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Simulations of K-α Emission from Short-Pulse-Irradiated Solid Targets

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Abstract

Bright quasimonochromatic K-α x-ray pulses from femtosecond laser-produced plasmas synchronized with the laser pulse are used in many applications to observe dynamic response of various materials. PIC code supplemented with temporally resolved Monte Carlo code is applied here in order to identify regimes where very short intense K-α emission from laser-heated solid targets may be achieved. Generation of intense extremely short (200 fs) K-α x-ray pulses is shown to be feasible.

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 and in the keV range. K-α emission is a particularly interesting x-ray source due to relatively high laser energy transformation efficiency and short 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 [1].

In our simulation of laser interactions with thick solid targets, the target is split into two spatial parts - coronal region and region of solid material far from interaction region. The coronal region is modeled by our PIC code that is used to study interaction of p-polarized obliquely incident laser radiation with plasma. Most of the laser energy is transferred to a group of hot electrons that penetrate deep into solid target. Region inside the target is described by means of our Monte Carlo code with temporal resolution. It is employed for simulation of hot electron transport into solid target. Hot electrons generate vacancies in K-shell of target atoms and a part of these vacancies is filled via radiative process generating K-α emission. Transport of the emitted photons to the front side of target is modeled in detail. The purpose of our study is not only to calculate efficiencies of laser energy transformation into K-α emission, but also to obtain durations and shapes of the emitted pulse.

2 PIC simulations of hot electron spectra

Interactions of subpicosecond moderate intensity p-polarized obliquely incident laser pulses with solid targets are studied here by means of computer simulations. Thick Aluminum targets or thick targets containing Al layer are assumed.

We present here our results calculated for the conditions of experiments [2] where 120 fs pulses of p-polarized Ti:Sapphire laser (λ = 800 nm) irradiated solid bulk Aluminum targets at the incidence angle of 45°. A prepulse of intensity 4×10^{14} W/cm^2 was applied at a variable time separation ahead of the main pulse of maximum intensity 4×10^{16} W/cm^2. We have also

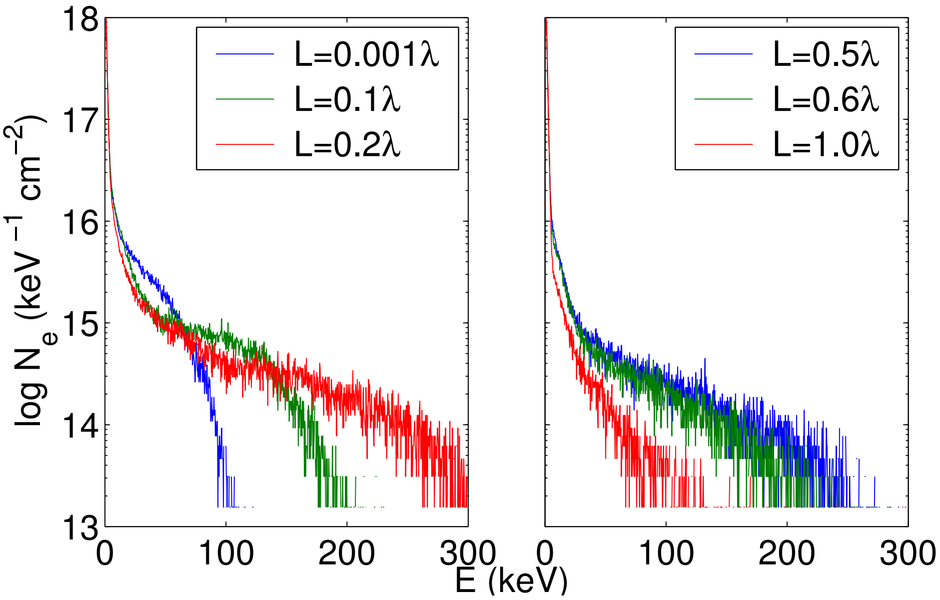

Figure 1: Spectra of energetic electrons ($\mathcal{E} > 1.5$ keV) entering the solid target region, calculated for various density scale lengths L.

performed calculations for similar, but slightly different conditions of experiments by Nakano et al. [3].

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. Our PIC code evolved from LPIC++ code [4], 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 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 and thus noise may be suppressed. In order to be able to study phenomena influenced by particle collisions, we have added an algorithm describing elastic short-range Coulomb collisions using methodology proposed by Takizuka and Abbe [5].

Exponential electron density profiles at plasma-vacuum boundary are assumed here 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 applied 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. 1 for various 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.

3 Hot electron transport into target and K-α emission

Moderate laser intensities are assumed here, as according to analytical estimates [6], subpicosecond K-α pulses are achievable only for intensities $I\lambda^2 \leq 10^{17}$ W/cm^2 $\times$ μm^2. 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. 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 [7].

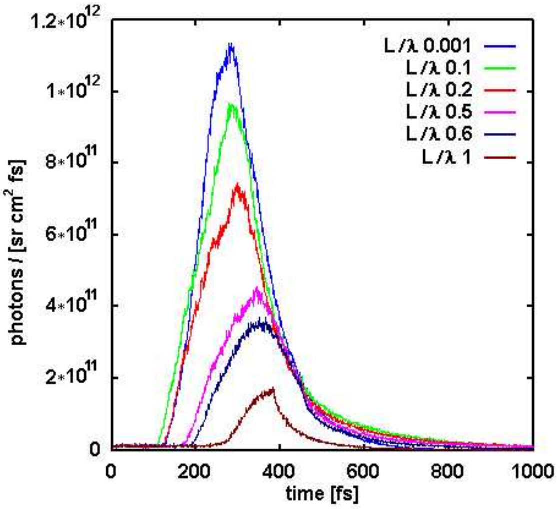

Figure 2: K-α pulses emitted normally from the target for various plasma density scale lengths L.

Our Monte Carlo code simulates electron trajectories with temporal resolution in detail including all elastic and inelastic scattering events. Cross section for elastic events is screened Rutherford, cross section for inelastic events is based on generalized oscillator strength (GOS) model as proposed in [8]. 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 [9]. 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. The number of photons that reach the front side of the target was then reduced according to the Beer's law, which gives the reduction of photon intensity depending on the material and photon energy. Photon's time of flight is also included.

Pulses of x-ray emission calculated for conditions of experiment [2] are plotted in Fig. 2. 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 presented in Fig. 3. The absolute photon numbers agree with the experimental values [2]. However, the decrease in the emitted energy with the plasma density scale lengths L is analogous to the simulations in [2], 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. Simulations were also performed for various finite thicknesses of Al layer on target from lower Z material.

The extremely short K-α pulses generated in the cold solid material are observed in experiment on the background of emission generated in hot plasma corona. The background emission from corona lasts typically much longer $\simeq 10$ ps [10]. We propose to use a suitable thin plastic layer on the target surface to reduce coronal emission in the spectral region of K-α emission.

4 Conclusions

Numerical simulations have been applied for studies of K-α emission from laser-heated solid targets that can be utilized as a suitable source for x-ray diagnostics with subpicosecond time resolution. We have modeled corona using 1D3V relativistic PIC code and dense cold target region by temporally resolved Monte Carlo code in order to calculate K-α emission. This simple model reproduces the efficiency of laser energy transformation into K-α emission, but further improvement is needed to reproduce experimental K-α energy dependence on plasma density scale length. Feasibility of generation of extremely short K-α pulse durations of order 200 fs is revealed.

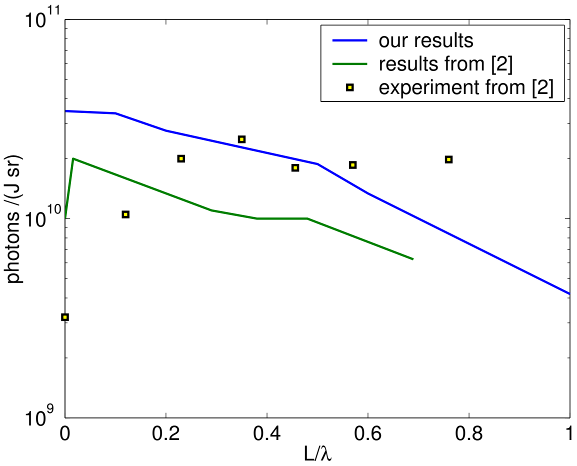

Figure 3: The transformation efficiency of laser energy into the K-α. Blue line denotes our results, green line and yellow boxes computed and experimental results taken from [2].

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