Laser absorption, electron acceleration and K-α emission in short–pulse laser–target interactions

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Elastic Coulomb collisions have been incorporated into our 1D3V relativistic electromagnetic PIC code and the impact of collisions on short laser pulse interactions with dense targets is demonstrated. PIC code has been supplemented with temporally resolved Monte Carlo code in order to model K-α emission from laser–heated solid targets. Simulations show that generation of intense extremely short (200 fs) K-α x–ray pulses is feasible.

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Key words: PIC simulations, Coulomb collisions, hot electrons, ultrashort x–ray pulses

1 Introduction

High–intensity ultrafast lasers with chirped pulse amplification have opened a new field of study of laser interaction with solid targets. Very short temporal and spatial scale plasmas are produced with highly transient and nonequilibrium properties. These plasmas have attracted attention as potential sources for ultrafast pulsed x–rays in the sub–keV energy range [1] and in the keV range [2], [3]. Experimental efforts for bringing picosecond time resolution in x–ray diffraction, spectroscopy, or microscopy of transient phenomena has been reported [4], [5].

Investigations of high–intensity short–pulse laser interactions with plasmas rely extensively on numerical computations. In most cases, plasma dynamics has been described by collisionless Vlasov equation solved either directly, or more frequently via Particle–In–Cell (PIC) approach. Collisionless approximation has often been used even though the impact of Coulomb collisions on interactions of laser pulses with solid targets is significant. Firstly, electron–ion collisions are responsible for the inverse bremsstrahlung absorption of laser energy. Secondly, they transfer energy from the electrons to the ions and from the transverse velocities to the direction parallel to the laser beam propagation.

In the first part of our paper the methodology is described how elastic Coulomb collisions are incorporated into our PIC code and the impact of collisions on short laser pulse interactions with dense targets is demonstrated. In the second part of paper, PIC code is a component of methodology that is used in a theoretical study of laser energy transformation into an ultrashort pulse of K-α emission suitable for material diagnostics. Here, hot electrons accelerated by p–polarized obliquely incident laser radiation penetrate deep into solid target where they produce vacancies in K-shell of target atoms and a part of these vacancies is filled via radiative process generating K-α emission.

2 PIC code and Coulomb collisions

Our PIC code evolved from LPIC++ code [6], which was developed at Max–Planck–Institute für Quantenoptik in Garching, Germany. The code is based on one–dimensional, electromagnetic, relativistic algorithm, where all three velocity components are included, and thus interactions of circularly polarized laser waves with plasmas can be modeled. The code enables to study oblique incidence of laser radiation by using boosted frame via relativistic Lorentz transformation. The code was originally intended for studies of laser interaction with thin foil targets. The code was parallelized by using PVM (Parallel Virtual Machine) library and thus its excellent performance enables using large number ($> 10^6$) macroparticles in order to suppress noise.

In order to be able to study phenomena influenced by particle collisions, we have added an algorithm describing elastic short–range Coulomb collisions. The implemented methodology was originally proposed by Takizuka and Abbe [7]. This method involves the following three steps:

1. Assort particles within the same cell in a random way into the groups of electrons and ions.
2. Particles are paired. In general, for two species plasma, there may be three kinds of pairs: electron–ion, electron–electron and ion–ion.
3. Small–angle collisions are performed pairwise so that small angle random deflections with the mean variance given by standard Rutherford scattering formula are taken into account.

The algorithm of our electromagnetic PIC code with collisions is schematically depicted in Fig. 1.

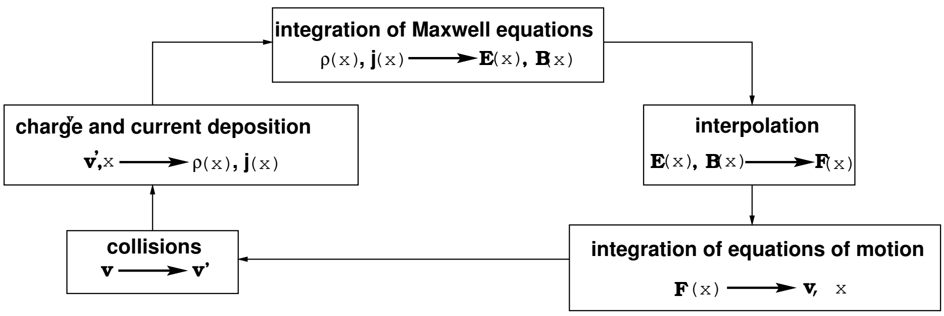

Fig. 1. Scheme of the computational time step in our PIC code with collisions included using methodology by Takizuka and Abe [7].

The applied method has also some disadvantages. Firstly, collisionless code is nearly three times faster in comparison with its collisional counterpart. Secondly, our experience shows that the noise in our PIC code is enhanced considerably when collisions are included. Consequently, it is essential to use a very high number of particles (> 1000) per one cell in order to obtain accurate and reliable results.

The algorithm of Coulomb collisions was extensively tested. The results of several model tasks: electron–ion relaxation, relaxation of uniform electron velocity distribution to a Maxwellian, and attenuation of a weak electromagnetic wave (inverse bremsstrahlung absorption) during its propagation through a homogeneous plasma were successfully compared [8] with analytical solutions.

Here we present our result demonstrating clearly how wrong collisionless model of interaction of intense short pulse with dense plasma may be. The experimental conditions are taken from early simulations by Wilks et al. [9], where collisionless shock wave induced by ponderomotive force of intense laser radiation was discovered. We have performed collisionless and collisional simulations of interaction of ultrashort 50 fs FWHM laser pulse of $\sin^2$-shape, normally incident on solid density Al foil. Laser wavelength $\lambda = 0.4\,\mu$m, maximum intensity $I = 2.6 \times 10^{18}$ W/cm^2 corresponds to normalized electron oscillation velocity $a_0 = e\,E/m_e\,\omega\,c = 0.55$, where E is laser electric field. Fully ionized ($Z = 13$) Aluminum of solid density is equivalent to the electron density $n_e = 125\,n_c$, where n_c is the critical density. Initial electron and ion temperatures are set to $T_e = T_i = 100$ eV. The plasma foil of thickness 250 Å is divided into 100 cells loaded evenly with 1000 macroparticles.

Plasma density profile at laser pulse maximum is presented in Fig. 2. The most significant effect of collisions is that shock–like structure caused by radiation pressure which can be seen in the collisionless case disappears when collisions are included. The other important fact is a significant enhancement of foil expansion due to plasma heating and ion acceleration in the presence of collisions. A very similar result was presented in [10], using an independent one dimensional PIC code with only 2 velocity components.

3 K-α emission from laser–heated solid Al targets

K-α emission is a particularly interesting x–ray source due to relatively high laser energy transformation efficiency and short pulse. This incoherent but nearly monochromatic x–ray emission is produced predominantly inside dense target and it is synchronized with laser pulse. It was already used in pump–probe experiments to measure dynamic response of various materials by means of x–ray diffraction with picosecond temporal resolution [5].

The purpose of our study is not only to calculate the efficiency of laser energy transformation into K-α emission, but also to obtain the duration and the shape of the emitted pulse. We will assume moderate laser intensities, as according to analytical estimates [11], subpicosecond K-α pulses are achievable only for intensities $I\lambda^2 \leq 10^{17}$ W/cm$^2 \times \mu$m^2. We present here the results calculated for conditions of experiments [12] where 120 fs pulses of p–polarized Ti:Sapphire laser ($\lambda = 800$ nm) irradiated solid bulk Aluminum targets at the incidence angle of 45°. Prepulse of intensity 4×10^{14} W/cm^2 was applied at variable time separation ahead of the main pulse of maximum intensity 4×10^{16} W/cm^2.

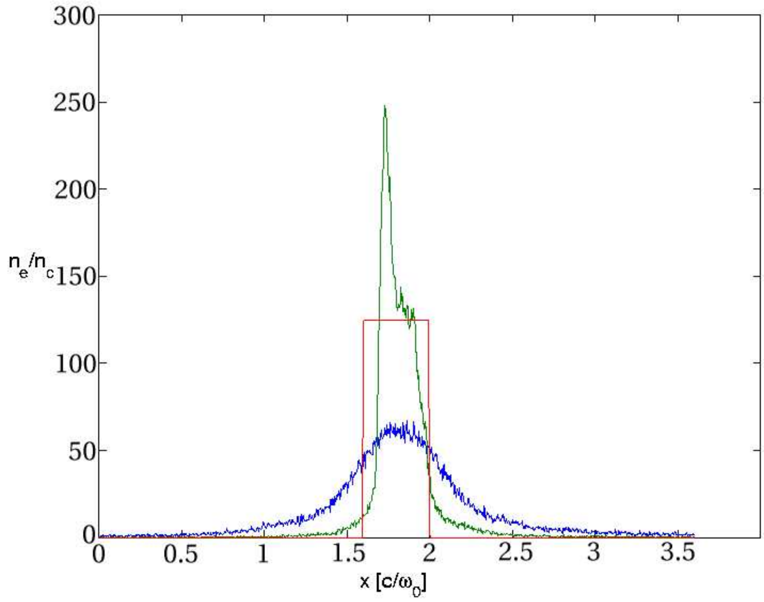

Fig. 2. Spatial profile of electron density. Red line denotes initial density profile at $t = 0$, the collisionless simulation result at laser pulse maximum ($t = 340\omega_0^{-1}$) is plotted with green line, while the collisional simulation result at the same time is drawn with blue line.

These experiments are modeled in one–dimensional planar geometry. The interactions of obliquely incident p–polarized femtosecond laser pulses with plasma are here investigated via our relativistic PIC code using "boost" frame. Exponential electron density profiles at plasma–vacuum boundary are assumed with density scale lengths L corresponding to various main pulse delays. Mean ion charge $Z = 10$ and initial temperatures $T_e = 600$ eV and $T_i = 100$ eV are taken from the experiment. Thick targets are assumed here and the simulation box is limited to a thin layer of highly ionized plasma near plasma–vacuum boundary. In the simulation box, exponential density profile is supplemented by a layer of thickness $\simeq \lambda$ of constant maximum density. For computational time–saving reasons, the maximum density is "ad hoc" fixed to $n_e = 10\ n_c$, where n_c is the critical density. The boundary condition at simulation box – target boundary ensures that electrons flowing out from simulation box are substituted by a flow of Maxwellian electrons at initial temperature. PIC code output for Monte Carlo code includes times when electrons cross the boundary and their velocity vectors.

The calculated spectra of electrons entering the target are plotted in Fig. 3 for different density scale lengths L. Only electrons with energy above K-shell ionization threshold are included. It is shown that maximum hot electron energy is achieved for density scale length $L/\lambda = 0.2$ when the resonance peak of longitudinal electric field near the critical surface is maximum.

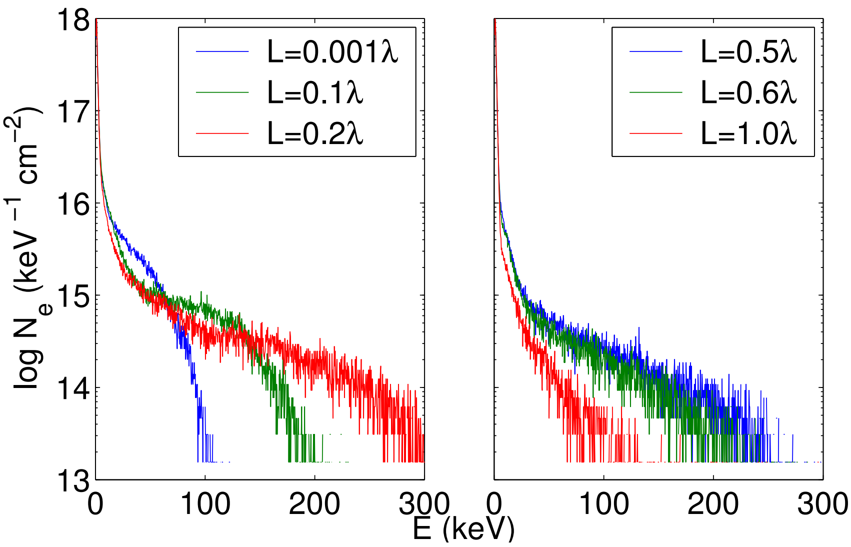

Fig. 3. Spectra of energetic electrons ($\mathcal{E} > 1.5$ keV) entering the target, calculated for various density scale lengths L.

Energetic electrons generated near the target surface during absorption of intense p–polarized laser radiation penetrate deep inside the target and shoot out electrons from the internal K-shell. Monte Carlo code simulates electron trajectories with temporal resolution in detail including all elastic and inelastic scattering events. Energy losses due to bremsstrahlung emission are incorporated in the continuos slowing down approximation. Cross section for the production of K-shell vacancies is taken from [13]. K-shell vacancies are preferentially filled via non–radiative Auger process, the fraction of radiative transitions leading to emission of K-α photons is assumed here 0.04 for Aluminum. At present, our Monte Carlo code does not include hot electron slowing down induced by self–generated electromagnetic fields in the solid target. However, this effect should be minor for the assumed laser intensities, though it is dominant for $I \geq 10^{18}$ W/cm^2 [14]. The reduction of photon number during their transport to the front side of the target according to the Beer's law is taken into account. Photon's time of flight is also included.

Pulses of x–ray emission calculated for conditions of experiment [12] are plotted in Fig. 4. Our simulations reveal extremely short K-α pulse length of order 200 fs (full width at half maximum), which is not possible to measure experimentally due to an insufficient resolution of state–of–art diagnostics. The integral energies of K-α emission are similar to the experimental values [12]. The decrease in the emitted energy with the plasma density scale lengths L is analogous to the simulations

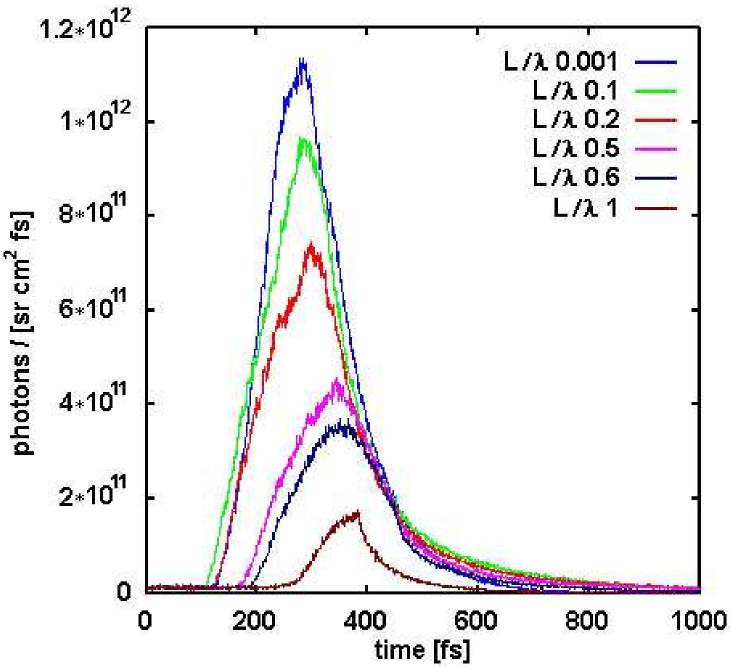

Fig. 4. K-α pulses emitted from target in the normal direction for various plasma density scale lengths L.

in [12], but it is in contradiction with their experimental results where maximum emission is observed for the main pulse delay 9 ps corresponding to the density scale lengths $L = 0.35\ \lambda$. Further refinement of our simulation model is needed to reach a good agreement with experiment.

4 Conclusions

Model of elastic Coulomb collisions was incorporated into our PIC code and inadequacy of collisionless models for simulations of interactions of intense short laser pulses with dense targets was clearly demonstrated.

PIC code was supplemented with our temporally resolved Monte Carlo code in order to model K-α emission from laser–heated solid targets that can be utilized as a suitable source for x–ray diagnostics with subpicosecond time resolution. For the first time, extremely short K-α pulse durations of order 200 fs are revealed.

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