4.3 Propagation of hot electrons inside the target

The propagation of an electron beam with a high current density inside the target is possible if its space-charge and current are neutralized. This phenomenon is not well understood, especially in dielectric targets. We have studied the propagation of a high current density ($4 - 400$ GA/cm^2) electron beam produced by a 40 fs laser pulse in a plastic target using our PIC code which includes both, ionization of neutral atoms (C and H) and collisions of newborn electrons. The initial velocity distribution of beam electrons has been uniform between 0.7 and 0.9 speed of light in the propagation direction. The density of the beam is also uniform and it has been varied in the range $10^{18} - 10^{20}$ cm^{-3}.

When the head of the beam enters the plastic target, the electric field grows rapidly in consequence of the electron charge accumulation and it starts to ionize atoms. In the maximum of the field, which does not exceed 10% of the atomic field, the density of newborn electrons is two orders of magnitude higher than the beam density, which is sufficient for the current neutralization. Cold electrons are accelerated by the field and heated, until they acquire enough energy for an efficient collisional ionization. Then, the avalanche ionization starts and the further increase of the cold electron density reduces plasma resistivity and the current in the tail of the electron beam is neutralized relatively easily. The electric field inside the beam



(a) The ionization process

(b) Ionization front velocity

Figure 3: The ionization process in PIC simulation is demonstrated in panel a). The 8 μm long electron beam with the density 10^{19} cm^{-3} propagates (from the left) inside the plastic target, which begins at 8 μm. Curves are normalized to the maximum values (see legend). The green and the red curves demonstate the fraction of electrons produced by the field and the collisional ionizations respectively. Temporal evolution of the propagation velocity of the ionization front is shown in panel b). This velocity is calculated from the positions of the field maxima in two adjacent times.

is an order of magnitude lower than in the ionization front and it drops to zero behind the beam. The ionization processes and the self-consistent electric field are demonstrated in figure 3 a).

The amplitude and the structure of the electric field in the ionization front depend on the beam density. This dependence implies two important consequences. The velocity of the ionization front decreases with the beam density and the dissipation of the beam energy is stronger for the beam with lower density. The dependence of front velocity on the beam density, which is presented in figure 3 b), is particularly important, as it may provoke development of the ionization instability [17].

Our most important conclusions are that the current neutralization is established in the ionization front, where initial population of plasma electrons is produced and accelerated toward the beam. Through collisional ionization, the density of plasma electrons behind the beam head, and the conductivity of plasma are increased several times. The self-consistent electric field in the beam head, which depends on the beam current density, plays an important role in the fast electron transport, as it defines the beam propagation velocity. On a longer distance, the propagation of a relatively short electron beam is significantly influenced by the beam energy dissipation. For higher beam densities, the dissipation may be enhanced by the two-stream instability in the beam tail.

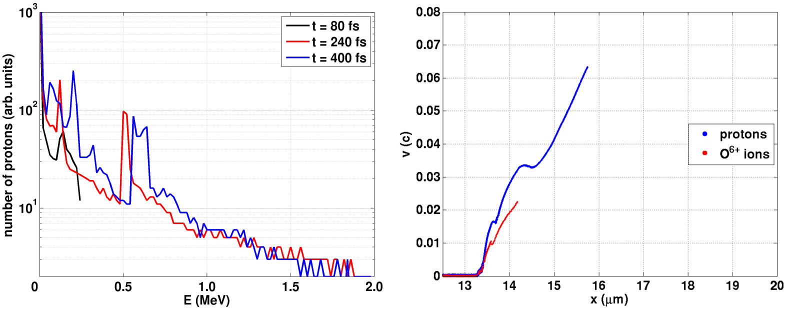
Simulations of high-current hot electron beam propagation in cold dielectric target have been performed in collaboration with Prof. Tikhonchuk and PhD student Debayle from University of Bordeaux. Our colleagues from Bordeaux have developed analytical theory covering hot electron beam propagation. Presented numerical simulations are complementary with their theory and a good agreement between both models has been demonstrated in our joint publication [16]. The results have also been presented at several international conferences in both poster and oral forms.

4.4 Acceleration of ions from the rear surface of thin foil target (TNSA)

The hot electron beam may penetrate almost freely through a thin foil. The vast majority of hot electrons arrive to the rear foil surface wherefrom they are emitted into vacuum. As a consequence, strong electric field builds up between the negatively charged hot electron cloud in the vacuum and the positively charged target. The amplitude of this field can be very high and its duration is also considerably long. Therefore, this field accelerates ions very efficiently.

In the most of experimental and theoretical works devoted to ion acceleration from the rear surface of laser irradiated foils much attention is paid to find the conditions for acceleration of ions to highest possible energy e.g. [23, 10]. However, energy distribution of accelerated ions is of at least the same importance from the application point of view [9]. As the target contains fraction of hydrogen atoms and possibly some other species either in a thin contamination layer on the surface or in the whole volume, the process of ion acceleration mostly involves multiple ion species where the 'heavy' ions serve to maintain the field in which the 'light' ions are accelerated. This offers some possibility to control the energy distribution of light ions and particularly to produce quasi-monoenergetic light ion beams.

Our PIC simulations are particularly intended to study the sit-



(a) Energy distribution of protons (b) Phase space of accelerated ions

Figure 4: Temporal evolution of the proton energy distribution taken from PIC simulation of laser interaction with water droplet is presented in panel a). Time is measured with respect to the end of the laser target interaction. Only protons behind the initial target surface are included. The phase space of accelerated protons and oxygen ions in the time 240 fs is plotted in panel b). Velocity of ions is normalized to the velocity of light.

uation of experiment with laser irradiated (heavy) water droplets performed in Max-Born Institute in Berlin [33]. In this experiment Ti:Sapphire laser delivering energy of about 750 mJ in a 40 fs long laser pulse was focused on water droplets with 20 μm in diameter. The main laser pulse intensity on targets was estimated to about 10^{19} W/cm^2. In many shots, the distribution of protons or deuterons accelerated in the laser propagation direction exhibited a quasi-monoenergetic structure.

In fact, the light ion acceleration process consists of several stages which are demonstrated on the temporal evolution of proton energy distribution in figure 4 a). Light ions are much more mobile than the heavy ones initially, and since all of them are crossing the steep plasma edge on the rear surface, they acquire approximately the same energy and form the first quasi-monoenergetic peak. This first quasi-monoenergetic peak is however not stable in our simulations. Since the Debye length of hot electrons is relatively long in comparison with the dimensions of the monoenergetic bunch of light ions, these ions experience a strong Coulomb repulsion due to non-neutralized positive charge. Together with the persisting ion acceleration process the repulsion destroys the monoenergetic spectrum on a relatively short time scale. Nevertheless, light ion acceleration process continues and the different motion of light and heavy ions results in a spatial separation of both species and in the formation of the electrostatic shock. As a consequence, a plateau is formed in the phase space of light ions (see figure 4 b) and a new quasi-monoenergetic peak appears in their energy distribution. As light ions with the same energy are now distributed over a larger volume and the bunch is less dense the charge is better neutralized and the quasi-monoenergetic bunch survives much longer time. Due to continuous Coulomb repulsion a double-energy spectrum may be formed in the distribution of light ions. However, cooling of hot electrons already prevents further acceleration and it suppresses significant Coulomb explosion of the bunch.

Explanation of the mechanism leading to the peak formation has been found by Dr. Brantov and Prof. Tikhonchuk and confirmed also in our PIC simulations with variable ionization. Several distinct mechanisms of formation of quasi-monoenergetic distribution of light ions have been identified and described. Particularly, it has been demonstrated that fast heavy ions push forward the light ions and shape their energy distribution. Central energy of the peak in the distribution of light ions is fully determined by the heavy ions and their ionization state. The above described mechanism is efficient in the case of both homogeneous and heterogeneous targets and we believe that it is able to explain the quasi-monoenergetic spectrum of light ions observed in experiments [9, 28, 33]. This work resulted in a joint publication [5] with our colleagues from Bordeaux and the experimental group from the Max Born Institute in Berlin.

5 Outputs and contributions of the thesis

The main contributions of the thesis to the problematics of short high intensity laser pulse interactions with solid targets and computer simulations of these interactions are listed below:

- Detailed review of the theory of electric field ionization, collisional ionization and elastic collisions in plasma.
- Development of algorithm for PIC simulations with variable plasma ionization and its implementation into the code LPIC++. Detailed description of the algorithm may serve as a 'cookbook' for extension of other Particle-in-Cell simulation codes.

- Reconsideration of the algorithm for elastic collisions and implementation of a new version with extended range of applicability.
- Application of the adapted code for investigation of a wide range of short pulse laser solid target interaction aspects including:
  - Acceleration of hot electrons in the laser target interaction region
  - Propagation of hot electron beam inside the target
  - Acceleration of ions from the rear side of laser irradiated foil target

6 Conclusions

In the thesis "Simulations of Ultrashort-Pulse Laser Solid-Target Interactions", numerical simulations based on the Particle-in-Cell method are applied to study interactions of ultrashort high intensity laser pulses with solid density targets and the phenomena closely related to this interaction. The Particle-in-Cell code used in this thesis has been enhanced by including additional physical processes relevant in the context of short pulse laser solid target interaction. Namely, electric field and collisional ionization have been implemented and the algorithm of elastic electron collisions has been revised.

In the presented thesis we attempt to stay in touch with the state of the art development in the field of short pulse high intensity lasers and via computer simulations address the questions which are of prime importance in the context of contemporary experiments. On one hand, most of the simulations are performed in accordance with certain recent experiments, on the other hand the theory provided for explanation of the results is mostly generalizeable.

The thesis is organized in order to provide an introduction to the generation and amplification of ultrashort laser pulses and their interaction with matter, to review the theory relevant in this context, to give details about our simulation technique, and finally to present and discuss the most important results obtained. Particularly, we demonstrate that:

- The efficiency of resonant absorption and hot electron acceleration may be significantly influenced by variable plasma ionization if the preplasma has a relatively long and slowly decreasing undercritical part of the density profile.

- Variable plasma ionization may have a significant effect on the divergence of laser accelerated hot electron beam for particular target materials and laser irradiation conditions.
- Electric field formed by the highest energy electrons at the head of a high-current relativistic electron beam propagating in dielectric material determines the beam propagation velocity, the shape of its distribution, and also its energy losses.
- The highly ionized heavy ions are responsible for shaping the energy distribution of light ions and formation of a quasi-monoenergetic peak in the target normal sheath acceleration process.

We believe that the presented simulations bring new and interesting information about the importance of ionization process in the short pulse laser solid target interactions. Hereafter, we would like to continue in the theoretical study of these interactions and particularly in the study of the charged particle acceleration and transport. We are convinced that this will be one of the leading trends in modern science and that the range of applications of short high intensity laser pulses will increase with further development of experimental techniques and devices as well as deeper theoretical understanding.

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Summary

The presented thesis is based on a theoretical study of short-pulse laser interactions with solid targets and related phenomena. We utilize relativistic electromagnetic code based on the Particle-in-Cell method to describe laser interaction with target and subsequent transport of fast charged particles in plasma. Our code is one-dimensional in space and three-dimensional in velocity and it evolved from the code LPIC++. In the frame of the thesis the code has been improved by incorporating ionization physics and revision of binary collisional algorithm. The theories of collisional ionization, electric field ionization and elastic collisions in plasma are reviewed and our computational algorithms based on these theories are described in details. Our code has been applied to study acceleration of electrons in the laser target interaction region, propagation of hot electron beam inside a cold dielectric target and acceleration of ions from the rear side of laser irradiated thin foils.

We demonstrate that electric field ionization decreases efficiency of electron acceleration due to resonance absorption in plasma with slowly decreasing undercritical density profile. Using this density profile our results show a good agreement with recent experiments of K-α emission from laser irradiated thin foils realized by the group of Dr. Zhavoronkov. It is also found that electric field ionization has a significant effect on the angular distribution of electrons accelerated by high intensity laser pulses, namely it increases the divergence of the hot electron beam.

In the study of hot electron beam transport in cold dielectric target carried out with Prof. Tikhonchuk we demonstrate that propagation of the beam is determined by self-induced quasistatic electric field. This field ionizes the target and provides seed population of free return current electrons. The shape and amplitude of the field depend on the hot electron beam density which results in relation between the beam density and its propagation velocity and energy losses.

In collaboration with Dr. Brantov acceleration of ions from the rear side of laser irradiated thin foils composed of multiple species of ions is studied. It is demonstrated that the process of acceleration of lighter ions in the presence of heavier ions results in formation of quasi-monoenergetic peak in the distribution of lighter ions observed in recent experiments.

Souhrn

Předkládaná disertační práce se věnuje studiu interakce velmi krátkých laserových pulsů s pevnými terči a jevy s touto interakcí souvisejícími. Ke studiu interakce laserového záření s terčem a transportu nabitých částic v plazmatu je použit počítačový kód založený na metodě Particle-in-Cell. Tento kód je relativistický, elektromagnetický, prostorově jednorozměrný, avšak třírozměrný co se týká rychlostí částic a složek elektromagnetických polí. Náš kód je odvozen od původního kódu LPIC++. V rámci této disertační práce byl kód vylepšen přidáním procesů ionizace a rozšířením algoritmu pružných srážek. V disertační práci jsou shrnuty teorie týkající se těchto procesů a detailně popsány použité výpočetní algoritmy.

Upravený PIC kód byl použit ke studiu urychlování elektronů v oblasti interakce laserového záření s terčem, šíření elektronového svazku s vysokou proudovou hustotou uvnitř nevodivého terče a urychlování iontů ze zadní strany laserem ozařované tenké fólie.

V práci je demonstrován vliv ionizace elektrickým polem laserové vlny na účinnost s jakou jsou urychlovány elektrony při rezonanční absorbci laserové vlny v podkritickém plazmatu. Výsledky prezentovaných výpočtů jsou v dobré shodě s experimenty prováděnými skupinou Dr. Zhavoronkova. V další části práce je rovněž demonstrován vliv ionizace polem laserové vlny na úhlové rozdělení s jakým rychlé elektrony opouští interakční oblast na povrchu terče.

Ve spolupráci s Prof. Tikhonchukem jsme studovali rovněž šíření elektronového svazku v nevodivém materiálu. Podařilo se nám vypočítat vlastnosti elektrického pole indukovaného v nevodivém materiálu, které materiál ionizuje a poskytuje tak volné elektrony potřebné ke vzniku zpětného proudu. Závislost profilu a maximální hodnoty elektrického pole na hustotě elektronového svazku vede k tomu, že se elektronové svazky s různou hustotou šíří různou rychlostí a s různými energetickými ztrátami.

Při studiu urychlování iontů ze zadní strany laserem ozařované tenké fólie jsme ve spolupráci s Dr. Brantovem rovněž ukázali, že v terčích složených z více druhů iontů souvisí vznik monoenergetického spektra lehkých iontů s urychlováním težších iontů.